CEMENT - NATURAL RUBBER LATEX STABILIZED RECYCLED CONCRETE AGGREGATE AS A PAVEMENT BASE MATERIAL

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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 2021

มวลรวมรีไซเคิลปรับปรุงคุณภาพด้วยปูนซีเมนต์และน้ำยางธรรมชาติสำหรับใช้เป็นวัสดุถนนชั้นรองพื้นทาง

เนียว วินห์ ดวง

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรดุษฎีบัณฑิต
สาขาวิชาวิศวกรรมโยธา ขนส่ง และทรัพยากรธรณี
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เนียว วินห์ ดวง : มวลรวมรีไซเคิลปรับปรุงคุณภาพด้วยปูนซีเมนต์และน้ำยางธรรมชาติ
สำหรับใช้เป็นวัสดุถนนชั้นรองพื้นทาง (CEMENT - NATURAL RUBBER LATEX
STABILIZED RECYCLED CONCRETE AGGREGATE AS A PAVEMENT BASE
MATERIAL) อาจารย์ที่ปรึกษา : ผู้ช่วยศาสตราจารย์ ดร. MENGLIM HOY, Ph.D., 169 PP.

คำสำคัญ: คอนกรีตรีไซเคิลรวม/การปรับปรุงคุณภาพด้วยซีเมนต์/น้ำยางธรรมชาติ/ถนนชั้นพื้นทาง

ในปัจจุบันนวัตกรรมการก่อสร้างถนนโดยการใช้วัสดุรีไซเคิลหรือวัสดุจากการรื้อถอนสิ่งปลูกสร้าง(C&D) เพื่อเป็นวัสดุมวลรวมทดแทนการใช้วัสดุมวลรวมจากธรรมชาติ เริ่มมีบทบาทสำคัญในหน่วยงานที่รับผิดชอบเกี่ยวกับการก่อสร้างถนนท้องถิ่นในหลายประเทศทั่วโลก เนื่องจากวัสดุมวลรวมจากธรรมชาติที่มีคุณภาพ มีปริมาณไม่เพียงพอต่อความต้องการในการใช้งานที่เพิ่มสูงขึ้น ซึ่งส่งผลให้ต้นทุนในการก่อสร้างถนนเพิ่มสูงขึ้น อีกทั้งยังส่งผลกระทบต่อสิ่งแวดล้อม วัสดุมวลรวมจากคอนกรีตรีไซเคิล (RCA) ประกอบไปด้วยซีเมนต์และมวลรวมเดิม โดยที่ RCA เป็นวัสดุ C&D ที่ได้จากการรื้อถอนโครงสร้างคอนกรีต อย่างไรก็ตามวัสดุ RCA นั้นมีคุณสมบัติไม่เพียงพอที่จะใช้เป็นวัสดุสำหรับก่อสร้างถนนชั้นพื้นทางและรองพื้นทาง ดังนั้นวัสดุ RCA จึงจำเป็นที่จะต้องได้รับการปรับปรุงคุณภาพซึ่งโดยทั่วไปจะใช้การปรับปรุงคุณภาพด้วยซีเมนต์ เพื่อให้วัสดุ RCA มีกำลังรับแรงอัดสูงและสามารถใช้เป็นวัสดุก่อสร้างถนนชั้นพื้นทางและรองพื้นทางตรงตามมาตรฐานเกณฑ์การคัดเลือกวัสดุของหน่วยงานที่รับผิดชอบเกี่ยวกับการก่อสร้างถนนท้องถิ่น แต่ปัญหาของวัสดุ RCA ปรับปรุงคุณภาพด้วยซีเมนต์คือความเปราะ, กำลังรับแรงดึงและแรงดัดต่ำ ซึ่งมักจะนำไปสู่ปัญหาด้านอายุการใช้งาน

งานวิจัยนี้มีวัตถุประสงค์เพื่อศึกษาความเป็นไปได้ในการใช้น้ำยางธรรมชาติที่มีความเป็นมิตรต่อสิ่งแวดล้อม เป็นสารผสมเพิ่มสำหรับการปรับปรุงคุณสมบัติทางวิศวกรรมของวัสดุ RCA ซึ่งปรับปรุงคุณภาพด้วยซีเมนต์เพื่อประยุกต์ใช้สำหรับถนนชั้นพื้นทางและรองพื้นทาง

การศึกษาจะประกอบไปด้วย 3 ส่วนหลัก คือ 1) การศึกษาคุณสมบัติพื้นฐานของวัสดุ RCA ปรับปรุงคุณภาพด้วยซีเมนต์และ RCA ปรับปรุงคุณภาพด้วยซีเมนต์และน้ำยางธรรมชาติ 2) อิทธิพลของน้ำยางธรรมชาติต่อสรรถนะของวัสดุ RCA ปรับปรุงคุณภาพด้วยซีเมนต์ภายใต้แรงกระทำจากการจราจรแบบพลวัตและ 3) ความทนทานของ RCA ปรับปรุงคุณภาพด้วยซีเมนต์และน้ำยางธรรมชาติภายใต้การกระทำของสภาพอากาศแบบวงจรเปียกสลับแห้ง การศึกษาครั้งนี้เลือกใช้ปริมาณซีเมนต์เท่ากับร้อยละ 3, 5, และ 7 และปริมาณยางธรรมชาติจะเลือกใช้เป็นอัตราส่วนยางแห้งต่อซีเมนต์ (r/c) เท่ากับร้อยละ 5, 10, และ 15 โดยที่ตัวอย่างในทุกอัตราส่วนจะได้รับการบ่มด้วยความชื้นภายใต้อุณหูมิ 25±2 °C เป็นเวลา 7 วัน

ผลจากการศึกษาพบว่าที่อัตราส่วน r/c เท่ากับร้อยละ 10, 5, และ 5 เป็นอัตราส่วนที่เหมาะสมที่สุดสำหรับปริมาณซีเมนต์เท่ากับร้อยละ 3, 5, และ 7 ตามลำดับ ซึ่งอัตราส่วน r/c ที่เหมาะสมส่งผลให้ตัวอย่าง RCA ปรับปรุงคุณภาพด้วยซีเมนต์มีกำลังรับแรงอัดสูงที่สุด อีกทั้งการเติมน้ำยางธรรมชาติยังสามารถช่วยเพิ่มความคงทนภายใต้การกระทำของสภาพอากาศแบบวงจรเปียกสลับแห้ง เพิ่มความเหนียวของวัสดุ RCA ปรับปรุงคุณภาพด้วยซีเมนต์ อีกทั้งอายุการล้า และความต้านทานการเกิดร่องล้อของวัสดุ RCA ปรับปรุงคุณภาพด้วยซีเมนต์สามารถพัฒนาได้โดยการใช้ยางธรรมชาติ รวมถึงกำลังรับแรงอัดในระยะยาวเมื่อผ่านวงจรเปียกสลับแห้งและความต้านทานความชื้นของวัสดุ RCA ปรับปรุงคุณภาพด้วยซีเมนต์ยังได้รับการพัฒนาได้โดยการใช้ยางธรรมชาติ

ผลลัพธ์จากการศึกษาในครั้งนี้จะส่งเสริมให้เกิดการประยุกต์ใช้ยางธรรมชาติเพื่อเป็นสารผสมเพิ่มในการก่อสร้างถนนชั้นพื้นทางและรองพื้นทางอย่างยั่งยืน

สาขาวิชา วิศวกรรมโยธา
ปีการศึกษา 2564

ลายมือชื่อนักศึกษา ____________
ลายมือชื่ออาจารย์ที่ปรึกษา ____________
ลายมือชื่ออาจารย์ที่ปรึกษาร่วม ____________

NHIEU VINH DUONG : CEMENT - NATURAL RUBBER LATEX STABILIZED
RECYCLED CONCRETE AGGREGATE AS A PAVEMENT BASE MATERIAL.
THESIS ADVISOR : ASST. PROF. MENGLIM HOY, Ph.D., 169 PP.

Keyword: Recycled Concrete Aggregate/Cement Stabilization/Natural Rubber Latex/ Pavement Base Applications

Recycled concrete aggregate (RCA), containing cement and aggregate, is one of the primary C&D materials obtained from the demolished concrete structures. Recently, innovative road construction methods using construction and demolition (C&D) materials as aggregates to replace natural aggregates are a priority for pavement authorities in many countries. The tendency to use C&D materials as a resource is due to the high demand for virgin aggregates, high construction costs and environmental concerns. However, due to the inferior engineering properties of pure RCA, the cement stabilized RCA is practically used for the road base layer. The cement stabilized RCA material generally has a high compressive strength, and meets the local road-authority requirements for stabilized pavement base course. However, cement-stabilized RCA shows brittle behavior with low tensile and flexural strengths.

This study aims to investigate the possibility of using NRL as a green polymer to enhance the geotechnical properties of cement stabilized RCA for pavement base applications. Besides, the influence of natural rubber latex (NRL) on the mechanistic performance of cement stabilized RCA mixtures is also evaluated.

This thesis consists of three parts: the geotechnical properties of cement stabilized RCA with and without NRL additive; the effectiveness of NRL on the performance properties of cement stabilized RCA under traffic (cyclic) loading conditions; the durability of cement-NRL stabilized RCA mixture under wetting – drying (w-d) conditions. Based on the previous studies, the cement content of 3%, 5%, and 7% with the ratio of dry rubber content in latex (r/c) of 5%, 10%, and 15% were chosen to prepare the stabilized RCA mixtures. All samples are cured for 7 and 28 days under a temperature condition of 25±2°C.

The results show that the r/c of 10%, 5%, and 5% were the optimum NRL additive for 3%, 5%, and 7% cement content that helped the strength of mixtures reach the maximum value. In addition, added NRL enhanced the ductility and toughness improvement for cement stabilized RCA. The brittle behaviour, fatigue life, and anti-rutting of stabilized RCA mixture were improved under the effects of NRL additive. The long-term performance, UCS values decreased with the increase of w-d cycles, and the mixtures with an optimum r/c ratio showed better to resist moisture damage.

The outcome of this study will promise reliable results for the utilization of NRL in pavement base applications as a sustainable additive.

School of Civil Engineering

Academic Year 2021

Student's Signature

Advisor's Signature

Co-Advisor's Signature

ACKNOWLEDGEMENTS

Completing this doctoral dissertation was made possible by the assistance, guidance, and encouragement of many individuals over the last three years. Thus, I would like to take this opportunity to thank the various individuals that helped me during my academic journey.

First and foremost, I would like to thank my academic supervisors, Asst. Prof. Menglim Hoy and Prof. Suksun Horpibulsuk, for their instruction, suggestions, and persistent support throughout this research.

Thanks also extend to the ISI-SUT for providing appropriate equipment and materials for this research. I would like to thank Dr. Apichat Suddeepong and the ISI-SUT’s technical personnel for their invaluable assistance in completing the tests for this research.

I am honored to have been a member of the Vietnam Society for Soil Mechanics and Geotechnical Engineering (VSSMGE) and am grateful to Assoc. Prof. D. Q. Thien, Assoc. Prof. T. T. Nhan, Dr. N. T. T. Nhan, and Dr. P. D. Long for providing me with background knowledge and encouragement over many years.

Friends who have been a rock for me since I came to Suranaree University of Technology including Suwaphit, Toon, Aon, Minnie, Narawit, Kanya, Laksikar, Jigme, Ashok,... over the three years will never be forgotten.

Special thanks are due to 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 sponsoring me during the study period.

Finally, and most importantly, I am eternally grateful to my parents, my sisters, my parents-in-law and my wife - Vicky Hoa, for their never-ending love, support and encouragement.

Nhieu Vinh Duong

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SYMBOLS AND ABBREVIATIONS

% = Percentage
AASHTO = American Association of State Highway and Transportation Officials
AC = Asphalt concrete
Al_2O_3 = Aluminum oxide
ASTM = American society for testing and materials
BS = British standards
BS-EN = British Standards - European Norm
C&D = Construction and demolition material
C_2S = Belite, Dicalcium silicate ($2CaO.SiO_2$)
C_3A = Aluminate, Tricalcium aluminate ($3CaO.Al_2O_3$)
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
C_c = Coefficient curvature
CH = Portlandite, Calcium hydroxide ($Ca(OH)_2$)
cm^3 = Cubic centimeter
CS = Creep slope
C-S-H = Calcium silicate hydrate ($CaO-SiO_2-H_2O$)
C_u = Coefficient uniformity
D = Thickness of sample
DOH, DH = Department of Highways (Thailand)
E = Elastic modulus

SYMBOLS AND ABBREVIATIONS (Continued)

E_{50} = Secant modulus of elasticity

EDS = Energy Dispersive X-ray Spectrometer

Fe_2O_3 = Iron oxide

FESEM = Field Emission Scanning Electron Microscope

FS = Flexural strength

g/cm^3 = Gram per cubic centimetre

G_s = Specific gravity

GW = Well-graded gravel

H = Recoverable deformation

HMA = Hot mix asphalt

HWTD = Hamburg wheel tracking device

Hz = Hertz

in = Inch

IT Mr = Indirect tensile resilient modulus

ITF = Indirect tensile fatigue

ITFL = Indirect tensile fatigue life

ITS = Indirect tensile strength

K_2O = Potassium oxide

Kg = Kilogram

kPa = Kilopascal

kV = Kilovolt

LA = Los Angeles abrasion loss

LOI = Loss on ignition

MDD = Maximum dry density

Mg/m^3 = Megagram per cubic metre

MgO = Magnesium oxide

mins = Minute

mm = Millimeter

MnO = Manganese oxide

SYMBOLS AND ABBREVIATIONS (Continued)

MPa = Megapascal
NA = Natural aggregate
Na_2O = Sodium oxide
NRL = Natural rubber latex
°C = Degrees Celsius
OLC = Optimum liquid content
OMC = Optimal moisture content
OPC = Ordinary Portland cement
P = Applied load
PCC = Portland cement concrete
pH = Potential of hydrogen
psi = Pound per square inch
PVA = Polyvinyl alcohol
r/c = Dry rubber to cement ratio
R^2 = Coefficient of determination
RAP = Reclaimed asphalt pavement
RCA, RCAs = Recycled concrete aggregate
RHA = Rice husk ash
SDS = Surfactant sodium dodecyl sulfate
SEM = Scanning electron microscope
SiO_2 = Silicon dioxide, Quartz
SIP = Stripping inflection point
SO_3 = Sulfur trioxide, Sulfite
SS = Stripping slope
TiO_2 = Titanium dioxide
TS = Total solids content
TSMA = Two-stage mixing approach
Tx Mr = Triaxial resilient modulus
TxDOT = Texas department of transportation

SYMBOLS AND ABBREVIATIONS (Continued)

UCS = Unconfined compressive strength
USCS = Unified soil classification system
υ = Poisson's ratio
w-d = Wetting-drying
WR = Waste rock
XRD = X-ray diffraction
XRF = X-ray fluorescence
α = Alpha
β = Beta
γ = Gamma
θ = Theta
μm = Micrometre
σ_c/σ_t = Ratio of compressive strength to tensile strength

DECLARATION

The author declares that there are no conflicts of interest. This is to declare that the contents of this thesis are my own work and were performed at the Suranaree University of Technology from 2019 to 2022.

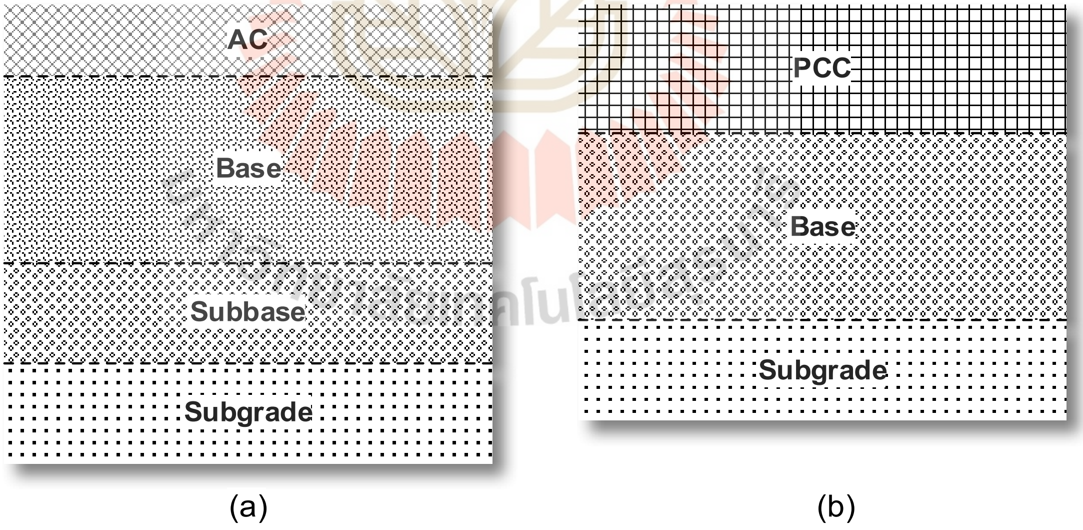
This thesis has not been submitted to any other institution for another degree.

CHAPTER I

INTRODUCTION

1.1 Background

Highway pavements play an essential role in supporting transport connectivity, mobility, and economic growth. There are three different pavement types consisting of flexible pavement, rigid pavement, and composition pavement; the first two types are the most popular (Huang, 1993). The typical cross-section of flexible and rigid pavement structures is illustrated in **Fig. 1.1**. For flexible pavement, the asphalt concrete (AC) layer is placed over the granular base and subbase layers, which are placed on top of the subgrade. For rigid pavement, the Portland cement concrete (PCC) slab can be placed either directly on top of the subgrade or on top of the base layer.



(a) (b)

Figure 1.1 Typical cross-section of flexible pavement (a) and rigid pavement (b).

The base layer is the key structural component for load-carrying capacity in flexible pavement. It provides a uniform and stable support for the overlay AC layer by absorbing a part of traffic loads and load-transferring to the underlying pavement. Therefore, the quality requirements for base materials are usually higher than that of subbase and subgrade. Over the past decades, pavement base materials came from natural sources such as crushed stone or quarry rock of granite, basalt, sandstone, limestone, etc. (Rahman et al., 2020).

Generally, the base materials with satisfied strength and stiffness specifications are typically compacted without any stabilization treatments called unbound base materials (Su et al., 2017). If the materials are unfulfilled with the minimum requirements for base material, they may also be used as subbase or subgrade material, which needs lower standards. In many cases, unsatisfied materials can be improved to fit the standard of pavement base material through chemical treatment such as Portland cement, lime, and fly ash.

The rapid economic and industrial growth worldwide has contributed to the high demand for virgin natural resources, especially in the pavement industry. The issue of natural resources shortage, environment pollution and C&D materials are highly concerned (Maduabuchukwu Nwakaire et al., 2020).

To reduce the dependence on the mineral aggregates from quarry extraction, as well as to improve economic and environmental benefits, several research on the replacement of natural aggregates by the construction and demolition (C&D) materials consisting of recycled concrete aggregate (RCA), reclaimed asphalt pavement (RAP), crushed brick (CB), and waste rock (WR) for pavement base/subbase layers have been conducted recently (Arulrajah et al., 2013; Arulrajah, Ali, et al., 2014; Arulrajah, Disfani, et al., 2014; Jitsangiam et al., 2015; Arisha et al., 2016; Li et al., 2017; Jayakody et al., 2019; Aboutalebi Esfahani, 2020; Pourkhorshidi et al., 2020).

Arulrajah et al. (2013) investigated the geotechnical properties of C&D material, and the result has shown that the geotechnical properties of RCA, CB, and WR are satisfied the specifications of pavement base material, and RAP is approached as a subbase material. However, the shortage of C&D material compared with natural aggregate (NA) are lower compressive strength, rutting resistance, and higher water absorption, which may inhibit the function and durability performance of C&D material for flexible pavement applications (Haider et al., 2014; Mohammadinia et al., 2015).

Thus, the use of stabilization agents for pavement base material becomes necessary during the pavement construction process (Gnanendran & Woodburn, 2003; Gómez-Meijide & Pérez, 2015; Mohammadinia et al., 2016, 2017; Arulrajah et al., 2017; Buritatun et al., 2020; Yaowarat et al., 2020).

1.2 Statement of the problem

Nowadays, the massive C&D materials have been reused in various civil engineering applications, mainly for pavement construction (Mohammadinia et al., 2015). In general, the RCA is occupied a large quantity compared with the stockpile of RAP and CB materials (Arulrajah et al., 2013). Thongkamsuk et al. (2017) reported that in Thailand, approximately 4.2 million tons of C&D materials were generated in 2014, and RCA accounts for 23% of all the C&D materials. Hence, the utilization of RCA materials for pavement construction to solve the disposal problems has become more urgent (Maduabuchukwu Nwakaire et al., 2020).

Currently, cement stabilized RCA is the most preferable in the world because of its high strength and low moisture susceptibility (Agrela et al., 2012; Blankenagel & Guthrie, 2006). As a result, many researchers have evaluated the geotechnical properties and performance characteristics of cement stabilized RCA in pavement foundations in recent years (Agrela et al., 2012; Arulrajah et al., 2015; Cai et al., 2020; S Chakravarthi et al., 2019; Sarella Chakravarthi & Shankar, 2021; Chhabra et al., 2021; Hou et al., 2019; Luo et al., 2021; Mohammadinia et al., 2015, 2019; Sheikh & Shah, 2021; Taha et al., 2020; Zhang et al., 2020, 2021).

The cement has a high contribution to the mechanistic performance of RCA for pavement construction, especially on durability in cement stabilized RCA for flexible pavement base layer. However, it was reported that brittle behavior and low flexibility of the cement stabilized RCA are susceptible to repeated loading which cause micro-crack growth and micro-cracks propagation (Chakravarthi et al., 2019; Mohammadinia et al., 2019). These issues can lead to the pavement distresses and decrease the service life.

To improve the shortcomings mentioned earlier and increase the bearing capacity of cement stabilized RCA mixture, some modified agents, such as fibers and polyvinyl alcohol, were added to the mixture. Crucho et al. (2021a; 2021b) studied the mechanical properties of cement stabilized RCA for the base/subbase layers reinforced by coconut fiber. The results indicated that the mixture had an adequate mechanical performance for pavement application. Similarly, Yaowarat et al. (2020) attempted to improve the quality of cement stabilized RCA by polyvinyl alcohol (PVA). The results have shown that cement-PVA stabilized RCA achieved better mechanical properties consisting of compressive strength and ductility with PVA content of 1.5 or 2.0% and cement content of 3%, respectively.

According to Shaban et al. (2019), polymers can be utilized to enhance the durability performance of RCA mixture due to the chemical interactions with the hydration products and the active polymer coating. Thus, the polymer agent has improved the physical and mechanical properties of the RCA mixture. Recently, natural rubber latex (NRL) has been considered as a polymer modified cement mixture in pavement construction (Buritatum et al., 2021; Udomchai et al., 2021; Yaowarat et al., 2021).

Natural rubber latex (NRL) is a natural polymer resource obtained from *Hevea brasiliensis* trees. The long polymer chain structure of NRL enables it to provide the latex film network across voids and micro-cracks, consequently impacting the strength, elastic properties, and durability performance of cement mixture (Muhammad & Ismail, 2012). Paotong et al. (2020) investigated the strength development of cement stabilized RAP modified by NRL. The results have shown that the stabilized RAP meets the strength requirements of the Thailand Department of Highways for pavement layers by mixing 5-15% NRL content and 3-7% cement content. Buritatum et al. (2021) studied the effect of NRL replacement on cement stabilized soil and found that NRL replacement contributes to enhancing the mechanical strengths due to an improved cohesion of the soil matrix. Udomchai et al. (2021) evaluated the durability of cement-NRL stabilized soil subjected to cycles of wetting and drying (w-d). The obtained results indicated that the optimum NRL replacement ratio of 20% could improve the durability against w-d cycles and enhanced the pavement service life.

Up to date, there is limited information about the effect of NRL on cement stabilized RCA mixture for pavement base application. Thus, it would be profitable to investigate the physical - mechanical properties and durability of cement-NRL stabilized RCA and understand the fundamental knowledge. Due to these reasons, the major target of this thesis is evaluating the geotechnical aspects of cement-NRL stabilized RCA as a pavement base material. Moreover, this research aims to determine the optimum dosage of NRL based on the cement content for achieving the best performance of cement-NRL stabilized RCA mixture. The outcomes of this research will reliably result in the promotion of NRL utilization as a “green polymer” agent for improving the strength and durability of cement stabilized RCA base material in Thailand and other countries.

1.3 Objectives of the study

This research focuses on the geotechnical laboratory properties of cement-NRL stabilized RCA as a pavement base material. The testing program was designed to clarify the optimum dosage of NRL that helps improving the physical and mechanical properties of cement stabilized RCA associated with the specification requirements of pavement base materials. The objectives of this research are addressed in aspects below:

1.3.1 To investigate the possibility of using NRL as a polymer additive for improving the strength characteristics of cement stabilized RCA material.

1.3.2 To study the performance properties of cement-NRL stabilized RCA under traffic (cyclic) loading conditions in the laboratory.

1.3.3 To evaluate the moisture susceptibility of wetting-drying (w-d) cycles on the strength of cement-NRL stabilized RCA.

1.4 Structure of thesis

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

Chapter I presents the introduction part, describing the background information, the problem statement, the objectives, and the thesis structure.

Chapter II presents the literature review of the physical, mechanical, and chemical properties of studied materials consisting of ordinary Portland cement (OPC), recycled concrete aggregate (RCA), and Natural rubber latex (NRL). The cement hydration products, the functional aspects of flexible pavement, and the utilization of RCA incorporating with cement stabilization agent for the pavement construction industry will also be included in detail in this chapter.

Chapter III presents the possibility of using NRL as an additive polymer to improve the strength and durability of cement stabilized RCA material for pavement base applications. The geotechnical characteristics of studied materials consisting of OPC, RCA, and NRL are presented. The influence of NRL on the compaction characteristic of cement-NRL stabilized RCA, and the mechanical properties, including unconfined compressive strength, indirect tensile strength of the mixtures, are exhibited and discussed. In this chapter, the experimental stress-strain relationships at various cement contents (3%, 5%, 7%) and the dry rubber contents in NRL (5%, 10%, 15%) are drawn to understand the behavior of the different RCA blends. The mineral components of mixtures were examined by X-ray diffraction (XRD) along the side of micro-structural aspects of cement stabilized RCA with and without NRL additive were observed by the scanning electron microscope (SEM). The two-stage mixing approach (TSMA) was used to homogenize the RCA blends, and the compacted samples are cured for 7 and 28 days at 25±2°C.

Chapter IV presents the examination of cement-NRL stabilized RCA under vehicle dynamic loading conditions in the laboratory. The resilient modulus, fatigue characteristics, and the resistance to permanent deformation will be investigated and analyzed.

Chapter V presents the effect of wetting-drying cycles on the compressive strength of cement-NRL stabilized RCA mixtures. The chapter will be realistic to assess the integrity and durability of cement-NRL stabilized RCA in severe conditions.

Chapter VI concludes the present work and recommends the topics for further study.

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CHAPTER II

LITERATURE REVIEW

2.1 Introduction

Increased construction and demolition (C&D) materials are one significant problem of global economic development and population growth (Maduabuchukwu Nwakaire et al., 2020). In Asia countries, construction and demolition waste annually generates about 760 million tons, which seems to be higher recently (Hoornweg & Thomas, 1999). According to Kofoworola and Gheewala (Kofoworola & Gheewala, 2009), Thailand generates approximately 1.1 million tons of C&D material per year, including concrete, bricks, tiles, wood, and steel reinforcement. Large volumes of construction waste are yielded and discarded in landfills, resulting in severe risks to human health and the environment.

Silva et al. (2021) analyzed and forecasted the high demand for construction aggregates due to the growth in global construction activity, approximately 48 billion metric tons in 2023. As a result, reuse and recycling of building and demolition waste have shown to be the most essential and promising efforts to minimize environmental issues while keeping construction costs as low as possible.

The primary component of C&D materials is the recycled concrete aggregate (RCA) (Tam, 2008). Over the last decade, many research studies on RCA characteristics and its possible utilization in the construction industry have been conducted (Tam et al., 2018). One of the advantages of RCA is that aggregates may be collected and reused throughout the construction process or repurposed for future construction projects such as pavement foundation layers (Maduabuchukwu Nwakaire et al., 2020). Shaban et al. (2019) discovered that the low quality of RCA is strongly linked to its weakly attached mortar. Additionally, it is critical to strengthen and improve the physical and mechanical properties of RCA to make them more similar to those of natural aggregates.

As a result, cement has been popularly utilized to develop the load-bearing capacity and provide a stiffer colloidal structure (Xuan et al., 2015). However, the challenges of cementitious RCA pavement base material are how to diminish the brittle behavior, strengthen the tensile strain, increase the compressive strength and intensify the durability performance of the mixture (Baghini et al., 2017).

This chapter summarizes the literature on the use of recycled concrete as a pavement base aggregate, as well as the basics of ordinary Portland cement (OPC), cement hydration products, RCA, and natural rubber latex (NRL) - a polymer admixture. This section also provides an overview of the functional and structural of flexible pavement. Finally, the literature on the geotechnical characteristics of cement stabilized RCA and cement-NRL composites is reviewed and stated.

2.2 Ordinary Portland cement (OPC)

2.2.1 Chemical composition of OPC

The most significant material in the construction industry is ordinary Portland cement. Therefore, understanding the characteristics of cement phases is critical for improving cement hydrate production and mixture performance. The OPC employed in all cementitious mixes was a compound of 75% clinker, 5% gypsum ($CaSO_4.2H_2O$), and 20% calcium carbonate ($CaCO_3$), respectively (Rodríguez R. et al., 2021). Clinker is manufactured by intimately mixing the raw ingredients (usually lime, silicate, alumina, and iron) and heating them to around 1450 degrees Celsius.

Clinker is usually composed of 67 % calcium oxide, 22% silicon dioxide, 5% aluminum oxide, 3% iron oxide, and 3% additional components (Barger et al., 2001). Clinker, itself has normally contained four major components called alite or tricalcium silicate ($3Ca.SiO_2$, C_3S), belite or dicalcium silicate ($2CaO.SiO_2$, C_2S), aluminate or tricalcium aluminate ($3CaO.Al_2O_3$, C_3A), and ferrite or tetracalcium aluminoferrite ($4CaO{\cdot}Al_2O_3{\cdot}Fe_2O_3$, C_4AF). Microscopical descriptions of clinker phases are shown in **Figure 2.1**.

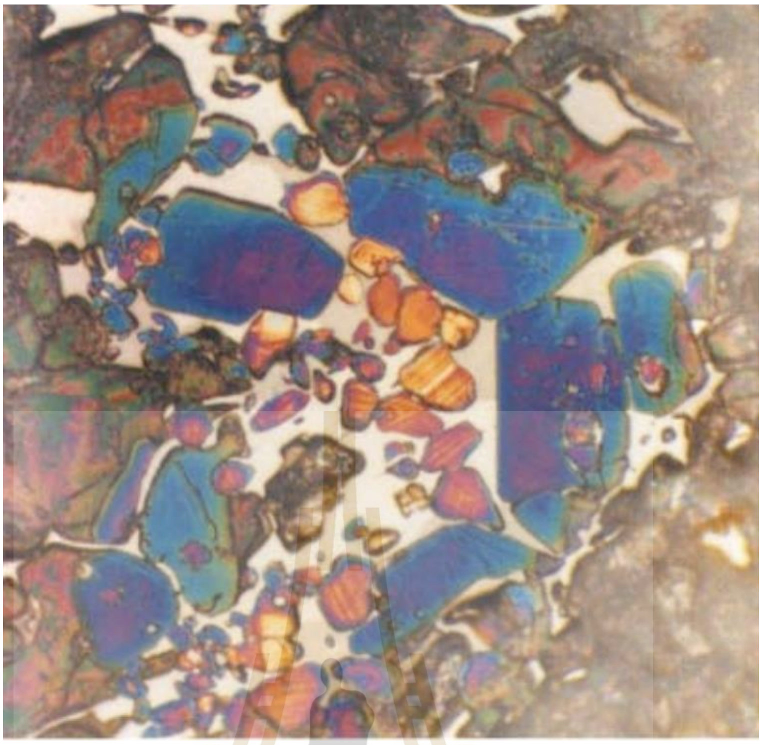


Figure 2.1 Portland cement clinker photomicrograph (Donald H. Campbell, 1999). (Alite is a large, blue-green angular crystal; belite is a tiny, tan-orange circular crystal; ferrite is a brilliantly reflecting crystal; aluminate is a pinkish-gray crystal).

Alite (C_3S) is the most significant component of all typical Portland cement clinkers, accounting for 45 - 60% of total clinker composition (Mamlouk & Zaniewski, 2017). C_3S was synthesized by sintering stoichiometric mixes of $CaCO_3$ and SiO_2 at a molar ratio of 3:1 at 1600°C after homogenization of these materials in a water suspension (Jiang et al., 2020). Due to the strong reactivity of C_3S with water, it is responsible for the cement's short-term characteristics and early strength (Song et al., 2012). According to a number of experimental X-ray diffraction (XRD) patterns, the alite's corresponding peak is a well-defined doublet between 32 and 33° (2θ) (**Figure 2.2**).

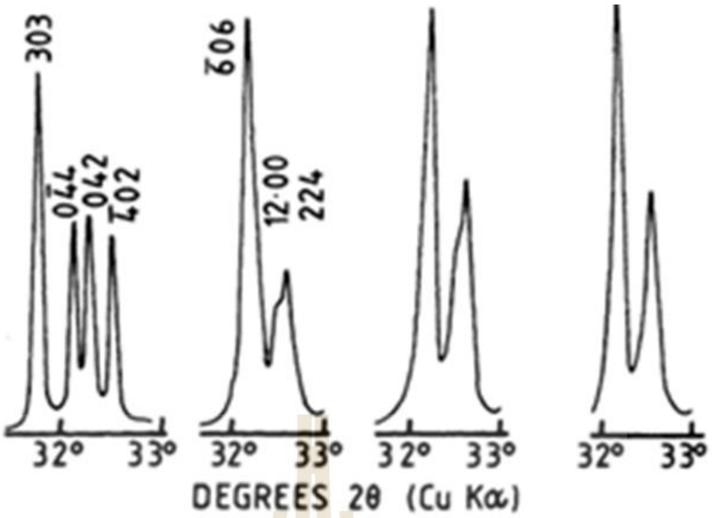
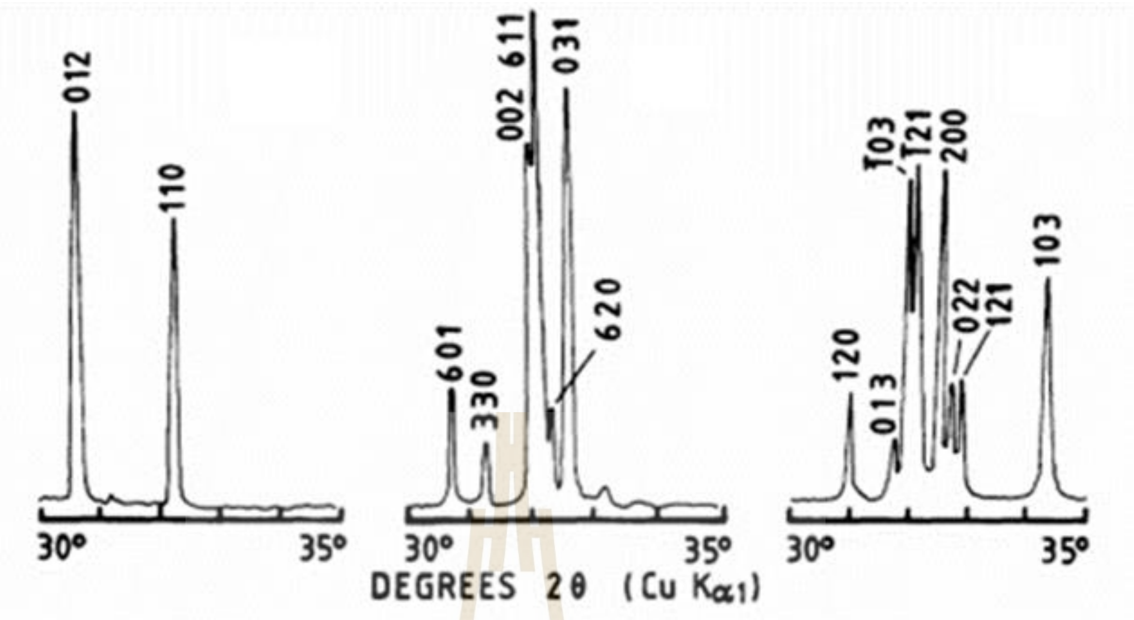


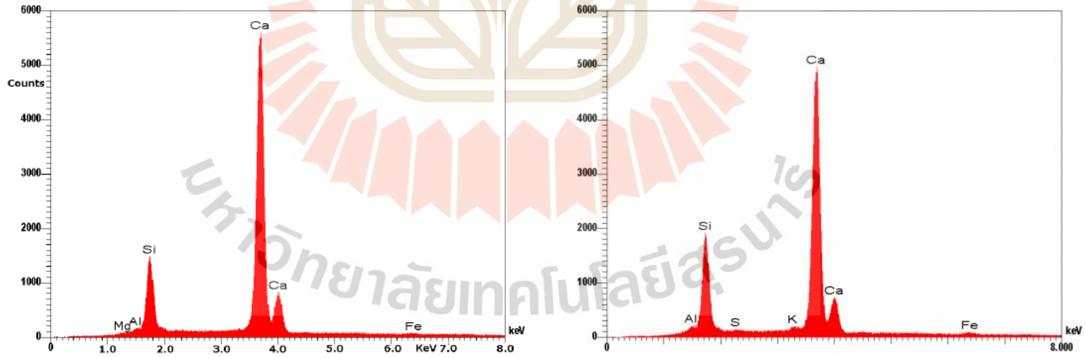
Figure 2.2 X-ray diffraction patterns of alite (C_3S) (Taylor, 1997).

Belite (C_2S) accounts for between 15% and 30% of ordinary Portland cement clinkers. C_2S may be generated under normal cement pre-calciner settings by either direct reaction of $CaCO_3$ with SiO_2 at high temperatures (between 800 and 920°C) and lengthy calcination periods (Alonso et al., 2019). It takes time for C_2S to interact with water, providing just a little amount to the first 28 days of strength but a substantial amount to the following increase in strength at older ages. When tested under comparable conditions over a period of one year, the strengths of pure alite and pure belite are almost identical. The data based on powder XRD patterns obtained for the C_2S are not always reliable, as seen in **Figure 2.3**. Pure C_2S contains 34.9% of SiO_2 and 65.1% of CaO compared to pure C_3S contains 26.3% of SiO_2 and 73.7% of CaO (**Figure 2.4**).



(a) **(b)** **(c)**

Figure 2.3 X-ray diffraction patterns of belite (C_2S) (Taylor, 1997).
(a) α-C_2S at 1500°C, **(b)** α'_L-C_2S at 1000°C, and **(c)** β-C_2S.



(a) **(b)**

Figure 2.4 X-ray spectrum of **(a)** alite and **(b)** belite (Nicholas B. Winter, 2012).

Aluminate (C_3A) covers up between 5% and 10% of the proportion of ordinary Portland cement clinker. C3A was synthesized at 1350°C by sintering a stoichiometric combination of $CaCO_3$ and γ-Al_2O_3 in a 3:1 molar ratio. C_3A in its purest form comprises 62.3 percent calcium oxide and 37.7 percent alumina. In reality, C_3A

interacts quickly with water and may result in an excessively rapid setting unless a setting agent, often gypsum, is added. Moreover, C_3A also plays an important role in thaumasite formation, which is a determining factor in the loss of cementitious strength. Aluminate's XRD powder pattern is distinguished by prominent, singlet peaks at about 33.3°, 47.7°, and 59.4° with 2θ, CuKα radiation (**Figure 2.5**) (Taylor, 1997).

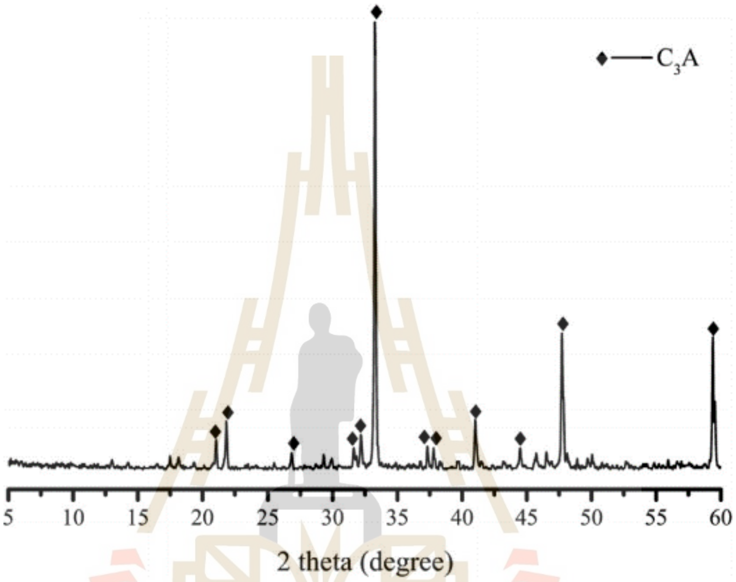


Figure 2.5 XRD pattern of the aluminate (C_3A) (Jiang et al., 2020).

Ferrite (C_4AF) accounts for 5 to 15 percent of Portland cement clinkers. The rate at which it interacts with water seems to be very variable, perhaps due to differences in composition or other characteristics, although it is often high at first and subsequently reduces to very low or very low levels as it matures (Taylor, 1997). Ferrite has the relatively lowest strength compared with alite, belite, and aluminate, but it is very ductile (Mamlouk & Zaniewski, 2017; Neville & Brooks, 2010) (**Figure 2.6**). C_3A and C_4AF contribute to the reduction of the temperature required to create C_3S from 2000°C to 1350°C, therefore conserving energy and lowering the cost of Portland cement manufacturing. C_4AF and its hydrates are responsible for the majority of the color effects that cause the cement to be gray (Kosmatka et al., 2008).

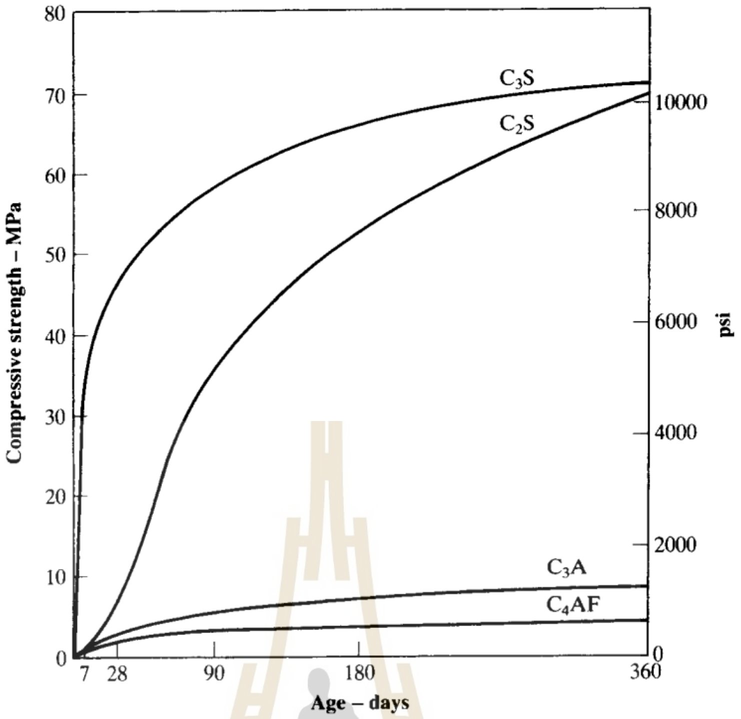


Figure 2.6 Strength development of OPC pure compounds (Neville & Brooks, 2010).

The chemical compositions of OPC as reported by different sources, are presented in **Table 2.1**. The OPC has a high concentration of calcium oxide (CaO) and silicon dioxide (SiO_2), which contributes to the cementitious mixture's desirable properties. All the reported values of the CaO composition of OPC have a range of 62.81 - 65.30%, and most of the SiO_2 values are around 20 to 21%.

Table 2.1 Chemical composition of ordinary Portland cement.

No.	**Chemical components**	**Specifications %, (*)**	**% Composition**		
			(a)	**(b)**	**(c)**
1	SiO_2	17 - 25	20.36	20.99	21.20
2	Al_2O_3	≤ 6.0	5.67	5.98	4.95
3	CaO	60 - 67	62.81	60.78	62.81
4	Fe_2O_3	≤ 6.0	3.84	4.10	2.82
5	MgO	≤ 6.0	2.68	0.96	4.00
6	SO_3	≤ 3.0	2.51	2.86	2.63
7	LOI	≤ 3.0	-	2.04	1.29

Note: **(*)** (Kosmatka et al., 2008) (ASTM C150, 2012), **(a)** (Du et al., 2019), **(b)** (Devi & Khan, 2020), **(c)** (Yoobanpot et al., 2020), LOI: Loss on ignition.

2.2.2 Physical and mechanical properties of OPC

Before OPC can be used in any building project, it must first pass a set of standard tests required by the nation in which the construction will take place (Maduabuchukwu Nwakaire et al., 2020). A conventional Portland cement production facility does not exist; each plant differs significantly in terms of architecture, equipment, and overall look (Barger et al., 2001). As a result, it is necessary to determine the physical and mechanical characteristics of OPC in order to use it in applications. This is done in order to verify that the end product produced via the use of OPC at the various projects meets the very minimal standards for things like specific area, particular gravity setting time, and strength, among other things. The physical and mechanical characteristics of OPC and specifications are mentioned in **Table 2.2**. The largest diameter of the cement particles, according to Kosmatka et al. (2008), is 0.09 mm, with 85 to 95 percent of the particles being less than 0.045 mm in diameter and an average diameter of 0.01 mm. About 7 trillion particles with a total surface area of 300 to 400 m^2 make up each kilogram of Portland cement.

Table 2.2 Physical and mechanical properties of ordinary Portland cement.

No.	**Properties**	**(a)**	**(b)**	**(c)**	**Specifications (*), (a)**
1	Specific surface area (m^2/kg)	300	-	350	≥ 260
2	Specific gravity	3.15	-	-	-
3	Initial setting time (min.)	62	180	215	≥ 45
4	Final setting time (min.)	270	228	290	≤ 375
5	Compressive strength at 28-days (MPa)	45.2	53.7	49.5	≥ 42.5
6	Flexural strength at 28-days (MPa)	-	9.3	8.8	≥ 6.5

Note: **(*)** (ASTM C150, 2012), **(a)** (Devi & Khan, 2020), **(b)** (Li & Hu, 2020), **(c)** (Huo et al., 2021).

2.2.3 Cement hydration reactions

Hydration occurs when the cement particles react chemically with the water. Cement and water mix to create a paste during this process, referred to known as hydration (cement and water). When mixed with aggregates (sand and gravel, crushed stone, or other granular materials like RCA), the paste serves as an adhesive, binding the aggregates together to create a specimen.

Due to the fact that Portland cement is comprised of many chemicals, several reactions occur simultaneously in cement paste. Additionally, gypsum is utilized to postpone the hydration of aluminate. The primary cement hydration reactions are shown in **Figure 2.7**. During silicate hydration, calcium silicate hydrate (C-S-H) and calcium hydroxide (CH) are formed. Mamlouk and Zaniewski (2017) indicated that if C_3S is fully hydrated, it generates 61 percent C-S-H and 39 percent CH, while C_2S produces 82 percent C-S-H and 18 percent CH.

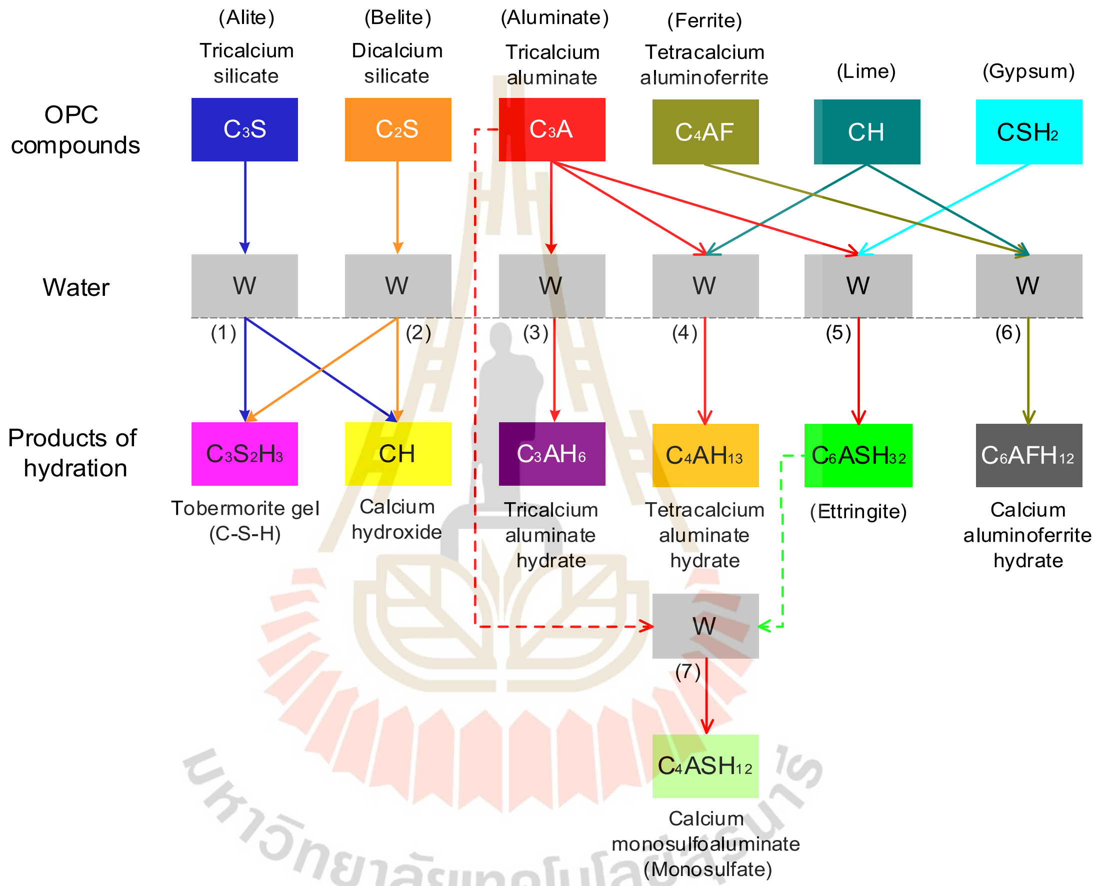


Figure 2.7 Primary chemical reactions of cement hydration process (Barger et al., 2001).

The hydration reactions of OPC as described in **Figure 2.7** may be written as (Mohamed, A. M. O., & Antia, 1998):

$2(3CaO.SiO_2) + 6H_2O \longrightarrow 3CaO.2SiO_2.3H_2O + 3Ca(OH)_2$ **(1)**

Or: $2C_3S + 6H \longrightarrow C_3S_2H_3 + 3CH$

$2(2CaO.SiO_2) + 4H_2O \longrightarrow 3CaO.2SiO_2.3H_2O + Ca(OH)_2$ **(2)**

Or: $2C_2S + 4H \longrightarrow C_3S_2H_3 + CH$

$3CaO.Al_2O_3 + 6H_2O \longrightarrow 3CaO.2Al_2O_3.6H_2O$ **(3)**

Or: $2C_3A + 6H \longrightarrow C_3AH_6$

$3CaO.Al_2O_3 + 12H_2O + Ca(OH)_2 \longrightarrow 3CaO.Al_2O_3.Ca(OH)_2.12H_2O$ **(4)**

Or: $C_3A + 12H + CH \longrightarrow C_4AH_{13}$

$3CaO.Al_2O_3 + 26H_2O + 3CaSO_4.2H_2O \longrightarrow 3CaO.Al_2O_3.\ 3CaSO_4.32H_2O$ **(5)**

Or: $C_3A + 26H + C_3S_3H_6 \longrightarrow C_6AS_3H_{32}$

$4CaO.Al_2O_3.Fe_2O_3 + 10H_2O + 2Ca(OH)_2 \longrightarrow 6CaO.Al_2O_3.Fe_2O_3.12H_2O$ **(6)**

Or: $C_4AF + 10H + C_2H_2 \longrightarrow C_6AFH_{12}$

$2(3CaO.Al_2O_3) + 4H_2O + 3CaO.Al_2O_3.\ 3CaSO_4.32H_2O \longrightarrow 3CaO.Al_2O_3.CaSO_4.12H_2O$ **(7)**

Or: $2C_3A + 4H + C_6AS_3H_{32} \longrightarrow 3C_4ASH_{12}$

Hydration occurs immediately upon contact of the cement with water, and the aluminates hydrate much faster than the silicates, extending the ultimate setting time and increasing the early strength of the cement mixture (Mamlouk & Zaniewski, 2017). The time-dependent reaction is a distinguishing feature of the cement hydration process (**Figure 2.8**). It can be seen the degree of reaction reaches a high level after 7 days.

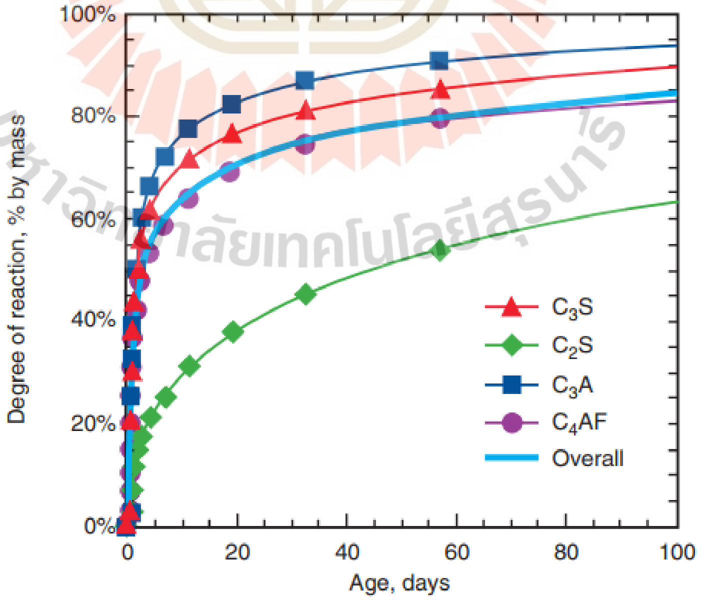
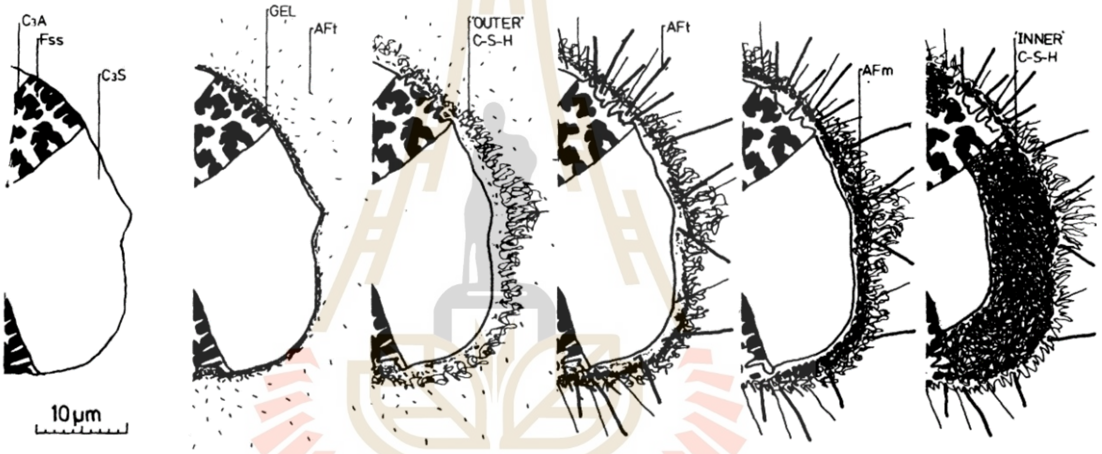


Figure 2.8 Hydration rate of cement compounds during cement hydration process (Kosmatka et al., 2008).

2.2.4 Cement hydration products

When cement comes into contact with water, its components begin to dissolve, resulting in the formation of hydration products such as tobermorite gel or calcium silicate hydrate (C-S-H), calcium hydroxide (CH), and the AFt and AFm phases. In hydrated cement, the AFt and AFm phases are composed of C_3A, anhydrite, and water. Ettringite is the most often occurring AFt phase, whereas monosulfate is the most frequently occurring AFm phase (**Figure 2.9**). In the hydrated cement process, the kind and quantity of solid hydrates produced are affected by several parameters such as cement composition, temperature, and reaction time (Pöllmann, 2017).



(a) (b) (c) (d) (e) (f)

Figure 2.9 Development of cement hydration products with time **(a)** un-hydrated cement grain, **(b)** 10 mins, **(c)** 10 hours, **(d)** 18 hours, **(e)** 1-3 days, **(f)** 14 days (Taylor, 1997).

a. Calcium silicate hydrate (C-S-H)

Combining calcium silicates with water results in the formation of calcium silicate hydrate (C-S-H). Several hours after the water and cement are mixed, crystals begin to form and may continue to develop indefinitely as long as there are undissolved cement particles and residual water in the mixture (**Figure 2.10**). C-S-H is a chemical that is not easily characterized; early morphological forms of C-S-H are the fibrous material with the fibers being up to about 2µm long at aged 10 hours or forming honeycombs (reticular networks) at aged 1 day, as seen in **Figure 2.11**.

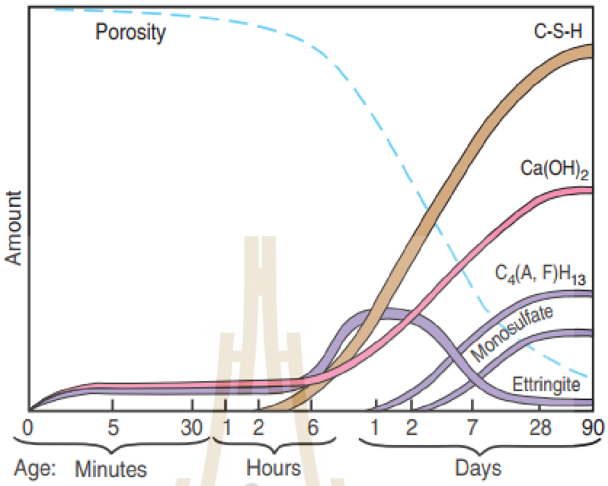
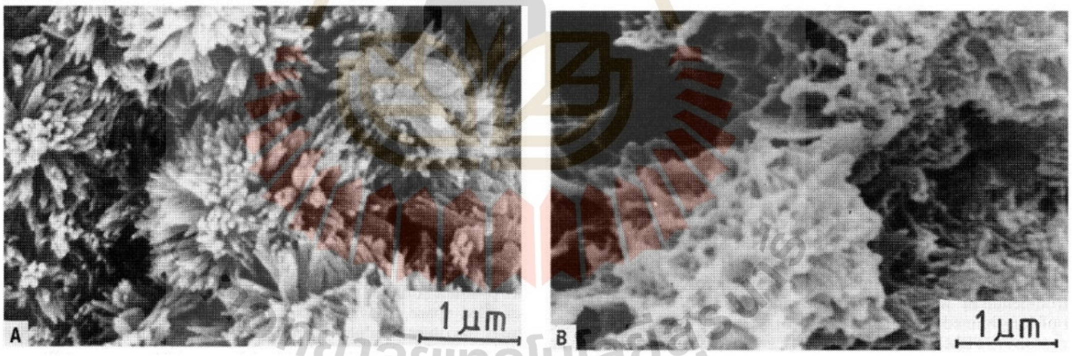


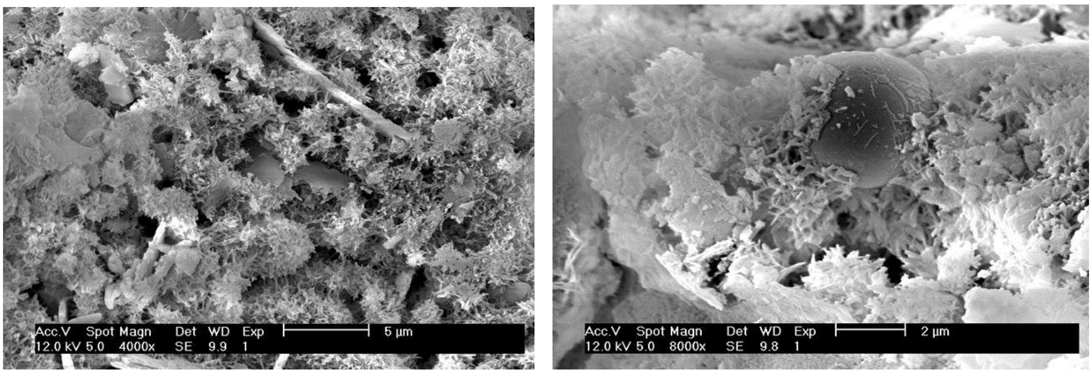
Figure 2.10 Major compounds of hydrating Portland cement with time (Kosmatka et al., 2008).



(a) **(b)**

Figure 2.11 Surface microstructure of C-S-H at **(a)** aged 10 hours and **(b)** aged 1 day (Taylor, 1997).

Cizer et al. (2007) used a scanning electron microscope (SEM) to investigate the cement hydration of rice husk ash (RHA) and indicated that By growing from the grain surface, C-S-H acts as a bridge between hydrated and un-hydrated cement components (**Figure 2.12**).



(a) **(b)**

Figure 2.12 SEM image of **(a)** flocs-like C-S-H phases formed in the matrix of RHA and **(b)** the precipitation of the C-S-H phases on the surface of an RHA grain (Cizer et al., 2007).

b. Portlandite (CH)

Calcium silicate hydrate (C-S-H) and calcium hydroxide ($Ca(OH)_2$ or CH) are produced when C_3S and C_2S react with water. Portlandite is the crystalline form of calcium hydroxide found in the cement hydration process. When C_3S is hydrated, it produces more portlandite than when C_2S is hydrated, as illustrated in equations **(1)** and **(2)**. Portlandite contains about 20 - 30% mass of cement hydration products. Portlandite appears as huge hexagonal crystals under an electron microscope, as shown in **Figure 2.13**.

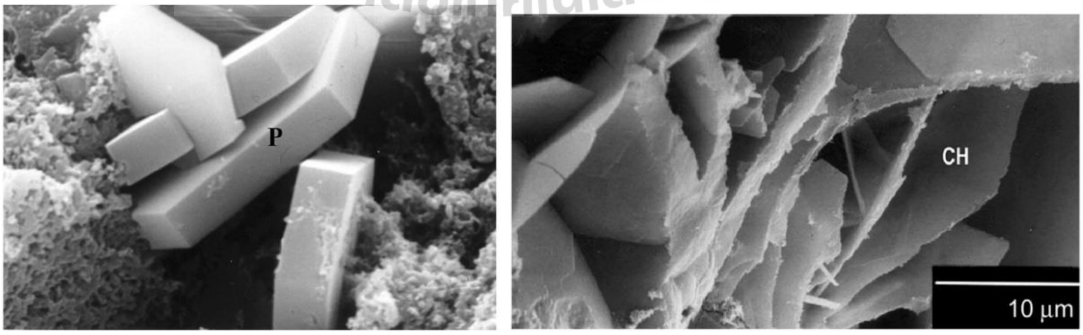


Figure 2.13 Microstructure of portlandite crystals (Aïtcin & Flatt, 2015).

On the aggregate surface, a layer of CH and C-S-H gel forms soon after the concrete components are mixed with water. According to Kurdowski (2014), the layer of perpendicularly aligned portlandite crystals on the top of sand or aggregate grains, as well as occasional occurrences in cement matrix (**Figure 2.14**).

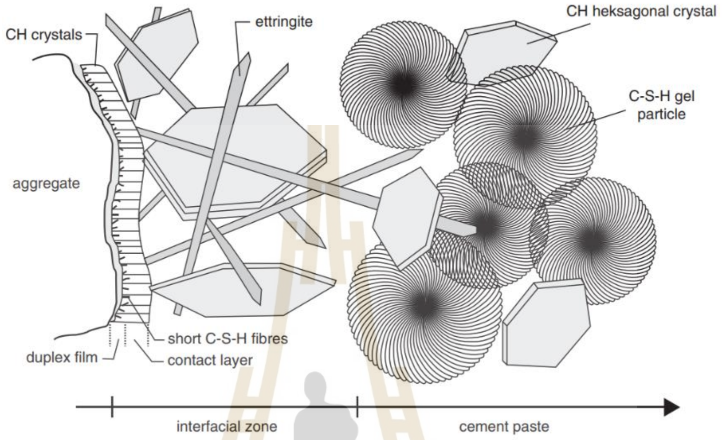


Figure 2.14 Scheme of the oriented crystal of portlandite (Kurdowski, 2014). ***c. Ettringite***

Calcium sulfate is added to and co-ground with the clinker throughout the manufacturing process to regulate C_3A hydration, thus preventing the fast setting and preserving the necessary time of workability before the setting. The hydration of C_3A in the presence of sulfates (in this case, gypsum) results in the precipitation of ettringite (**Equation 5**). Klemm and Adams (1990) found that ettringite was formed during the first 24h and decreased in amount only slightly thereafter. It was discovered by Ogawa and Roy (1982) that the ettringite crystals were originally produced as extremely tiny, unoriented crystals. It is only at this point that the degree of reaction (as measured by the amount of ettringite produced) begins to increase. At this point, the ettringite begins to form as radial growths of needle-like crystals.

Ettringite may be found in a number of morphologies, each of which is determined by the amount of supersaturation present. There are a variety of shapes and sizes available, ranging from little hexagonal prisms to long needles (**Figure 2.15**). Ettringite is stable in the system for as long as sulfates are present, which is normally many days. After reaching the sulfate depletion threshold, the residual C_3A interacts with the ettringite, resulting in the formation of monosulfoaluminate. (Aïtcin & Flatt, 2015). Generally, the initial hydration products of OPC include the ettringite, which can be formed in substantial amounts and appears to provide much of the early strength, as shown in **Figure 2.10**.

(a) (b)

Figure 2.15 Micrographs of ettringite crystals (a) and ettringite is formed in hydrated Portland cement system (b) (Cody et al., 2004).

2.3 Recycled concrete aggregate (RCA)

A material that can form part of construction activities (construction and demolition waste) is Portland cement concrete; crushed Portland cement concrete becomes recycled concrete aggregate (RCA). RCAs differ from natural aggregates (NA) in several physical, chemical, and mechanical characteristics, owing to the presence of bonded mortar (**Figure 2.16**) (De Juan & Gutiérrez, 2009).

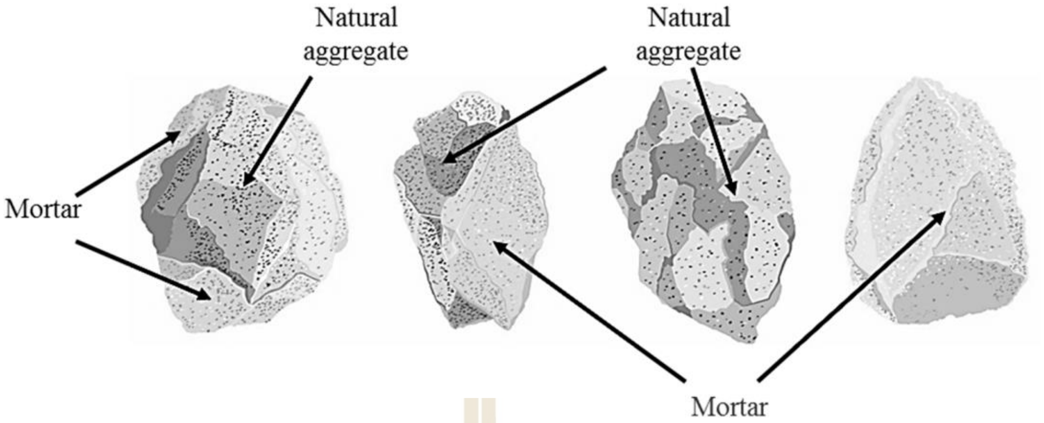


Figure 2.16 Typical recycled concrete aggregate conformations (Sánchez-Cotte et al., 2020).

2.3.1 Geotechnical properties of RCA

In geotechnical application, it was necessary to evaluate the quality of aggregates by carrying out some laboratory tests. The major geotechnical properties of RCA include particle size distribution, specific gravity, water absorption, organic content, flakiness index, Los Angeles abrasion (LA) loss, density, optimum moisture content, and California bearing ratio (CBR) (A. Arulrajah et al., 2013).

Rao et al. (2019) also emphasized that the amount and quality of adhering mortar, the source of old concrete, the strength of the parent concrete from which the RCA was formed, the moisture condition of aggregates, and the technique of crushing all influence the quality of RCA.

According to Maduabuchukwu Nwakaire et al. (2020), the physical characteristics of RCA change depending on the source. The type of RCA source would have a significant impact on the characteristics of the combination. The quality of RCA concrete produced from highway or airbase rehabilitation is better than that acquired from waste recycling facilities using demolition debris (Yang & Lee, 2017). The main physical and mechanical characteristics of RCA with various sources are shown in **Table 2.3**.

Table 2.3 Geotechnical characteristics of NA and some RCA sources.

Properties	RCA (a)	RCA (b)	RCA (c)	RCA (d)	Standard requirements*
Specific gravity - coasse (g/cm^3)	-	2.32	-	-	> 2.5
Specific gravity - fine (g/cm^3)	-	2.66	2.64	-	-
Water absorption - coasse (%)	4.7	9.68	6.50	9.7	< 3
Water absorption - fine (%)	9.8	-	7.35	13.6	
Organic content (%)	2.3	-	-	3.07	-
Coefficient curvature (C_c)	0.9	-	-	1.3	-
Coefficient uniformity (C_u)	31.2	-	-	38.8	-
Fine content (%)	3.6	-	-	6.0	-
Flakiness index	11.0	5.98	-	16.44	< 10
LA abrasion (%)	28.0	34.68	-	30.8	< 35
Maximum dry density (g/cm^3)	1.95	-	1.75	1.96	-
Optimum moisture content (%)	11.0	-	13.2	12.49	-
California bearing ratio (%)	118-160		90-95	-	-

Note: **(a)** (A. Arulrajah et al., 2013), **(b)** (Lee et al., 2012), **(c)** (Jayakody et al., 2019), **(d)** (Mohammadinia et al., 2015), **(*)** (Maduabuchukwu Nwakaire et al., 2020).

These results show that RCA particles absorb more water, have a lower density, and are less resistant to abrasion. Water absorption levels for RCA have been reported to be higher than the specified 3 percent. In all of the cases studied, fine RCA absorbs more water than coarse RCA. In comparison to NA, the presence of remaining mortar on the RCA particles causes RCA to create a more porous surface texture. This porous surface may be rougher and have a greater specific surface area, according to scanning electron microscopy (SEM) research. This helps to explain why RCA has a greater water absorption rate (Maduabuchukwu Nwakaire et al., 2020).

2.3.2 Chemical compositions of RCA

Because of the wide variety of RCA origins and the widely different doses of their original concrete components, the chemical and mineralogical compositions of RCAs are diverse and do not follow a general pattern in terms of elements, compounds, and concentrations (Sánchez-Cotte et al., 2020).

The result of X-ray fluorescence (XRF) tests from various researchers to determine the chemical compositions are summarized in **Table 2.4**. The CaO composition of RCA has varied in the range of 12.01 to 17.38%, whereas that of NA is 2.37. The NA has a lot of silica and aluminum oxide. The RCA has a silica content decrease ranging from 3.22 percent to 14.47 percent but has five to seven times the CaO composition of NA. These indicate a substantial difference in SiO_2 and CaO compositions between RCA and NA. The presence of attached mortar and absorbed cement binder in the RCA causes this.

Table 2.4 Chemical compositions of NA and RCA.

Properties	NA (a)	RCA (a)	RCA (b)	RCA (c)	RCA (d)	RCA (e)
SiO_2	68.59	54.67	54.42	62.56	58.29	65.37
Al_2O_3	12.96	8.58	9.59	12.52	7.69	5.33
CaO	2.37	17.38	14.1	12.01	13.27	13.93
Fe_2O_3	5.40	3.21	3.31	5.82	6.12	2.16
Na_2O	1.97	1.32	1.38	2.69	1.45	1.19
MgO	2.18	2.10	3.28	1.83	2.28	1.91
SO_3	-	-	-	-	-	-
K_2O	3.17	2.08	1.92	1.3	0.8	0.61
TiO_2	0.56	0.33	0.38	0.62	0	0.22
MnO	0.07	0.07	0.1	0.12	0.16	0.05

Note: **(a)** (Yang & Lim, 2018), **(b)** (Bianchini et al., 2005), **(c)** (Bui et al., 2018), **(d)** (Medina et al., 2015), **(e)** (Limbachiya et al., 2007).

2.4 Natural rubber latex (NRL)

Nowadays, polymer latexes are increasingly being employed in civil engineering applications as organic modifiers in paints and coatings, as well as co-binders in conjunction with mineral binders, such as cement (Muhammad et al., 2012; Vo & Plank, 2018). According to Loykaew and Utara (2020), polymer latex has become more common to utilize polymer latex in cementitious materials to increase a variety of qualities such as durability, imperviousness, adhesiveness, mechanical strength, toughness, flexural strength, and water resistance, among others. Latex polymers give cohesiveness to the new mortar and adherence to a variety of surfaces due to their ability to generate flexible and homogenous polymer films. Natural rubber latex (NRL) is an example of a latex polymer that has been widely utilized in cement. NRL is a biodegradable and ecologically friendly material (Kohjiya & Ikeda, 2014).

After air, water, and petroleum, natural rubber is the fourth most significant natural resource on the modern planet. Southeast Asia provides around 90% of the world's natural rubber (Kohjiya & Ikeda, 2014). NRL is composed mostly of cis-1,4-polyisoprene (94% hydrocarbon) and a few nonrubber components (6%), which are spontaneously polymerized from the *Hevea brasiliensis* tree (**Figure 2.17**) (Loykaew & Utara, 2020). NRL is a significant commercial material in the rubber industry, notably in the construction of rubber tyres, because of its outstanding physical qualities, which include high elasticity, high tensile strength, and minimal heat build-up (Muhammad et al., 2012).

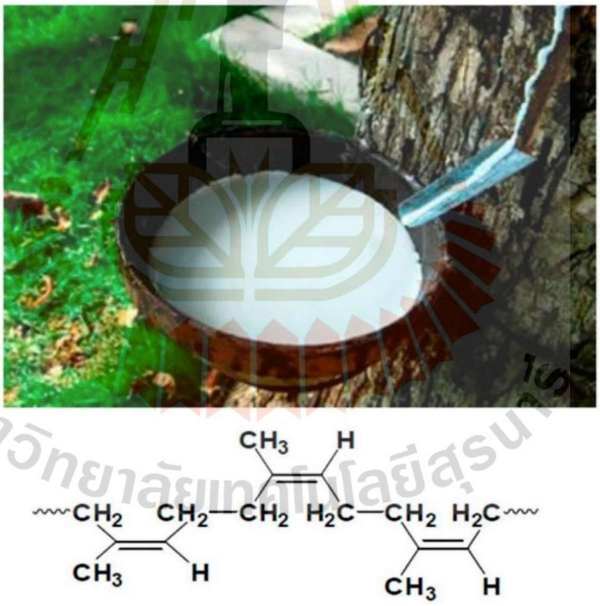


Figure 2.17 Natural rubber latex extracted from a rubber tree and chemical structure of cis-1,4 polyisoprene from NRL (Phomrak et al., 2020).

Due to the fact that *Hevea brasiliensis* latex is the cytoplasm of laticiferous cells, it includes a variety of minerals (**Table 2.5**), all of which remain in NRL samples. Minerals are found in the majority of rubber latex fractions, including the rubber cream that contains rubber particles. The minerals potassium, sodium, magnesium, and phosphorus are the most abundant in latex. Their concentrations vary with clone and season (Rolere et al., 2016).

Table 2.5 The mineral composition of NRL (Loykaew & Utara, 2020).

Mineral	K	Na	Mg	P	Ca	Fe	Rb	Cu	Mn, Zn, Pb
Range of concentration (mg per 100g of latex)	100 - 500	7 - 100	1 - 120	10 - 70	0.05 - 30	1 - 12	0.7 - 4	0.2 - 0.5	Trace

There have been several investigations on the structure of the NR particle surface (Nawamawat et al., 2011). The rigid membrane of the NRL particles is also visible under scanning electron microscopy (SEM), proving that the inner rubber core is fluid. Rubber particles in latex have sizes ranging from 0.01 to 5 µm, with the majority being between 0.1 and 2 µm (**Fig. 2.18**) (Sakdapipanich & Rojruthai, 2012).


(a) (b) (c)

Figure 2.18 Scanning electron micrograph of NRL particles, the bar is 1 µm for **(a, b)** and 2 µm for **(c)** (Kohjiya & Ikeda, 2014).

NRL is a particular kind of cytoplasm that contains a suspension of rubber and non-rubber particles, according to Rejikumar and Philip (2010). When the bark of a tree is tapped, a milky fluid is generated that comprises 30-40% rubber hydrocarbon particles and a few percent nonrubber particles. As shown in **Table 2.6**, commercial NRL is obtained from field latex with additional chemicals and centrifuged to create a concentrated latex with a dry rubber concentration of approximately 60%. Additionally, NRL includes between 2% and 4% of other non-rubber compounds, including lutoids, carbohydrates, proteins, lipids, and inorganic salts. Fresh rubber tree latex is a thixotropic neutral milky fluid with a density of around 0.98 g/cm^3.

Table 2.6 The physical and chemical properties of NRL.

Properties	(a)	(b)	(c)
Total solids content (TS %)	61.50	61.54	62.84
Dry rubber content (%)	60.00	60.09	59.23
Non-rubber content (%)	2.00	1.45	1.40
Volatile fatty acid	0.050	0.018	0.016
pH	11.00	10.07	8.10
Specific gravity at 25°C	0.94	-	1.1

Note: **(a)** (Loykaew & Utara, 2020), **(b)** (Muhammad & Ismail, 2012), **(c)** (Rath et al., 2020).

Finally, it is well known that latex is stabilized with mostly non-ionic surfactants and stirred to guarantee full mixing and avoid rubber particle coagulation (Kohjiya & Ikeda, 2014). Surfactants are divided into four classes based on the nature of the polar head groups, which are shown in **Table 2.7**: anionic, cationic, amphoteric, and nonionic (or polymeric).

Table 2.7 Surfactants in natural rubber latex (Singh & Mei, 2013).

Class	Example
Anionic	Carboxylic acid salts, sulphonic acid salts, sulphuric acid ester salts, phosphoric and polyphosphoric acid esters.
Cationic	Long-chain amines and their salts, quaternary ammonium salts, polyoxyethylenated long-chain amines.
Amphoteric	β-N-alkylaminopropionic acids, imidazoline carboxylates, N-alkylbetaines, sulphobetaines.
Nonionic	Alcohol ethoxylates, alkyl phenol ethoxylates, fatty acid ethoxylates, sorbitan ester ethoxylates, ethylene oxide-propylene oxide copolymers

2.5 Flexible pavement structure

A flexible pavement structure is typically composed of several layers of material such as asphalt layers or surface course, road base/subbase layers, and subgrade. Each layer gets the loads from the layer above, distributes them, and then sends them to the layer below. In flexible pavements, material layers are typically arranged in ascending order of load-bearing capacity, from the greatest load-bearing capacity material (and most costly) to the lowest load-bearing capacity material (and least expensive). Thus, the deeper a layer is in the pavement structure, the less load (in terms of force per area) it must bear (**Figure 2.19**).

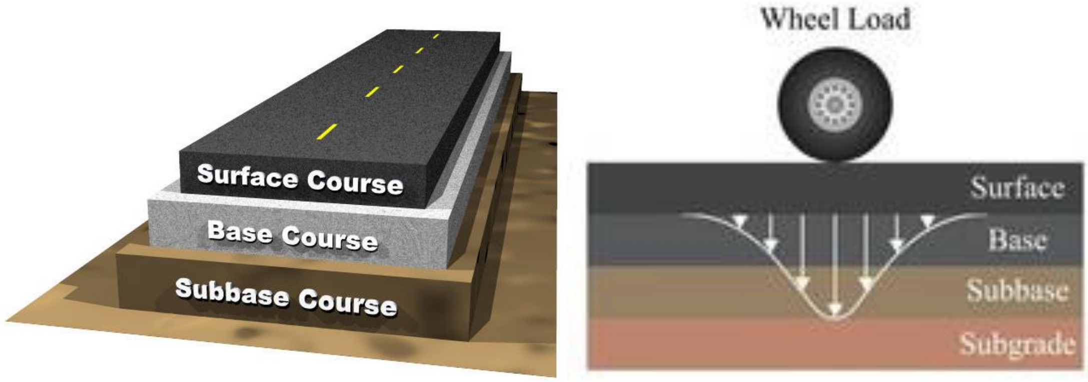


Figure 2.19 Typical cross-section and stress distributions at the top of base layer under wheel load (Zornberg & Gupta, 2010).

2.5.1 Pavement subgrade material

An unconstructed road pavement's subgrade is the natural material that lies underneath it. Prior to the building of a road, it is usual practice to compact subgrade materials. It could be formed by natural soil but also by external supply material. They are sometimes stabilized by the addition of lime (Kang et al., 2015; Prusinski & Bhattacharja, 1999; Tang et al., 2011), Portland cement (Ardah et al., 2017; Pandey et al., 2017; Portelinha et al., 2012; Sinha & Iyer, 2020) or other modifiers such as polymers (Iyengar et al., 2013), rice husk ash (Adeyanju et al., 2020), fly ash (Zumrawi, 2015), glass fiber (Rabab'ah et al., 2021), etc. The subgrade is the pavement structure's foundation, upon which is constructed the subbase or road base. California Bearing Ratio (CBR) tests, falling weight deflectometer back calculations, and other procedures are used to determine the load-bearing strength of the subgrade (Tarefder et al., 2010). According Department of Highway - Thailand (DH S201/2556, 2013) and Asphalt Institute Method (Asphalt Institute, 1970), the required CBR values for pavement structure are presented in **Table 2.8**.

Table 2.8 CBR specifications for pavement layers.

Layers	Base	Subbase	Selected material	Subgrade
CBR values (%)	≥ 80	≥ 25	≥ 8	≥ 4

2.5.2 Pavement subbase layer

The subbase layer is directly underlain a base layer in the pavement structure; it is typically including an unbound coarse aggregate with the thickness of 0.2 to 0.3 m and is placed directly onto a prepared subgrade (Courard et al., 2020). A subbase layer is an optional component of the base course that is often composed of lower-quality crushed aggregate with a CBR value ≥ 25%. It is put under the base course to save money or limit capillary action beneath the pavement. According to a standard specification (ASTM D1241, 2014), the subbase material shall consist of hard, durable, and sound particles with abrasion loss value less than 50%. The gradation requirements for subbase material are the grading ranges (i.e., the upper and lower limits) of the standard specifications, as shown in **Table 2.9**.

Table 2.9 Gradation requirements for crushed aggregate subbase, base, and surface course (ASTM D1241, 2014).

Sieve size (mm)	Gradation A	Gradation B	Gradation C	Gradation D	Gradation E	Gradation F
50	100	100	...	...	...	...
25	...	75 - 90	100	100	100	100
9.5	30 - 65	40 - 75	50 - 85	60 - 100	...	...
4.75	25 - 55	30 - 60	35 - 65	50 - 85	55 - 100	70 - 100
2	15 - 40	20 - 45	25 - 50	40 - 70	40 - 100	55 - 100
0.425	8 - 20	15 - 30	15 - 30	25 - 45	20 - 50	30 - 70
0.075	2 - 8	5 - 15	5 - 15	8 - 15	6 - 15	8 - 15

For several decades, construction and demolition (C&D) waste aggregate has gained widespread acceptance for usage as subbase material in pavement construction. As a result of its high water absorption and abrasion loss, as well as its low California bearing ratio (CBR) value, the use of C&D material for pavement applications has its limits, and it does not meet the requirements of many local road authority regulations as shown in **Table 2.10**. RCA, on the other hand, nearly completely meets these criteria and is suitable for use in pavement subbase layers (A. Arulrajah et al., 2014).

Table 2.10 Typical local-road specifications for the base, subbase materials (A. Arulrajah et al., 2012).

Properties	Standard requirements*
Specific gravity - coasse (g/cm^3)	> 2.0
Specific gravity - fine (g/cm^3)	> 2.0
Water absorption - coasse (%)	< 10
Water absorption - fine (%)	< 10
Organic content (%)	< 5
pH	> 7
Fine content (%)	< 5
Flakiness index	< 15
LA abrasion (%)	< 35
Maximum dry density (g/cm^3)	> 1.8
Optimum moisture content (%)	8 - 15

2.5.3 Pavement base layer

Directly underneath the surface course is the base course. It aids in the distribution of weight and drainage, as well as providing frost resistance. Base courses are often comprised of gravel or hot mix asphalt (HMA). Stabilization of aggregates may be used to increase their stiffness and strength durability. According to Wegman et al. (2017), base stabilization is the process of permanently improving the elastic and strength properties of a base aggregate layer, resulting in a bonded structural pavement layer. Performance evaluations vary according to the stabilizing process and additive used (**Figure 2.20**).

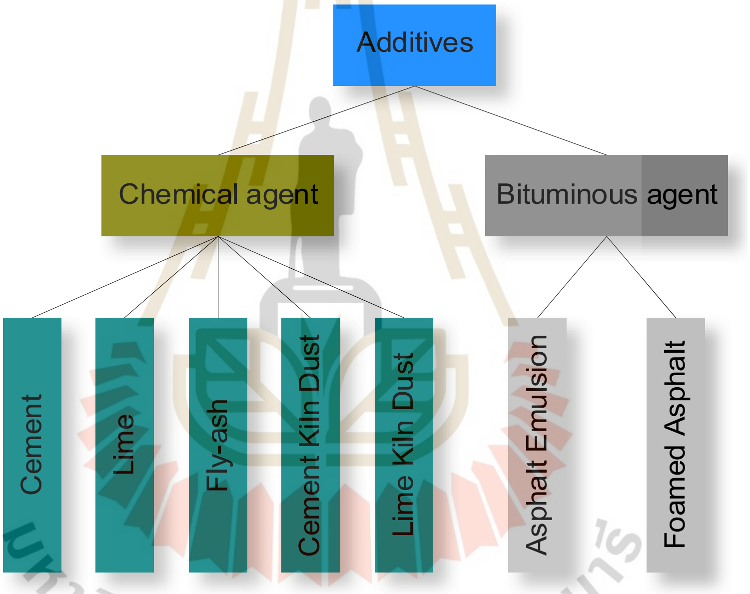


Figure 2.20 Classification of some popular additives in stabilized pavement base.

Stabilizing a base layer may result in a more cost-effective overall equivalent pavement structure with a surface layer that is thinner but not overly thin due to the increased structural capacity resulting from the stabilization of the base (Lav et al., 2006; Marandi & Safapour, 2009; Nagrale & Patil, 2018).

A laboratory mix design is necessary to optimize the kind and amount of additives to be put into the combination in order for it for fulfilling the strength, elasticity, and durability performance criteria (**Table 2.11**).

Table 2.11 The criterion for selecting an appropriate pavement base, subbase materials (Yoobanpot et al., 2020).

Materials	7-day UCS (MPa)	Typical vertical modulus, E (MPa)
Base quality gravel	-	300
Subbase quality materials	-	250
Soil-cement stabilized base	1.724	-
Soil-cement stabilized subbase	0.689	-
Class M, stabilized road base, subbase (TxDOT, 2010)	1.2	-
Class L, stabilized road base, subbase (TxDOT, 2010)	2.0	-

2.5.4 Surface course

Typically, the surface layer is composed of the finest materials. It has properties like as friction, smoothness, noise reduction, resistance to ruts and pushing, and drainage (**Table 2.12**). Additionally, it aids to prevent excessive amounts of surface water from entering the underlying layers such as the base, subbase, and subgrade.

Table 2.12 Typical characteristics of the materials and bituminous mixtures (Thailand Industrial Standards Institute, 2020).

Properties	Standard requirements
Polished stone value	> 50
Flakiness index	< 25

Table 2.12 Typical characteristics of the materials and bituminous mixtures (Thailand Industrial Standards Institute, 2020). (Continued)

Properties	Standard requirements
LA abrasion (%)	< 20
Voids in aggregates	> 15
Voids in mixture (%)	4 - 6
Marshall stability (kN)	> 15
Deformability (mm)	2 - 3
Ratio binder/aggregate (%)	> 4.75
Ratio filler/binder (%)	> 1.3

Aside from that, bitumen standards and a particle size distribution curve must be assessed, and local supplies and manufacturing demands must be available.

2.5.5 Critical stresses/strains

Flexible pavements allow for the redistribution of traffic loads from the contact surface to the underlying layers of the pavement. Stresses are transferred across a larger area than the tire footprint as a result of the bending of the pavement when the tire is under load. When designing a flexible pavement, two critical strains of the pavement structure are taken into consideration: (1) the horizontal tensile strain at the bottom of the asphalt layer, which should be maintained as low as feasible to prevent fatigue cracking, and (2) the vertical stress on the subgrade's top, which should be kept as low as possible to avoid permanent deformations (**Figure 2.21**). The allowed vertical stress at the top of the subgrade is affected by the subgrade's shear strength. Thus the base layer in flexible pavement should be thick enough to minimize vertical deformation to a value less than the permitted distress threshold (Zornberg & Gupta, 2010).

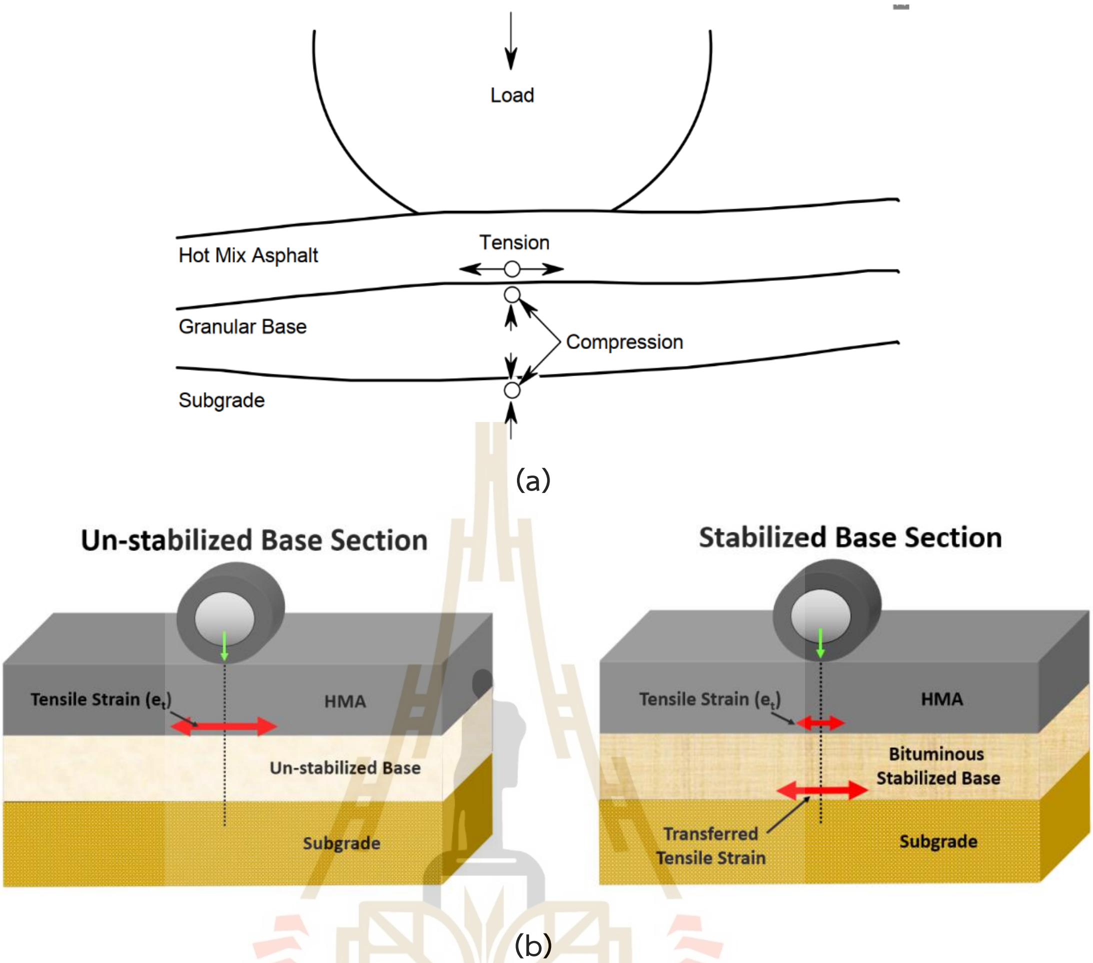


Figure 2.21 Tensile and compression strains in flexible pavement **(a)**, horizontal tensile strain in un-stabilized and stabilized pavement sections **(b)** (Wegman et al., 2017).

2.6 Cement stabilized RCA in pavement base applications

As previously stated, recycling aggregates is less expensive and requires less energy than processing raw aggregates. RCA is a mixture of aggregates and cement mortar that may be utilized as the base material for pavement construction (Obla & Kim, 2009). Numerous studies investigated the use of recycled concrete aggregates in pavement bases, and some limits in terms of environmental issues were discovered (Blankenagel & Guthrie, 2006; Chen et al., 2013).

Cement stabilization of RCA is often used in pavement foundation applications to increase load-bearing capacity and stiffness. Cement stabilized RCA is made by mixing cement with RCA aggregate, compacting it, and allowing it to cure for a certain amount of time to enhance its mechanical qualities (**Figure 2.22**). Furthermore, cement stabilized RCA extends the pavement life even at greater traffic loads and performs better than natural aggregate base material that has not been stabilized (Taha et al., 2020). The unconfined compressive strength (UCS), flexural strength (FS), indirect tensile strength (ITS), modulus, permanent deformation, fatigue, and other performance characteristics of the cement-treated bases were taken into consideration.

Figure 2.22 The preparation of cement stabilized RCA samples (Zhang et al., 2021).

2.6.1 Compaction characteristics

The optimal moisture content (OMC) and maximum dry density (MDD) of the pavement foundation layer are critical in producing the pavement's good compactability. Compaction is normally done in accordance with ASTM D1557 (2012) using a modified Proctor compaction test. In this test, a mold with a diameter of 102 mm and a height of 127 mm is employed, and each layer is compacted using a 4.5 kg hammer dropped from a height of 457 mm. According to Lim and Zollinger (2003), the increased OMC reported for RCA mixes compared to conventional aggregates is due to the RCA's higher water absorption, and coarse RCA has a larger water requirement than fine RCA. Li and Hu (2020) found that when cement content increased, MDD and OMC increased as well (**Table 2.13**). Due to RCA being a blend of NA particles and mortar, its MDD is lower than that of natural aggregate.

Table 2.13 The modified compaction test result of cement stabilized RCA mixtures.

Cement content (%)	MDD (g/cm^3)	OMC (%)
4	2.007	8.5
5	2.015	9.4
6	2.026	10.1

2.6.2 Unconfined compressive strength (UCS)

Unconfined compressive strength (UCS) is an essential metric in pavement design for cement stabilized pavement base materials. The differences in strength and stiffness of the base material with changes in mixing ratio are shown by UCS test results (Imtiaz et al., 2020). According to ASTM D1633 (2017), the specimen size utilized in this test is generally 100 mm in diameter and 200 mm in height, compacted at their optimal conditions (MDD and OMC). In several investigations, a diameter of 100 mm and a height of 100 mm were used (Buritatun et al., 2020; Meng et al., 2021). The produced samples are cured for different lengths of time (such as 7 days and 28 days) before being evaluated for compressive strength on standard compression testing equipment.

TxDOT (2010) specifies guidelines for the building of a pavement base course in Item 276, "Cement Treatment (Plant Mixed)," which includes minimum strength standards for each Class indicated on the designs. The required minimum 7-day unconfined compressive strength for Class L is 300 psi (2070 kPa), whereas the listed minimum compressive strength for Class M is 175 psi (1207 kPa) (Arul Arulrajah et al., 2020). The UCS rises with increasing cement dosage in the cement stabilized RCA samples due to the enhanced interparticle bonding strength within the RCA particles (**Figure 2.23**).

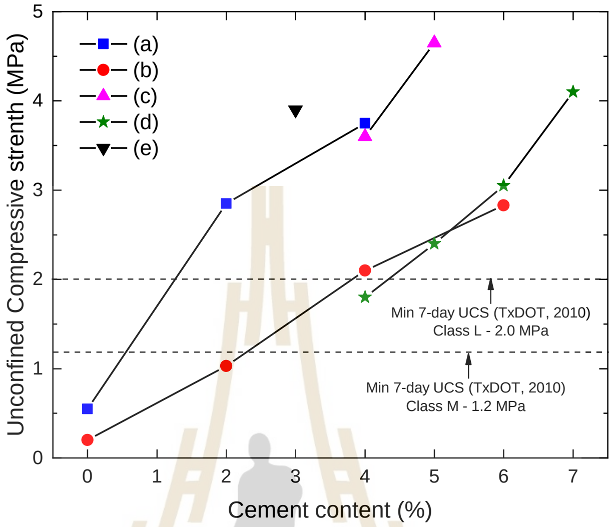
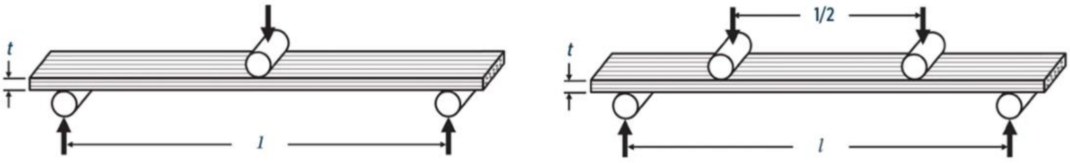


Figure 2.23 Various UCS values with cement content at 7-day curing samples. **(a)** (Mohammadinia et al., 2015)**, (b)** (Faysal et al., 2016)**, (c)** (Hou et al., 2019)**, (d)** 3-days (Ebrahim Abu El-Maaty Behiry, 2013)**, (e)** (Arul Arulrajah et al., 2020)

2.6.3 Flexural strength (FS)

Flexural strength (FS) is simply resistance to bending, which is a critical metric for cement-treated bases due to the bending that occurs during traffic movement. It may be determined using either a one-point or three-point bending test (ASTM C293, n.d.), but more often four-point bending (ASTM C78, 2010), by applying a constant rate of loading.

In three-point flexural bend testing, the greatest or maximum bend stress occurs under the loading anvil. The maximum flexural stress is distributed over the beam's section between loading points in four-point bend tests. Additionally, the three-point test works best with homogenous materials, such as plastics. If the material is not homogenous, a four-point test is often the best option (Khan, 2019). According to the standards, specimens with dimensions of 7×7×28 cm^3 or 10×10×40 cm^3 are acceptable. The flexural strength test is configured as shown in **Figure 2.24**.



(a) (b)

Figure 2.24 Three-point **(a)** and four-point **(b)** flexural strength test apparatus.

Flexural strength is dependent on curing time, cement quantity and typically varies between 10% and 20% of the UCS (Ebrahim Abu El-Maaty Behiry, 2013; Euch Khay et al., 2015). In general, recycled materials have about the same flexural strength as virgin aggregates. According to Disfani et al. (2014), the flexural strength of cement stabilized RCA with a cement content of 3% is 1.23 MPa.

2.6.4 Indirect tensile strength (ITS)

The indirect tensile strength (ITS) of cement stabilized pavement foundation materials is one of the most important qualities since the tensile stresses induced by traffic loads must be kept to a minimum to prevent bottom-up cracking. The tensile forces created at the bottom of cement-treated bases are significant in general, resulting in bottom-up cracking. Test specimens with a diameter of 100 mm and a height of 63 mm, or a diameter of 100 mm and a height of 200 mm, or a height of 150 mm and a diameter of 150 mm are commonly employed. The samples are loaded on a diametric plane and evaluated for ITS at various curing times and cement concentrations (**Figure 2.25**).

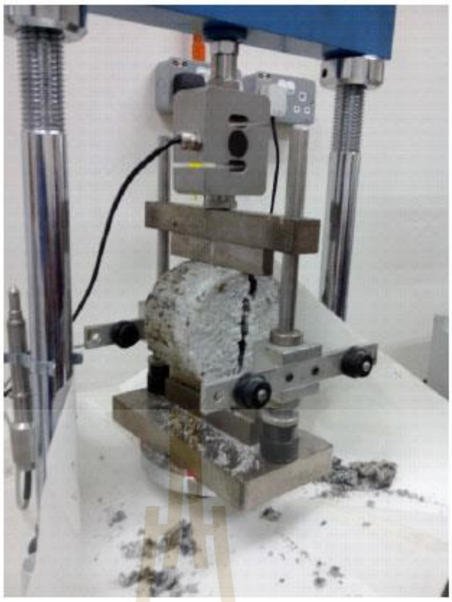


Figure 2.25 Indirect tensile strength testing (Baghini & Ismail, 2015).

The ITS of cement stabilized RCA mixes rises as the curing time and cement content increase (S Chakravarthi et al., 2019; Ebrahim Abu El-Maaty Behiry, 2013). In most countries, cement-treated materials are specified in terms of ITS at a 7-day curing period, as shown in **Table 2.14**. The literature research database's results on the ITS of cement stabilized RCA fulfill the standards (**Figure 2.26**).

Table 2.14 The ITS requirement value for cement stabilized material (Autelitano & Giuliani, 2016).

Country	**Cement content (%)**	**ITS at 7-days (MPa)**	**Note**
Italy	2 - 4	0.32 - 0.60	Gyratory compactor
		> 0.25	Proctor hammer
South Africa	1.5 - 3.0	> 0.25	-
	3 - 5	> 0.20	-

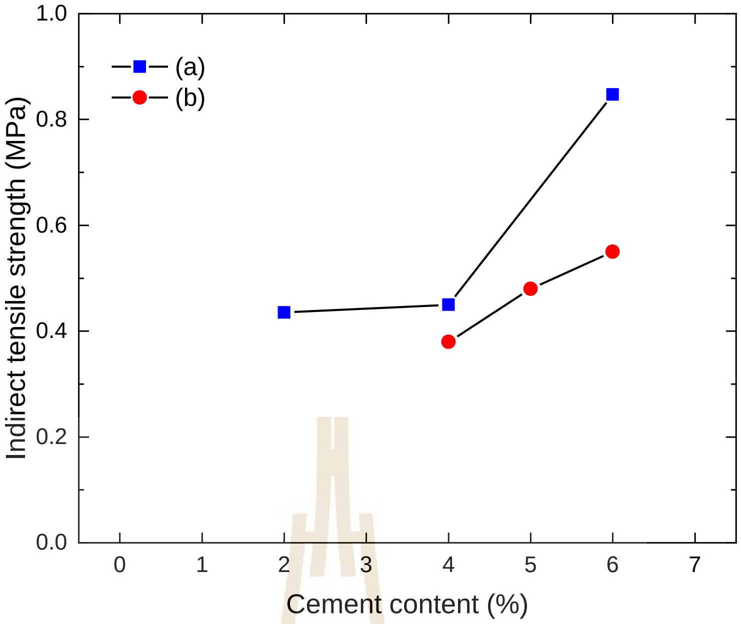


Figure 2.26 ITS results of cement stabilized RCA at 7-day curing samples. **(a)** (S Chakravarthi et al., 2019)**, (b)** (Li & Hu, 2020)

2.6.5 Modulus characteristics

The word modulus is used to describe the stiffness of a material. Depending on the status of the application, there are many types of moduli. To describe pavement material, the triaxial resilient modulus (Tx Mr), elastic modulus, shear modulus, and secant modulus are often utilized (Sarella Chakravarthi & Shankar, 2021). The resilient modulus (Tx Mr) is the most typical modulus used to analyze pavement base materials. The indirect tensile resilient modulus (IT Mr) has recently been proposed as a feasible option for acquiring the stiffness properties of cement stabilized granular materials in a cost-effective and reliable manner (Gnanendran & Piratheepan, 2010).

When compared to unstabilized NA, cement stabilized RCA mixes have greater stiffness values. Mr value of cement stabilized RCA rises with an increase in cement amount and curing time, according to Ebrahim Abu El-Maaty Behiry (2013). **Table 2.15** and **Figure 2.27** describe some of the moduli evaluated on cement stabilized granular material, including RCA.

Table 2.15 Summary of Tx Mr results of cement stabilized RCA mixtures.

Research	Cement content (%)	Tx Mr range (MPa)	Note
(a)	0	125 - 400	NA, unstabilized
(b)	0	370.3 - 1191.0	RCA, unstabilized
(c)	3	370 - 1420	RCA, 7-day curing
(d)	3	520 - 2085	RCA, 28-day curing

Note: **(a)** (A. Arulrajah et al., 2013), **(b)** (Perera et al., 2019), **(c)** (Arul Arulrajah et al., 2020), **(d)** (Yaowarat et al., 2020)

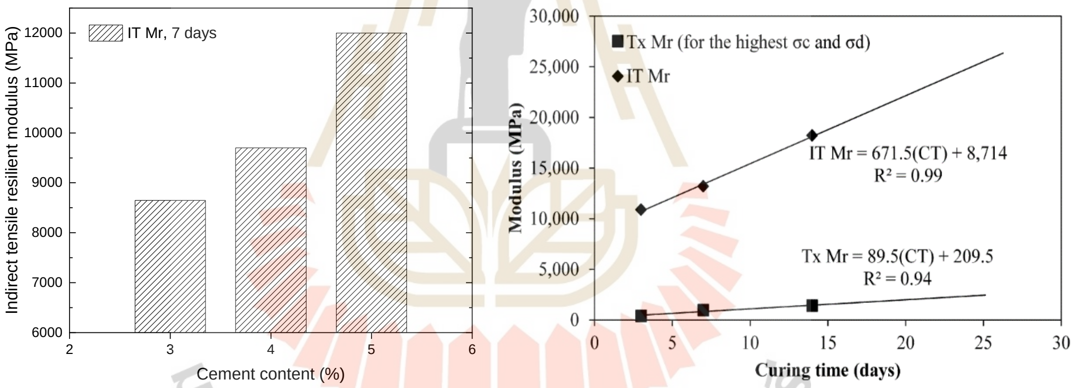


Figure 2.27 Variation in IT Mr of cement stabilized granular materials versus cement content **(a)** (Gnanendran & Piratheepan, 2010), and the relationship between moduli with curing time **(b)** (Fedrigo et al., 2018).

2.6.6 Permanent deformation characteristics

When a material acquires a plastic condition or is unable to restore its original position after many vehicle passes or typical load applications, it is said to be permanently deformed. The load applied in laboratory studies is based on real traffic. Permanent deformation occurs in all or certain layers of the pavement (Sarella Chakravarthi & Shankar, 2021).

Cement stabilization is one of the strategies that may help to reduce permanent deformation (Tutumluer et al., 2021). In comparison to untreated RCA and conventional bases, treated RCA as basis materials demonstrate less permanent deformation (Abass & Albayati, 2020; Sarella Chakravarthi et al., 2020; Ebrahim Abu El-Maaty Behiry, 2013).

2.7 Cement-natural rubber latex composite

Due to the established procedure and advantages, cement stabilization is one of the most extensively utilized stabilizing processes. However, since cement stabilized RCA has a greater stiffness value than unstabilized NA, the increased stiffness causes premature cracking when the material becomes brittle (Buritatum et al., 2021; Louw et al., 2016; Scullion, 2002). Natural rubber latex (NRL) has been utilized to modify cementitious stabilized pavement material in recent years owing to the benefits of the NRL addition, which result in increased compression strength, flexural strength, tensile strength, and ductility of cement stabilized mixes (Buritatum et al., 2021; Buritatun et al., 2020; Pinwiset et al., 2018; Sukmak et al., 2020; Udomchai et al., 2021; Verdolotti et al., 2021; Vo & Plank, 2018; Yaowarat et al., 2021).

Buritatun et al. (2020) investigated the effect of NRL additive on the strength development of cement stabilized soil and discovered that for all cement contents and NRL replacement ratios assessed, the cement-NRL stabilized samples had a higher UCS than the cement stabilized samples, as shown in **Figure 2.28a**. Additionally, it was shown that cement stabilized foundation material considerably increases flexural strength (**Figure 2.28b**). According to microstructure study, the strength development of mixes is due to a composite of cement hydration and the formation of a latex film, which functioned as reinforcement, and samples with a lower cement content may absorb more NRL at the densest packing stage (**Figure 2.29**).

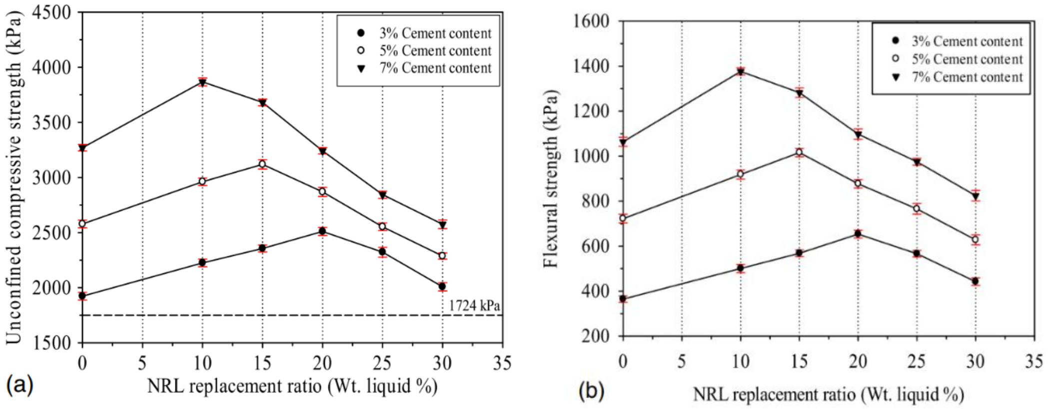


Figure 2.28 Strength development of cement stabilized soil with various cement contents and NRL replacement ratios (Buritatun et al., 2020).

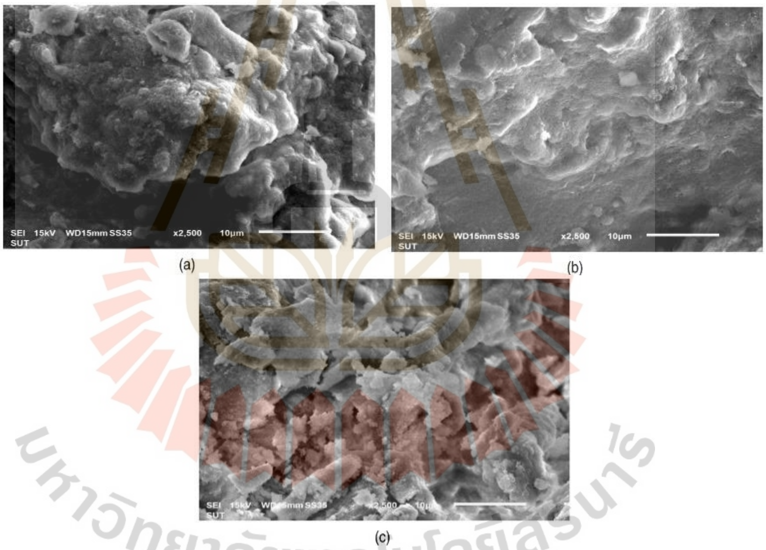
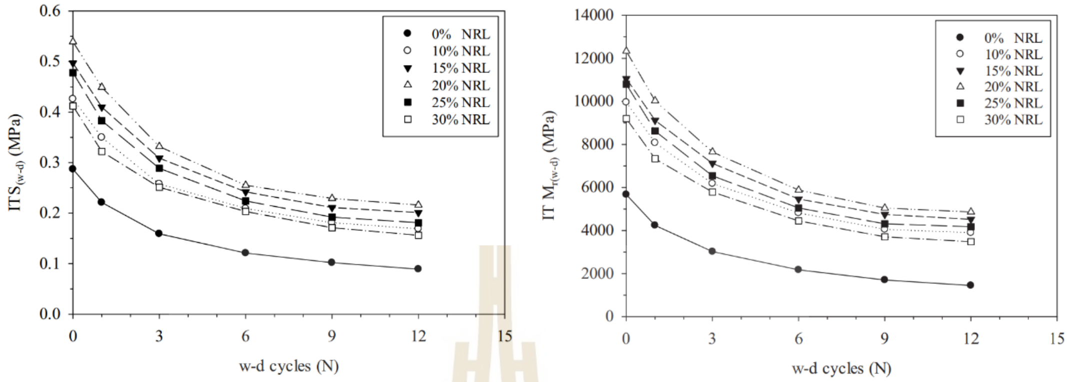


Figure 2.29 Rubber latex films cover soil particles with cement content of (a) 3%, (b) 5%, (c) 7% and at maximum NRL replacement ratios (Buritatun et al., 2020).

Udomchai et al. (2021) discovered that soil mixtures stabilized with cement and NRL had better resilient characteristics, reducing plastic deformation and preventing sudden damage from repeated tensile loads. The NRL replacement may increase the cement-stabilized soil's resistance to moisture damage (wetting-drying cycles) (**Figure**

2.30). Additionally, it was discovered that NRL extends the service life of cement stabilized soil as an unpaved material by preventing fatigue cracking failure.



(a) **(b)**

Figure 2.30 Relationship between the number of w-d cycles versus indirect tensile strength **(a)** and indirect tensile resilient modulus **(b)** for varied NRL replacement ratios. (Udomchai et al., 2021).

Vo and Plank (2018) revealed the presence of numerous polymer films within the cementitious matrix and the enhanced mechanical flexibility of the hardened matrix as a result of the NRL films interconnecting with the cement hydrates and bridging the pore space (**Figure** 2.31).

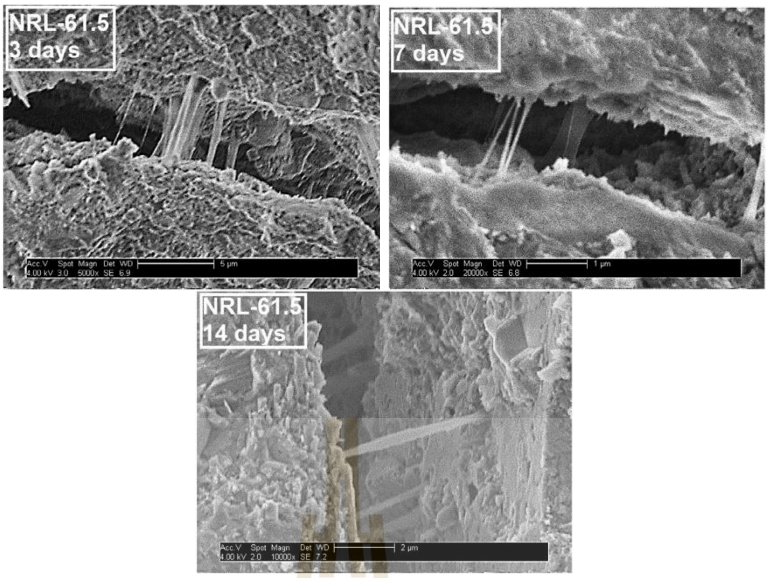


Figure 2.31 NRL films interconnect with cement hydrates and bridge the pore space (Vo & Plank, 2018).

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CHAPTER III

CEMENT-NATURAL RUBBER LATEX STABILIZED RECYCLED CONCRETE AGGREGATE AS A PAVEMENT BASE MATERIAL

3.1 Statement of the problem

The construction of roadways requires a vast amount of high-quality aggregates for the pavement structures such as base and subbase courses. Recently, the innovative road construction methods by using recycled materials or construction and demolition (C&D) materials as aggregates to replace the natural aggregate is placed as a priority for pavement authorities in many countries. This is due to the high demand for virgin aggregates increasing construction costs and the environmental concerns. Recycled concrete aggregate (RCA), containing cement and aggregate, is one of the main C&D materials, which is abundantly obtained from the demolished concrete structures. Due to the inferior properties of RCA, cement stabilization is practically adopted for the road base layer (Ebrahim Abu El-Maaty Behiry, 2013; Maduabuchukwu Nwakaire et al., 2020; Verian et al., 2013). One of the advantages of cement stabilized RCA material is high compressive strength, which meets the local road-authority requirements for stabilized pavement base. However, the cement stabilized RCA often exhibits brittle behavior and leads to low tensile and flexural strength, which results in the reduced service life of roadways (Chakravarthi et al., 2019; Sukmak et al., 2020; Yaowarat et al., 2020). To solve this shortcoming, many research works attempted to improve the performance of cement stabilized RCA by mixing with fibers, synthetic polymers and geopolymers (Arulrajah et al., 2017; Heeralal et al., 2009; Mohammadinia, Arulrajah, Sanjayan, Disfani, Bo, et al., 2016; Mohammadinia, Arulrajah, Sanjayan, Disfani, Win Bo, et al., 2016; Shaikh, 2016; Sukprasert et al., 2019; Yaowarat et al., 2018, 2020).

Thailand is known as the world's largest producer of natural rubber latex (NRL) products obtained from rubber tree plants (*Hevea Brasiliensis*). Fresh NRL contains approximately 30% to 35% of dry rubber content (Sukmak et al., 2020). The surfactant contents containing ammonia, zinc oxide, sodium dodecyl sulfate were added to prevent the coagulation of latex by engaging together rubber particles (Buritatun et al., 2020). The Government of Thailand has been promoting the usage of NRL in roadway construction alternative to the imported synthetic polymers.

Previous research works on NRL in concrete and mortar applications indicated that NRL was an environmentally friendly polymer with excellent elasticity and ductility properties, which can significantly improve the tensile and flexural strengths of concrete structure (Buritatun et al., 2020; Nagaraj et al., 1988; Poltue et al., 2019; Sukmak et al., 2020). Previous study revealed the NRL replacement in cement pastes increased tensile strength and toughness of the mixture but reduced compressive strength (Sukmak et al., 2020). Muhammad et al. demonstrated that NRL could be stable in the acidic and sulfated environment, and had good resistance to thermal deterioration (Muhammad et al., 2012; Vo & Plank, 2018).

In addition, several recent studies have focused on the compatibility between NRL and cement with natural soil in pavement base/subbase (Buritatum et al., 2021; Buritatun et al., 2020), and pavement concrete (Yaowarat et al., 2021). The NRL can improve the cyclic properties and increase service life of pavement structure. To the best of authors' knowledge, there is a lack of research on employing NRL as a polymer to improve mechanical properties of cement stabilized recycled aggregate as pavement materials. Therefore, this research aims to investigate the possibility of using NRL as a promising green polymer to enhance the tensile and flexural strengths of cement stabilized RCA for pavement base in roadway construction. The studied influence factors including cement content by total weight of RCA and dry rubber content in NRL to cement content (r/c) ratio were evaluated in this study. The microstructural analyses using X-ray diffraction and Scanning Electron Microscopy were carried out to investigate the development of mineral and chemical reactions of cement- and cement-NRL stabilized RCA. The outcomes of this research will facilitate the efficient utilization of NRL in cement stabilized RCA as a pavement material.

3.2 Materials and sample preparation

3.2.1 Materials

The RCA obtained from a concrete crusher machine with a nominal maximum size of 20 mm was used in this research (**Figure 3.1**). The particle distribution curve of RCA sample was implemented in accordance with ASTM D422 (2007). **Figure 3.2** indicated that the gradation curve of RCA was within the upper and lower boundary gradation for pavement base material specified by the Department of Highways (DOH), Thailand (DH-S201/2556 (2013)). **Table 3.1** presents the basic geotechnical properties of RCA. According to the Unified Soil Classification System (USCS) (ASTM-D2487, 2017), RCA was classified as well-graded gravel (GW). The flakiness index and Los Angeles (LA) abrasion value of RCA was respectively 15.6 and 38.1, which indicated that RCA is suitable for pavement base material in accordance with DOH, Thailand (i.e., Flakiness index < 35 and LA < 40) (DH-S201/2556 (2013)). The organic content in RCA was low of only about 2.56 while its pH value was greater than 7, which demonstrated that RCA was an alkaline environment by nature. The water absorption of coarse aggregates was lower than that of fine aggregates because the larger specific surface of fine particles can absorb more water than the coarse ones. Since RCA contained the amount of concrete mortar, the water absorption of RCA is higher than the natural crushed aggregates (Poon & Chan, 2006).

Figure 3.1 Photos: (a) concrete crusher machine, (b) concrete beams, (c) RCA particles.

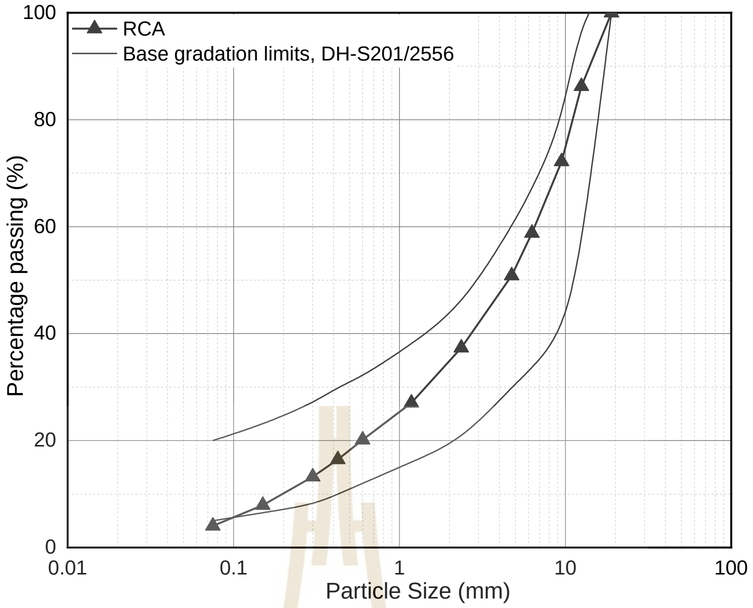


Figure 3.2 Particle size distribution curve of RCA.

Table 3.1 Geotechnical properties of RCA.

Properties	Values	Typical values $^{(*)}$	Standard method
Specific gravity - coarse	2.30	> 2	ASTM C127
Specific gravity - fine	2.17	> 2	ASTM C128
Water absorption - coarse (%)	6.32	< 10	ASTM C127
Water absorption - fine (%)	7.95	< 10	ASTM C128
Organic content (%)	2.56	< 5	ASTM D2974
Fine content (%)	4.0	< 10	ASTM D422
Sand content (%)	46.8	-	ASTM D422
Gravel content (%)	49.2	-	ASTM D422

Table 3.1 Geotechnical properties of RCA. (Continued)

Properties	Values	Typical values [(*)]	Standard method
Coefficient curvature (C_c)	1.65	-	ASTM D2487
Coefficient uniformity (C_u)	34.0	-	ASTM D2487
Soil classification	GW	GW, GS	ASTM D2487
Flakiness index	15.6	< 35	BS 812:105.1
Los Angeles abrasion loss	38.1	< 40	ASTM C1311
pH	12.2	7 - 12	ASTM D4972
Maximum dry density (Mg/m^3)	1.89	> 1.8	ASTM D1557
Optimum moisture content (%)	11.7	8 - 15	ASTM D1557
Californica bearing ratio (%)	195	> 80	ASTM D1883

Note: (*) (Verian et al., 2013)

Table 3.2 shows the chemical compositions of ordinary Portland cement (OPC) type I used in this research. The main components of NRL are summarized in **Table 3.3**. A surfactant sodium dodecyl sulfate (SDS) was added into NRL to remove the protein and to stabilize the colloidal dispersion of the latex.

Table 3.2 Chemical compositions of cement.

Composition	SiO_2	CaO	Al_2O_3	Fe_2O_3	MgO	SO_3	LOI
Content (%)	20.1	65.0	4.7	3.2	2.6	3.3	0.9

Table 3.3 Properties of natural rubber latex.

Property	Value
Total solid contents (% by weight)	33.06
Dry rubber contents (% by weight)	30.79
Sludge content (% by weight)	2.46
Coagulum content (% by weight)	0.024
Specific gravity (Gs)	0.96
pH	8.0

3.2.2 Sample preparation

In order to investigate the influence of NRL additive on strength development of the cement stabilized RCA, the mechanical properties and microstructure of cement stabilized RCA and cement-NRL stabilized RCA were investigated and compared in this research. The cement stabilized RCA samples were the mixtures of RCA with different cement contents of 3%, 5%, and 7% (by mass of RCA), namely 3C-RCA, 5C-RCA, and 7C-RCA. While the cement-NRL stabilized RCA samples were the mixtures of RCA, cement, and NRL, whose dry rubber to cement (r/c) ratios were 5%, 10%, and 15% (by mass of cement). The ingredient and labels of studied mixtures are summarized in **Table 3.4**.

Table 3.4 The mix design in this study.

Mixture Ingredient	Mixture Name
100% RCA	100RCA
100% RCA + 3% Cement	3C-RCA

Table 3.4 The mix design in this study. (Continued)

Mixture Ingredient	Mixture Name
100% RCA + 3% Cement + 5% Dry Rubber	3C5R-RCA
100% RCA + 3% Cement + 10% Dry Rubber	3C10R-RCA
100% RCA + 3% Cement + 15% Dry Rubber	3C15R-RCA
100% RCA + 5% Cement	5C-RCA
100% RCA + 5% Cement + 5% Dry Rubber	5C5R-RCA
100% RCA + 5% Cement + 10% Dry Rubber	5C10R-RCA
100% RCA + 5% Cement + 15% Dry Rubber	5C15R-RCA
100% RCA + 7% Cement	7C-RCA
100% RCA + 7% Cement + 5% Dry Rubber	7C5R-RCA
100% RCA + 7% Cement + 10% Dry Rubber	7C10R-RCA
100% RCA + 7% Cement + 15% Dry Rubber	7C15R-RCA

The samples were mixed based on the two-stage mixing approach (TSMA) (Tam et al., 2005) to ensure the uniformity of the blends and the quality of the samples with the suitable mixing time. **Figure 3.3** illustrates the process of sample preparation. The sample preparation of cement stabilized RCA was first started by mixing RCA with half of the required water for 30 seconds and then with cement for 30 seconds and followed by the final half of water for another 30 seconds. Finally, the sample was thoroughly mixed for another 60 seconds to ensure the homogenous mixture. The same procedure was used to produce the cement-NRL stabilized RCA samples, while the desired NRL content was added and mixed for another 30 seconds prior to the final stage. The mixed liquid content was the additional water and liquid rubber content, which was measured by mass of the solid phase (RCA, cement, and dry rubber content). In other words, the total mixing time was 2.5 mins and 3 mins for cement-RCA blend and cement-NRL-RCA blend, respectively.

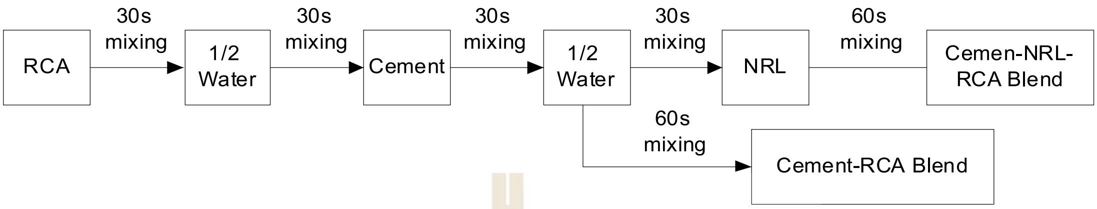


Figure 3.3 TSMA mixing procedures for cement- and cement-NRL stabilized RCA.

3.3 Laboratory experimental programs

3.3.1 Basic laboratory tests of recycled concrete aggregate

Laboratory tests on basic geotechnical properties of RCA included particle size distribution, water absorption, particle density, flakiness index, organic material content, Los Angeles abrasion loss, pH and modified Proctor compaction. The results are summarized in **Table 3.1**.

3.3.2 Modified Proctor compaction test

Modified Proctor compaction tests were carried out to determine the maximum dry density (MDD) and optimum liquid content (OLC) of RCA, cement stabilized RCA, and cement-NRL stabilized RCA in compliance with ASTM D1557 (2012).

3.3.3 Unconfined compressive strength test

The unconfined compressive strength (UCS) tests were conducted in accordance with the ASTM D1633 (2017) to assess the influence of the NRL additive on the compressive strength of cement stabilized RCA. Metallic molds with an internal diameter of 101.6 mm and a height of 116.8 mm were used to produce at least three samples for each mixture. UCS samples were compacted in five layers under modified compaction effort with 25 blows per layer to attain the target MDD at OLC. The samples were demolded after 24 hours and then wrapped with plastic sheet and cured for 7 and 28 days in the curing room temperature (25±2°C) prior to the UCS test. The

UCS samples were tested using a universal test machine with a compression rate of 1 mm/min.

3.3.4 Indirect tensile strength test

Indirect tensile strength (ITS) tests were conducted in accordance with ASTM D6931 (2017) to evaluate the tensile and stress-strain characteristics of the cement stabilized RCA and cement-NRL stabilized RCA samples. The test samples with a diameter of 101.6 mm and a height of 78 mm were compacted under the modified compaction effort (compacted in three layers with 28 blows per layer) to attain the MDD and OLC values. The prepared samples were cured in the mold for 24 hours to ensure that they could be demolded without damage. The samples were then wrapped by plastic sheet and cured for 7 and 28 days at room temperature (25±2°C). A monotonic loading test at a vertical deformation rate of 1 mm/min was used to determine the ITS while the stress-strain curves were automatically collected.

3.3.5 Scanning electron microscope

The scanning electron microscope (SEM) is a high-performance system to investigate the microstructure of geochemical stabilized material. SEM analysis was performed to examine the morphological of cement hydration products between RCA particles and the interactions between rubber film network and cement hydration products. The SEM samples were gathered from the middle parts of the tested UCS samples. Small pieces of each sample were frozen after UCS testing at 28 days of curing by soaking in liquid nitrogen at -195 ^{0}C, afterward broken to satisfactory dimension for identifying the internal structure. The samples were coated with gold for about 60-seconds before SEM analysis. The current and operating distance of 15 kV and 15 mm were respectively selected for sample morphological analysis.

3.3.6 X-ray diffractometry

X-ray diffraction (XRD) analysis was conducted on cement- and cement-NRL stabilized RCA powders to investigate the development of chemical reactions and mineral compositions. A D2-PHASER diffractometer with Cu-Kα radiation equipped with a sensitive detector was used. The XRD pattern was obtained by scanning from 5° to 65° at an angle of 2θ, and the scan increment size is 0.02.

3.4 Result and discussion

3.4.1 Compaction characteristics

Figure 3.4 presents the modified Proctor compaction test result of RCA, cement stabilized RCA with various cement contents and cement-NRL stabilized RCA with various r/c ratios. When compared with the unstabilized RCA sample, the MDD values of cement stabilized RCA samples were increased by 1.9%, 2.0%, and 2.2% with increasing 3%, 5%, and 7% cement content, respectively.

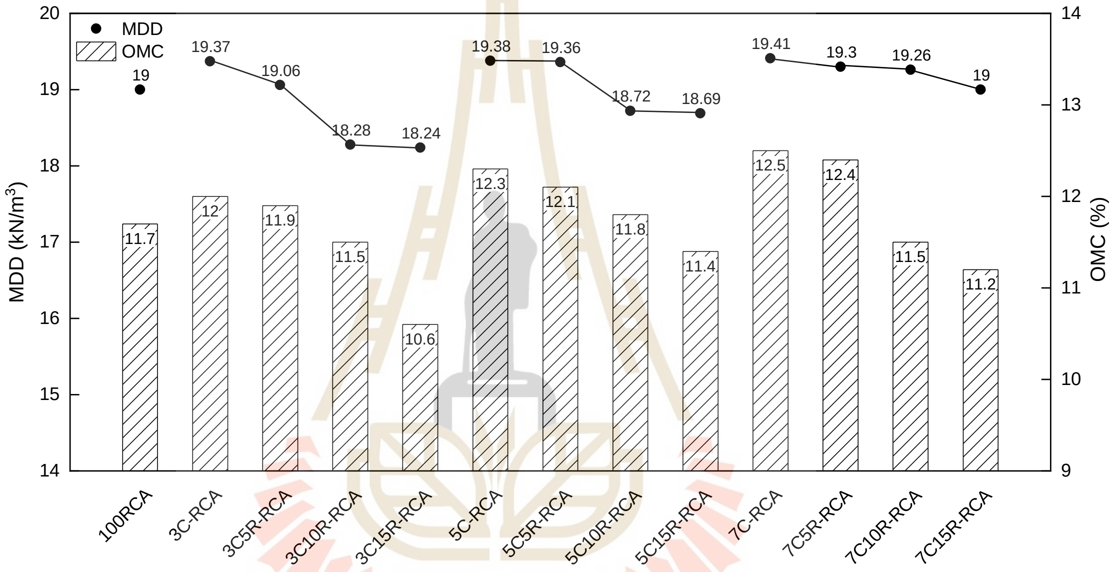


Figure 3.4 Compaction test result of RCA, cement- and cement-NRL stabilized RCA.

At a particular cement content, the cement stabilized RCA samples had higher MDD values than the cement-NRL stabilized RCA samples for all r/c ratios. Although the MDD values of the 3%, 5%, and 7% cement stabilized RCA samples decreased with increasing the r/c ratio, the samples with higher cement contents had lower rate of MDD reduction with increasing the r/c ratio. Initially, the higher cement content led to a higher MDD of cement stabilized RCA samples because the compactability of RCA particles is improved by the cation exchange and cementitious products. Consequently, the matrix between the RCA particles is denser with the addition of cement content; similar observations were also reported by Alireza et al.

(2015). and Chakravarthi et al. (2019). However, with the NRL additive, the solid phase of NRL within the RCA-cement matrix caused the decrease of compressibility of the mixtures. Buritatun et al. (2020). and Baghini et al. (2015). also indicated that the NRL additive reduced MDD of cement stabilized soil. Meanwhile, the OLC values of cement stabilized RCA samples were also slightly increased with increasing the cement content. This is because a higher cement content caused a higher water absorption (Bekhiti et al., 2019).

The OLC value of cement-NRL stabilized RCA shown in **Figure 3.4** decreased with increasing the r/c ratio for all cement contents. The OLC value was reduced by about 1%, 4%, and 10% for r/c ratios of 5%, 10%, and 15%, respectively. Jose and Kasthurba (2021) reported that the decrease of OLC due to the hydrophobic behavior of rubber, and this might be one of the reasons the OLC of cement-NRL stabilized RCA decreased.

3.4.2 Unconfined compressive strength

Figure 3.5 shows the 7-day and 28-day UCS values of unstabilized RCA, cement stabilized RCA, and cement-NRL stabilized RCA samples with various cement contents and r/c ratios. The dashed horizontal line indicates the minimum UCS requirement for pavement base material specified by the Department of Highways (DOH), Thailand (DH-S204/2532, 1996). It is evident that the unstabilized RCA has very low UCS value, which is similar to the previous research (Arulrajah et al., 2016, 2017; Chakravarthi et al., 2019; Mohammadinia et al., 2015) while the UCS of cement stabilized RCA samples was found to meet the minimum requirement. In addition, UCS values of cement stabilized RCA increased with increasing the cement content and/or curing time (**Figure 3.5**), which is typical for cemented materials.

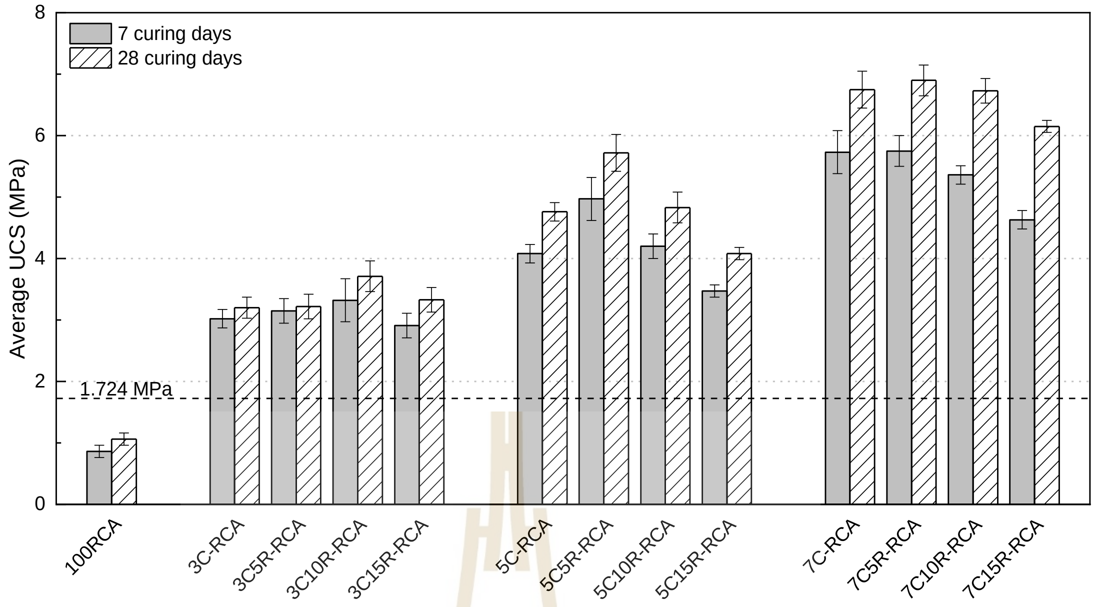


Figure 3.5 Unconfined compressive strength of cement- and cement-NRL stabilized RCA.

The influence of the r/c ratios on UCS of cement-NRL stabilized RCA is also illustrated in **Figure 3.5**. It is evident that the NRL additive can improve the UCS of cement stabilized RCA. The highest UCS values were found at the optimum r/c ratios of 10%, 5%, and 5% for 3%, 5%, and 7% cement, respectively for both 7 and 28 days of curing. At the optimum r/c ratio, the 7-day UCS values of 3C10R-RCA, 5C5R-RCA, and 7C5R-RCA were improved up to 9.9%, 21.8%, and 0.3% higher than UCS values of 3C-RCA, 5C-RCA, and 7C-RCA, respectively. The percent of improvement was the highest for 5% cement with 5% dry content. This result implies that the strength improvement by NRL is dependent upon the cement content. The percent of improvement increased with cement content up to the optimum cement content of 5% and then decreased. The similar relationship between 28-day and 7-day UCS of cement- and cement-NRL stabilized RCA is shown in **Figure 3.6**. It is therefore worthwhile mentioning that NRL has no effect on the UCS development over time of cement stabilized RCA even though it affects the UCS at a particular curing time.

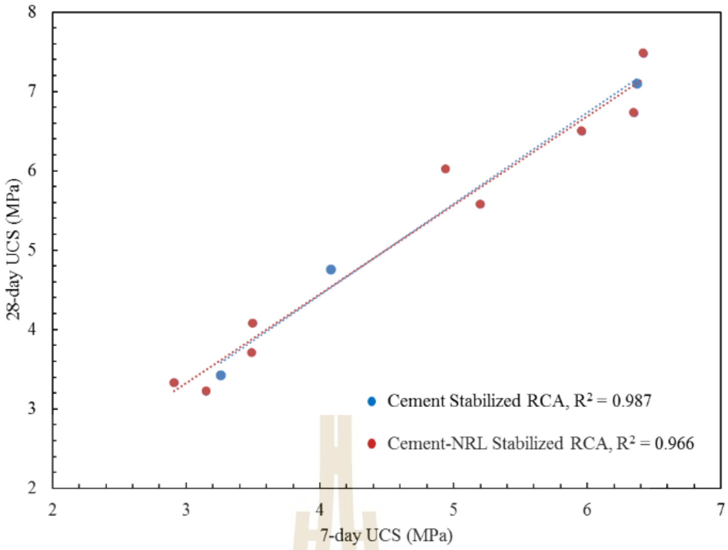


Figure 3.6 Relationship between 28-day and 7-day UCS of cement- and cement-NRL stabilized RCA.

3.4.3 Indirect tensile strength

Indirect tensile strength (ITS) is an essential property in the pavement design (Chakravarthi et al., 2019). The ITS characteristics of cement stabilized RCA and cement-NRL stabilized RCA cured for 7 and 28 days were therefore evaluated in this research. The mean ITS values of triplicated samples for each studied mixture are shown in **Figure 3.7**. The results demonstrated that the ITS of cement stabilized RCA can be enhanced by NRL additive. For a particular cement content, the highest ITS of cement-NRL stabilized RCA was found at the optimum r/c ratio. In addition, the ITS of cement-NRL stabilized RCA also increased with increasing the cement content (i.e., the ITS of 7C5R is higher than 5C5R and 3C10R, respectively). The optimum r/c ratios were found to be the same for both UCS and ITS. The 7-day ITS values of 3C10R-RCA, 5C5R-RCA, and 7C5R-RCA was up to 12.5%, 13%, and 1.3% higher than those of 3C-RCA, 5C-RCA, and 7C-RCA, respectively. The 5C5R-RCA had the highest percent improvement of both UCS and ITS when compared with the other ingredients. Similar to UCS, at a particular cement content, ITS of cement-NRL stabilized RCA decreased when the r/c ratios were beyond the optimum value.

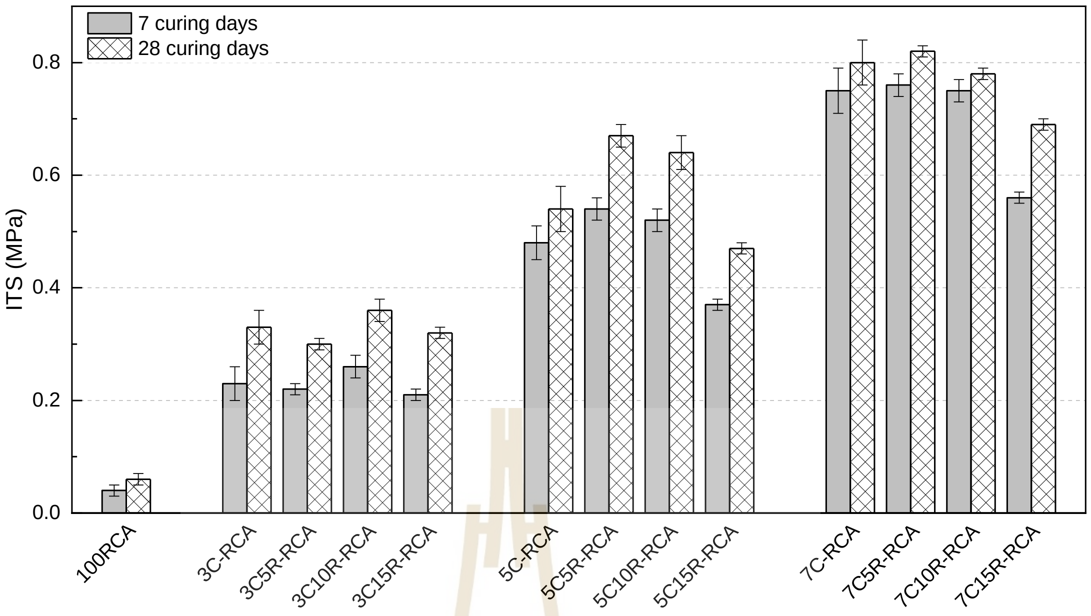


Figure 3.7 Indirect tensile strength of RCA, cement- and cement-NRL stabilized RCA.

3.4.4 Stress-strain and toughness characteristics

Figure 3.8 shows the tensile stress-strain curves of RCA, cement stabilized RCA, and cement-NRL stabilized RCA samples at an early age (7 days of curing). Cement stabilized RCA samples for all cement contents demonstrated brittle behavior with small strain at failure (around 1%), similar to previous research (Buritatun et al., 2020). The NRL additive improved the peak tensile stress and ductility of cement stabilized RCA samples. The previous research on polymer-modified concrete and NRL stabilized lateritic soil also indicated this similar finding (Baghini et al., 2015; Yaowarat et al., 2020).

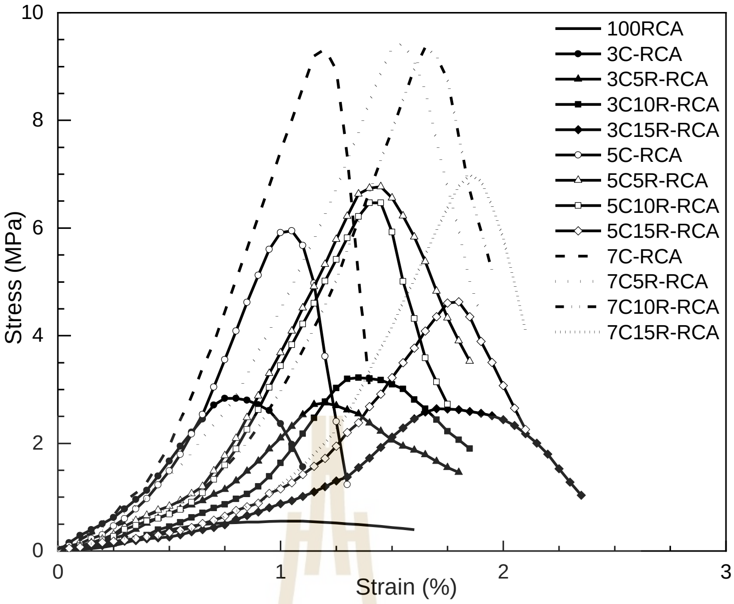


Figure 3.8 Stress-strain curves of RCA, cement- and cement-NRL stabilized RCA.

The maximum strain values at failure of all cement-NRL stabilized RCA samples were found at the highest r/c ratios for all cement contents due to the highest elastic properties. Chakravarthi et al. (2019) reported that the larger area under the stress-strain curve represents the more energy stored in the sample. The NRL additive improves the resilient characteristic of the cement stabilized RCA, which is advantageous to the long-term durability under traffic loading of cement-NRL stabilized RCA as a pavement base material.

In general, the UCS test is more convenient and time-saving than the ITS test. Since the UCS and ITS of cement-NRL stabilized RCA samples yield the highest values at the same r/c ratios for all cement contents, it is logical to develop a relationship between ITS and UCS for pavement engineering design asshown in **Figure 3.9** and the following equation:

$$\mathrm{ITS} = 0.0514(\mathrm{UCS})^{1.4945}\ (R^2 = 0.97) \tag{3.1}$$

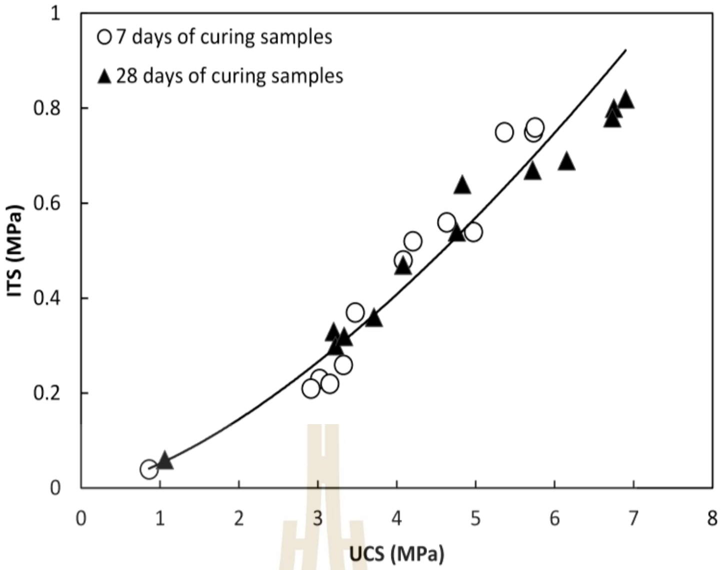


Figure 3.9 Relationship between ITS and UCS of cement- and cement-NRL stabilized RCA.

The equation is very useful to predict the ITS at any curing times, cement contents and NRL replacement ratios once the corresponding UCS is known. Toughness is an essential factor when evaluating the ability of the material to absorb energy before rupture (Wang et al., 2005). Toughness can be determined from various tests including compressive, flexural, tensile and plate tests (Sreekala et al., 2006). In this study, the toughness of cement- and cement-NRL stabilized RCA samples was estimated by the ratio of compressive strength to tensile strength (σ_c/σ_t); the results were presented in **Figure 3.10**. The lower σ_c/σ_t ratio indicates the higher toughness of the sample (Wang et al., 2005). It is found that the σ_c/σ_t ratio of RCA samples was very high when compared with cement- and cement-NRL stabilized RCA samples.

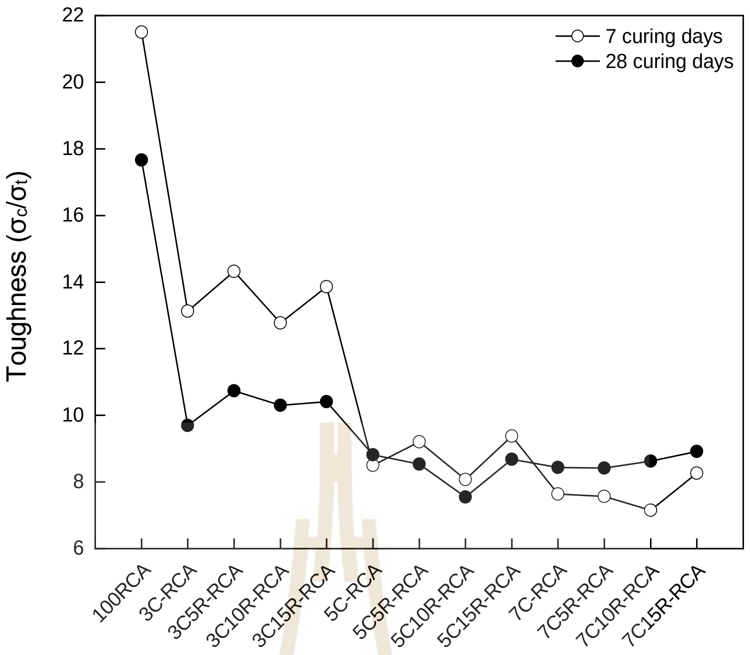


Figure 3.10 Toughness characteristic of RCA, cement- and cement-NRL stabilized RCA.

From **Figure 3.10,** the σ_c/σ_t ratios of cement- and cement-NRL stabilized RCA samples at 3% and 5% cement content after 28 days of curing were lower than those after 7 days of curing. In other words, the samples at age of 28 days had higher toughness that the samples at age of 7 days. This indicated the toughness improvement over time. On the other hand, the σ_c/σ_t ratios of the 7% cement samples after 7 days of curing were lower than those after 28 days of curing for all r/c ratios. It implies that the rate of compressive strength development is higher than the rate of tensile strength development at an early age for the 7% C sample, leading to a rapid acceleration of cement hydration and brittle behavior. The toughness of cement- and cement-NRL stabilized RCA samples at 3% cement content after 28 days of curing was remarkably higher than that samples after 7 days of curing. Whereas the cement- and cement-NRL stabilized RCA samples at 5% cement content after 28 days of curing had slightly higher toughness than the samples after 7 days of curing. It demonstrates that the 3% cement samples required longer curing time for tensile strength development. At 28 days of curing, the toughness of cement-NRL stabilized RCA samples at all r/c ratios was lower than that of 3% cement stabilized RCA. On the other hand, the 5% cement-NRL stabilized RCA samples at all r/c ratios had higher toughness than the 5% cement stabilized RCA and the 5C10R-RCA sample exhibited the highest toughness.

3.5 Microstructural analysis

3.5.1 X-ray diffractometry

Figure 3.11 shows the XRD patterns of cement- and cement-NRL stabilized RCA samples with 3% and 5% cement contents and with various r/c ratios after 28 days of curing. The XRD patterns indicate the defections of the particle size while the peak integrated intensities indicate specific chemistry and atomic arrangement (Sorokhaibam & Ahmaruzzaman, 2014). The XRD patterns are the identification of the different amount of crystalline phase formation that represents the original aggregates and the cement hydrates. The XRD patterns of cement-NRL stabilized RCA samples with 3% and 5% cement contents were similar, whose major phases were calcite ($CaCO_3$), quartz (SiO_2), dolomite ($CaMg(CO_3)_2$), portlandite ($Ca(OH)_2$), gypsum ($CaSO_4(H_2O)_2$), ettringite ($C_6(Al(OH)_6)_2(SO_4)_3(H_2O)_{26}$), and C_3S_3H Rosenhahnite ($C_3(Si_3O_8)(OH)_2$).

Based on major peak value, the quartz (SiO_2) and calcite ($CaCO_3$) phases appeared in high volume fraction. The presence of these crystalline phases showed significant changes in the composition due to the carbonation of cement hydrates in the cement paste adhering to RCA particles, consisting mainly of portlandite ($Ca(OH)_2$) and C-S-H ($CaO\text{-}SiO_2\text{-}H_2O$). These phases are carbonated in the way described in equations **(3.2)** and **(3.3)** as follows (Moreno-Pérez et al., 2018):

$$\mathrm{Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O} \qquad (3.2)$$

$$\mathrm{C\text{-}S\text{-}H + CO_2 \rightarrow CaCO_3 + SiO_2.nH_2O} \qquad (3.3)$$

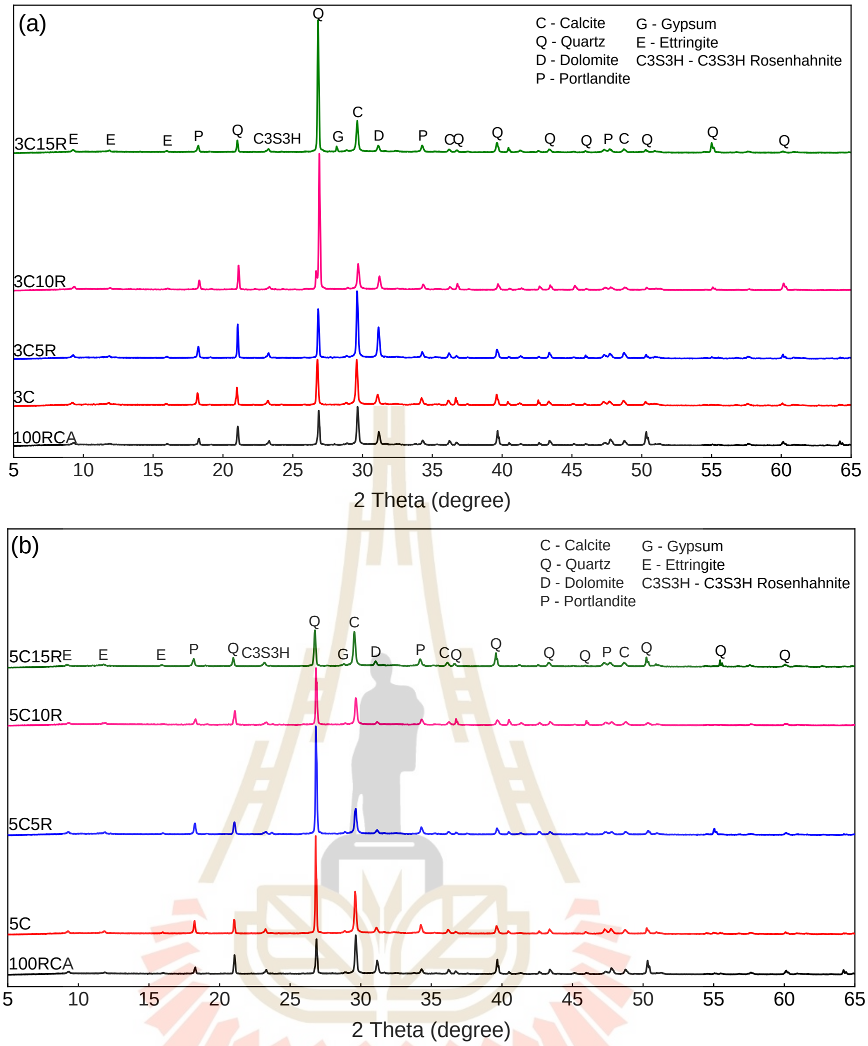


Figure 3.11 XRD patterns of RCA, cement- and cement-NRL stabilized RCA at 28 days of curing.

When compared with cement-stabilized RCA samples, it was observed that the peak intensity of quartz increased while calcite decreased in the cement-NRL stabilized RCA at the optimum r/c ratios (i.e., 3C10R-RCA and 5C5R-RCA). On the contrary, beyond the optimum r/c ratios, the quantity of quartz decreased, while the quantity of calcite increased. This indicated that NRL additive significantly affected the chemical reaction of cement hydration and therefore influenced the strength development of cement-NRL stabilized RCA samples. Similarly, Inoue and Harasawa (2013) and Diab et al. (2013). performed XRD analysis on polymer and latex modified soil and revealed that the change of cement hydration degree was relatively influenced by the presence of rubber latex network as valuable assistance.

Kunther et al. (2017) investigated the influence of Ca/Si ratio on the compressive strength of cemented samples and found that the lower Ca/Si ratio resulted in the highest strength for all studied hydration times of the samples. In this study, the Ca/Si ratios of cement- and cement-NRL stabilized RCA samples were determined and demonstrated in **Figure 3.12**. The lowest Ca/Si ratios were found at the optimum r/c ratios for both cement-NRL stabilized RCA at 3% cement (3C10R-RCA) and 5% cement (5C5R-RCA). The XRD analyses and Ca/Si ratio results clearly confirmed the influence of NRL additive on the UCS and ITS development of cement-NRL stabilized RCA, in which the highest UCS and ITS values were found at the same optimum r/c ratio for a particular cement content (see **Figure 3.5** and **3.7**).

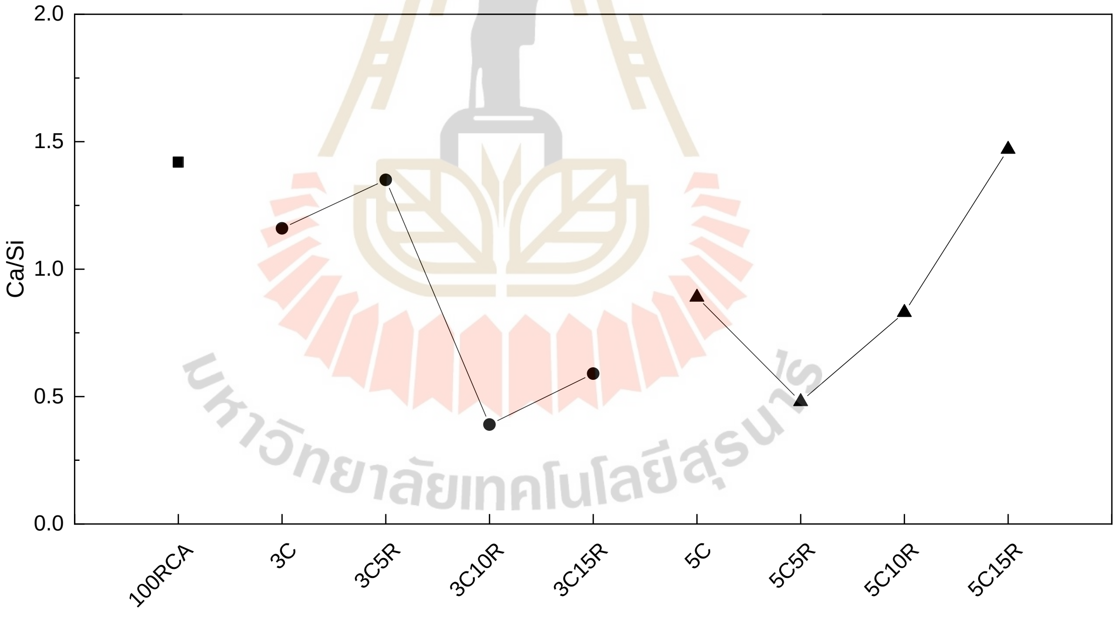


Figure 3.12 Ca/Si ratio of RCA, cement- and cement-NRL stabilized RCA.

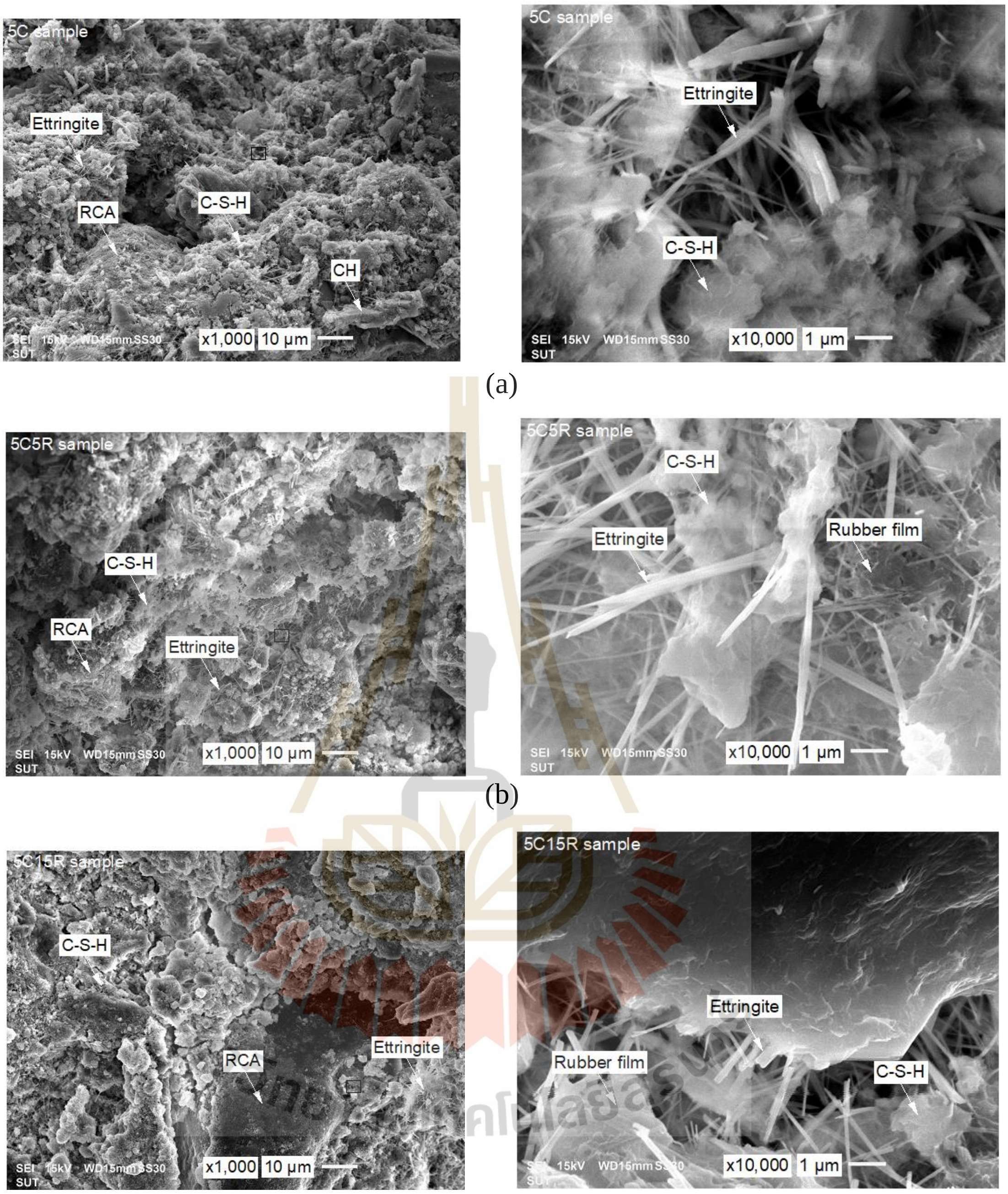
3.5.2 Scanning electron microscopic images

The morphological investigation using scanning electron microscopy (SEM) analysis was carried out to confirm the chemical reaction in cement- and cement-NRL stabilized RCA samples. The SEM images of 5C-RCA, 5C5R-RCA, and 5C15R-

RCA samples after 28 days of curing are displayed in **Figure 3.13**. The SEM image of the cement stabilized RCA sample (without NRL), 5C-RCA is shown in **Figure 3.13(a)**. In this case, cement hydration products detected by SEM analysis were calcium hydroxide (CH) as the large hexagonal plate crystals, needle-like crystals of ettringite form, and calcium silicate hydrate (C-S-H) phase, which indicated a common reticular form, honeycomb shape or resemblance to the crystalline minerals of tobermorite (Chen et al., 2004). The existence of C-S-H, ettringite and CH forms fills the gaps (air voids) in the cement paste and enhances the bonding strength between the RCA particles, thus improves the strength development of the mixture (Horpibulsuk et al., 2010). Imtiaz et al. (2020) demonstrated that the C-S-H phase strongly affects the behavior and strength characteristics of hardened cement paste.

Figure 3.13(b) shows the SEM image of cement-NRL stabilized RCA at the optimum r/c ratio (5C5R-RCA). It was noted that rubber films were intermingled and intergrown inside the cement hydrates, which covered the C-S-H phase and ettringite needles at the air void surface between the particles. The rubber films act as the bridges to connect the cement hydration products, serving as an additional interparticle forces to bond the RCA particles together. Similarly, Bean and Husbands (1986) also indicated that the polymer matrix acts as a barrier that helps retain the high degree of internal moisture (preventing moisture removal due to evaporation) for the progress of cement hydration. In other words, it creates a polymer network that enhances the mixture properties such as durability and toughness. Therefore, the existing amount of C-S-H and ettringite crystals with rubber films generated by NRL additive at the optimum r/c ratio resulted in the highest UCS and ITS development of cement-NRL stabilized RCA.

Figure 3.13(c) shows the SEM image of cement-NRL stabilized RCA with r/c ratio of 15% (> optimum r/c ratio) (5C15R-RCA).The excessive volume fraction of NRL created a continuous NRL films, which abundantly covered the hydrating cement grains and the RCA aggregates. In other words, the formation of thicker rubber film was widely distributed over the particle surface, which generated the jelly-like surface and retarded the cement hydrations. Consequently, the UCS and ITS were low.



(a)

(b)

(c)

Figure 3.13 SEM images of: (a) 5C-RCA, (b) 5C5R-RCA, (c) 5C15R-RCA.

From XRD and SEM analyses, it is evident that at optimum r/c ratio, the cement hydration products were remarkably high while the rubber films increase the adhesion of the RCA particles, leading to the higher interparticle bonds between the RCA aggregates and UCS and ITS development. In addition, the presence of rubber films result in the improvement of the plastic strain resistance of cement stabilized RCA; hence, the improvement of overall stress-strain behavior and toughness of the cement-NRL stabilized RCA as shown in **Figures 3.8** and **3.10**. However, the excessive NRL additive over the optimum r/c ratio resulted in a negative influence on the development of the cement hydration process.

The outcome of this research ascertains the cement-NRL stabilized RCA as a pavement base material, which is more advantageous than conventional cement stabilized RCA in terms of UCS, ITS, ductility, and toughness properties. Therefore, the utility of cement-NRL stabilized RCA with the optimum r/c ratio will enhance the service life and durability of roadway applications.

3.6 Conclusions

This research investigates the possibility of using natural rubber latex (NRL) as a promising green additive to enhance the unconfined compressive strength (UCS) and indirect tensile strength (ITS) of cement stabilized recycled concrete aggregate (RCA) as a pavement base material. The studied influence factors including cement contents: 3%, 5%, and 7% by total weight of RCA and the dry rubber in NRL to cement (r/c) ratios: 5%, 10%, and 15% (dry rubber content by total weight of cement) were investigated. The microstructural analyses using x-ray diffraction (XRD) and scanning electron microscopy (SEM) were performed to investigate the chemical reactions and morphological developments of cement- and cement-NRL stabilized RCA. The significant conclusions can be drawn as follows:

1. When compared with cement stabilized RCA, the maximum dry density (MDD) and the optimum liquid content (OLC) of cement-NRL stabilized RCA decreased with increasing r/c ratios for all cement contents. This is because the solid phase of NRL within the RCA-cement matrix causes the decrease of compressibility of the mixtures while the hydrophobic molecules and surfaces of rubber repel water absorption.

2. The UCS and ITS values of both cement- and cement-NRL stabilized RCA were increased with increasing the cement content and curing time. At a particular cement content, the UCS and ITS values of cement-NRL stabilized RCA at the optimum

r/c ratios were higher than that of cement stabilized RCA (without NRL). The optimum r/c ratios providing the highest UCS and ITS of cement-stabilized RCA were the same, which were 10%, 5%, and 5% for 3%, 5%, and 7% cement content, respectively. The UCS and ITS values of 3C10R-RCA < 5C5R-RCA < 7C5R-RCA. Although the UCS and ITS values of cement-NRL stabilized RCA decreased when the r/c ratios were beyond the optimum values, all UCS values were greater than the minimum requirement specified by DOH, Thailand (i.e., UCS > 1.724 MPa) for base material.

3. The maximum strain values at failure of all cement-NRL stabilized RCA samples were at the highest r/c ratios for all cement contents. It implies that the higher r/c ratio can enhance the soft hardening behavior of cement stabilized RCA. The toughness of cement- and cement-NRL stabilized RCA at 3% and 5% cement contents improved over time.

4. The XRD and SEM analyses indicated that at optimum r/c ratios, the cement hydration products were remarkably high while the NRL films can enhance the adhesion, leading to the increased interparticle bonds between RCA particles and UCS and ITS development. In addition, NRL films can enhance the plastic strain, the overall stress-strain behavior and toughness of the cement-NRL stabilized RCA. However, the excessive NRL additive over the optimum r/c ratio retarded the cement hydration and resulted in low UCS and ITS development.

The outcomes of this research will facilitate the efficient utilization of NRL in cement stabilized RCA as a pavement material, which provides advantages to traditional cement stabilized recycled material in terms of compressive, tensile, ductility, and toughness properties.

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CHAPTER IV

STIFFNESS AND FATIGUE PERFORMANCE EVALUATION OF CEMENT-NATURAL RUBBER LATEX STABILIZED RECYCLED CONCRETE AGGREGATE

4.1 Statement of the problem

Road infrastructure is an essential element of the public assets, which makes an important contribution to economic growth nationally and globally. As such, pavement design and maintenance are crucial to preserve those benefits; the short service life or the premature failure of the road infrastructure results in escalating costs and a major financial problem. Though the performance of pavement is influenced by many factors, they can be merged into three main groups including climate condition, traffic condition, and pavement materials (Officials, 2015; Qiao et al., 2022). For traffic condition, the repeated loading generated by the mobility of the vehicles is a principal factor affecting the mechanical performance of pavements and directly causing different types of distresses. The rutting and fatigue cracking are the critical distresses associated with the pavement design, pavement maintenance, and rehabilitation. Rutting distress is the permanent vertical deformation along the wheel paths of pavement under repeated traffic loads. This permanent deformation can occur in any layer of the pavement structure including surface, base/subbase, and subgrade during the first few years of the traffic operation (Mohammad et al., 2017). While fatigue cracking is resulted from the fatigue fracture at the bottom of the asphalt surface or stabilized base, in which the horizontal strain concentration is the highest under traffic loading (Huang, 2004). The materials used for pavement construction are selected and designed to reduce the distresses during the lifespan or to prevent the premature failure of the pavement (Liu et al., 2021; Sun, 2016). Espinoza-Luque *et al.* (2018) indicated that the durability of the pavement and its service life can be enhanced by reducing the distresses (rutting and fatigue cracking).

Therefore, improving the mechanical properties of the materials is of great significance to pavement design due to the increase of heavy load and high speed of the traffic loads, and aggressive climate conditions. In recent years, many pavement researchers and relevant road construction industries studied the improvement of pavement material in both laboratory scale and field investigation. Meanwhile, seeking an environmental-friendly pavement material with good mechanical properties alternative to natural material is in press based on the global environmental protection issues. To lower the burden to the environment, pavement engineers and researchers addressed more attention to the reusing and recycling of waste materials such as construction and demolition (C&D) wastes.

In recent years, recycled concrete aggregate (RCA) is one of the most C&D materials used in the pavement construction industry. The attempt is to produce a green pavement by reducing the dependence on natural resources while saving construction costs. RCA is generated from the demolition of concrete structures such as old buildings, rigid pavements, and bridges. Several studies indicated that the Portland cement stabilized RCA could be used as a pavement base layer (Arulrajah et al., 2020; Mohammadinia et al., 2019; 2015; Yaowarat et al., 2022), due to its effective strength gain at a reasonable price (Xiao et al., 2018). Cement stabilized RCA demonstrates the better compressive strength and stiffness characteristics when compared with the unstabilized RCA material (Arulrajah et al., 2020; Faysal et al., 2016; Li & Hu, 2020; McGinnis et al., 2017). However, cement stabilized RCA often indicates brittle behavior and formation of mini-cracks under traffic loading (Onyejekwe & Ghataora, 2014; Yaghoubi et al., 2017; Yaowarat et al., 2022); these issues can potentially affect the pavement performance and reduce its service life due to a sudden failure under heavy traffic load.

One of the pioneers of the application of polymers in pavement engineering, Wilson and Crisp (1975) used carboxylated ionic polymer, to modify the engineering properties of soil for road construction for military vehicles. Then, the production of natural and synthetic polymers has gained more attention in the research field of soil-polymer stabilization in purpose of improving the soil engineering properties and pavement performance (Huang et al., 2021; Orts et al., 2007).

Natural rubber latex (NRL) is a natural polymer obtained from the sap of rubber trees (*Hevea Brasiliensis*) (Yaowarat et al., 2021). Several studies reported that NRL could enhance flexural/tensile strength and the durability of soil-cement as a pavement base material (Buritatum et al., 2021; 2022; 2020; Udomchai et al., 2021). The cement-NRL stabilization has therefore been attested to be more eco-friendly when compared to the only cement stabilization, which has significant greenhouse gas emissions from the cement production and energy consumption of natural resources.

On the other hand, the laboratory and/or field study on cement-NRL stabilized recycled materials as a pavement base is very limited, especially under cyclic condition. Previous study revealed that the compressive strength, tensile strength, and toughness characteristic of the cement-NRL stabilized RCA at an optimum dry rubber to cement (r/c) ratio were improved when benchmarked with the cement stabilized RCA under static load condition (Duong et al., 2022). Udomchai et al. (2021) indicated that NRL had positive effect on resilient modulus and fatigue behavior of cement-NRL stabilized soil when subjected to cycling tensile loading under severe wet/dry environment. Typically, the marginal soil with higher fine content is requied to be stabilized with cement, hence the stabilized soil contains high fine particles than the stabilized RCA. The polymer film formation can fill the micro-pores of soil-cement mixture and reduce its volumetric shrinkage and improve isotropic and compressible properties. As a result, the tensile strength, shear strength, and resilient modulus increased with increasing polymer ratio until it reaches the optimum value (Azzam, 2014; Huang et al., 2021). The resilient modulus and fatigue mechanisms of cement-NRL stabilized RCA, which has larger pore space and smaller fine particles might be different from those of cement stabilized soil and are required to clearly understand for confidient usage in real construction.

Therefore, this study aims to evaluate the performance characteristics of cement-NRL stabilized RCA under vehicle cyclic loading conditions through advanced laboratory tests; namely, indirect tensile resilient modulus, indirect tensile fatigue, and rutting susceptibility using Hamburg wheel tracking device. On the laboratory scale tests, the haversine load pulse with a specific frequency is suggested to simulate a loading regime of the vehicle speed (AASHTO-T307, 2007; Loulizi et al., 2002). This research will provide scientific evidence on the role of NRL on the improved cyclic performance of cement stabilized RCA as a pavement base. The outcome of this research will contribute to an effective demolition waste management in road and highway construction projects.

4.2 Materials and sample preparation

4.2.1 Materials

In this research, the materials studied were recycled concrete aggregate (RCA), ordinary Portland cement (OPC), and natural rubber latex (NRL). RCA had a nominal maximum particle size of about 19.5 mm and was originated from waste concretes after being crushed and graded by a crusher machine. The grain size distribution curve of RCA was within the upper and lower boundary limits authorized by the Department of Highways (DOH) Thailand (DH-S201/2556) for pavement base material (**Figure 4.1**) (DH-S203/2556, 2013). The geotechnical properties of RCA were summarized in **Table 4.1**. NRL was procured from Srijanoen rubber company (Thailand), which contained 30.8% of dry rubber content by weight. The NRL in the liquid form was treated with surfactant, namely sodium dodecyl sulfate (SDS) for a colloidal stability to prevent the rubber particle coagulation (Vo & Plank, 2018).

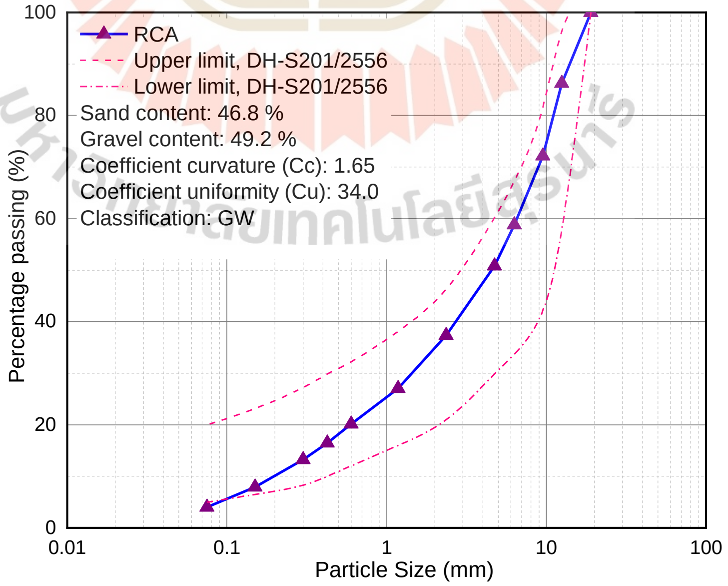


Figure 4.1 Particle size distribution curve of RCA.

Table 4.1 Basic geotechnical engineering properties of RCA.

Properties	Values	Standard method
Specific gravity - coarse	2.30	ASTM C127
Specific gravity - fine	2.17	ASTM C128
Water absorption - coarse (%)	6.32	ASTM C127
Water absorption - fine (%)	7.95	ASTM C128
Organic content (%)	2.56	ASTM D2974
Flakiness index	15.6	BS 812:105.1
Los Angeles abrasion loss	38.1	ASTM C1311
pH	12.2	ASTM D4972
CBR	195	ASTM D1883
Maximum dry density (Mg/m^3)	1.89	ASTM D1557
Optimum liquid content (%)	11.7	ASTM D1557

4.2.2 Sample preparation

In order to evaluate the influence of NRL replacement on the performance of cement-NRL stabilized RCA under cyclic loadings, three advanced laboratory tests consisting of indirect tensile resilient modulus (IT M_r), indirect tensile fatigue (ITF), and wheel tracking tests were performed. On the basis of the previous study (Duong et al., 2022) and the environmental and economic perspectives (Mohammadinia et al., 2015), 3% cement content by weight was selected to prepare the cement stabilized RCA (3C-RCA) samples and cement-NRL stabilized RCA samples with different r/c ratios at 5%, 10%, and 15% (3C5R-RCA, 3C10R-RCA, and 3C15R-RCA). All the testing samples were compacted to attain the target maximum dry density (MDD) and optimum liquid content (OLC) based on the modified Proctor compaction test results (Duong et al., 2022). **Table 4.2** demonstrates the target MDD and OLC of the studied mixtures.

Table 4.2 The design compaction parameters of tested samples.

Name of Sample	Mixture	Target MDD (Mg/m^3)	Target OLC (%)
3C-RCA	3% cement + RCA + Water (r/c ratio = 0)	1.937	12.0
3C5R-RCA	3% cement + NRL + RCA (r/c ratio = 5%)	1.906	11.9
3C10R-RCA	3% cement + NRL + RCA (r/c ratio = 10%)	1.828	11.5
3C15R-RCA	3% cement + NRL + RCA (r/c ratio = 15%)	1.824	10.6

The IT M_r and ITF tests were carried out on the samples with a dimension of 101.6 mm (4 in) in diameter and 78 mm (3 in) in height. Each sample was compacted in three layers (approximately 25 mm per layer) with 28 blows per layer to attain the modified Proctor compaction effort. Besides, the samples with a diameter of 150 mm (6 in) and a thickness of 61 mm (2.4 in) were compacted in 2 layers and 65 blows per layer by the Marshall automatic compactor for rutting test using Hamburg wheel tracking device (HWTD). At least three replicate samples were prepared for each designed test. The test temperature condition was maintained at 25±2°C.

4.3 Laboratory experimental programs

4.3.1 Indirect tensile resilient modulus (IT Mr) test

Resilient modulus or stiffness is a crucial input parameter for pavement design (Mohajerani et al., 2020). Resilient modulus of pavement base material can be determined using repeated load triaxial test or flexural beam test (Arulrajah et al., 2020). Recently, the indirect tensile resilient modulus (IT M_r) test was suggested as an economical and reliable method to determine the stiffness of base materials (Arabani & Azarhoosh, 2012; Fedrigo et al., 2018; Carthigesu et al., 2008; 2010; Jitsangiam et al., 2015). Thus, the ASTM D7369 standard test procedure (ASTM-D7369, 2020) was adopted for determining the IT M_r of cement stabilized RCA, and cement-NRL stabilized RCA samples in this study. The IT M_r samples were cured at a controlled temperature of 25 ± 2°C for 7 and 28 days. The test was carried out on at least six samples for each mixture to ensure data consistency, and the mean value was reported. For each mixture, three samples were used to determine the ITS, and the three remaining samples were used for the IT M_r test subsequently. A haversine wave-form repeated load at a frequency of 1 Hz with an applied load of 40% of the ITS was subjected along the vertical diametral plane of the sample. During the test, the axial strain data was collected until the required number of load pulses of 100 was accomplished. The IT M_r data was reported as the average value from the last 50 pulses, while the first 50 pulse measurements were neglected due to the inconsistency in applied force and contact point (Arulrajah et al., 2020; Fedrigo et al., 2018). The IT M_r is calculated by the following expression:

$$\text{IT } M_r = 1000.\frac{P(0.27+\upsilon)}{HD} \tag{4.1}$$

where P is applied load (N), $\boldsymbol{\upsilon}$ is Poisson's ratio ($\boldsymbol{\upsilon}$ of 0.2 is commonly utilized (Austroads, 2012; Carthigesu et al., 2010)), D is the thickness of sample (mm), H is recoverable deformation acquired from the last 50 repeated load cycles (mm).

4.3.2 Indirect tensile fatigue (ITF) test

Fatigue cracking or fatigue life is a significant characteristic related to the long-term durability of pavement material before it deteriorates due to the repeated load cycles (Carthigesu et al., 2010). In this study, the ITF test was carried out according to BS EN 12697 (BS-EN-12697-24, 2018) to compare the anti-cracking property between cement-NRL stabilized RCA and cement stabilized RCA as the control sample. The haversine load was fixed at 70% of the coressponding ITS, and the cyclic frequency of 1 Hz with a duration of 0.5s loading and 0.5s resting was set. The indirect tensile fatigue life (ITFL) of a stabilized sample is the number of load cycles corresponding to its reduction of 50% in the initial stiffness modulus (Arulrajah et al., 2020). In this research, ITFL is obtained by interpreting the number of load cycles corresponding to the nonlinear trend of deformation in zone 3 as shown in **Figure 4.2** (AASHTO-T324, 2019; Carthigesu et al., 2010; Graeff et al., 2012).

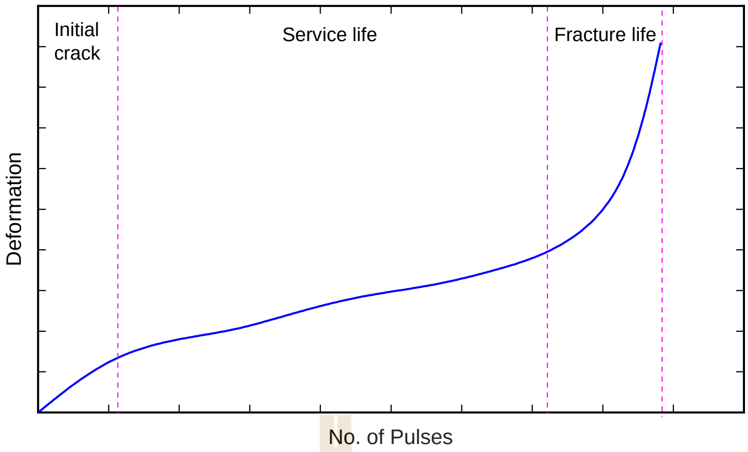


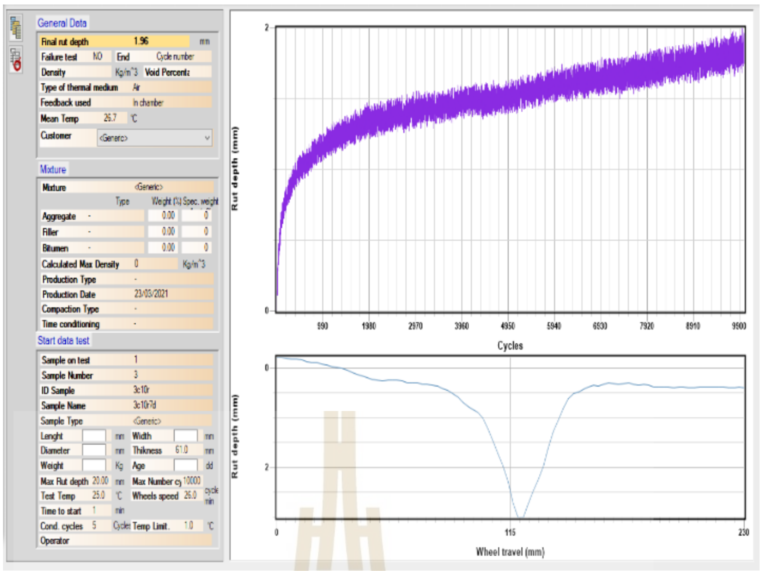
Figure 4.2 A typical plot of deformation versus repeated load pulses of ITF test.

4.3.3 Rutting susceptibility test using Hamburg wheel tracking device (HWTD)

The HWTD is suitable for estimating the rutting susceptibility of the sample similar to real traffic loading conditions (Maghool et al., 2021). The rutting susceptibility test on cement-stabilized RCA samples in the HWTD was performed in accordance with AASHTO T324 (AASHTO-T324, 2019). The experiments were carried out on the samples at an age of 7 days in a maintaining temperature condition (25 ± 2°C) by a steel wheel roller with a diameter of 203 mm (8 in) and width of 47 mm (1.85 in). The tire pressure of 600 kPa was kept constant throughout testing by an axial load of 8 kN and the wheel speed was set up at 26 cycles per minute (52 passes/min) (Arulrajah et al., 2020). Stop criteria for the wheel tracking test were met either the number of load cycles of 10,000 cycles (20,000 passes) or the rutting depth of 20 mm, whichever reached foremost (Rahman & Hossain, 2014). **Figure 4.3** shows the HWTD testing setup.

Figure 4.3 Hamburg wheel tracking device (HWTD) test setup.

The test result was presented in the relationship between rutting depth versus number of wheel passes or cycles, in which one cycle is equal to two passes (**Figure 4.4a**). From **Figure 4.4b**, the output parameters can be defined from the typical HWTD rutting curve, including creep slope (CS), stripping slope (SS), and stripping inflection point (SIP) (Lv et al., 2019). According to Rahman and Hossain (2014), CS and SS are the linear slopes ahead and behind the SIP and are calculated by the number of wheel passes required to create 1 mm rut depth. CS is related to primary rutting, which is associated with the plastic flow while SS is related to moisture damage of the mixture. The SIP is the number of wheel passes at the intersection of CS and SS, which defines an abrupt behavior of the sample at the beginning of the significant moisture damage in the mixture.



General Data

Final rut depth 1.96 mm
Failure test NO End Cycle number
Density Kg/m^3 Void Percenta
Type of thermal medium Air
Feedback used In chamber
Mean Temp 26.7 °C
Customer <Generic>

Mixture

Mixture <Generic>

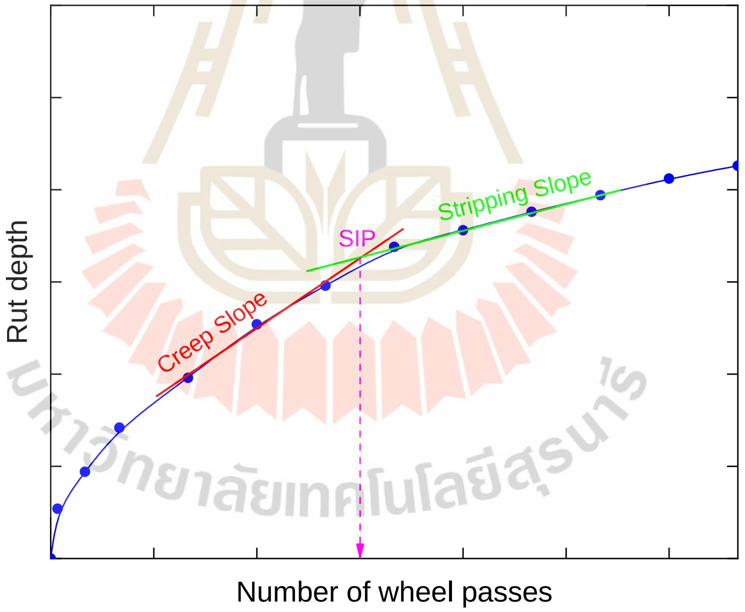
	Type	Weight (%)	Spec. weight
Aggregate	-	0.00	0
Filler	-	0.00	0
Bitumen	-	0.00	0

Calculated Max Density 0 Kg/m^3
Production Type -
Production Date 23/03/2021
Compaction Type -
Time conditioning -

Start data test

Sample on test 1
Sample Number 3
ID Sample 3c10r
Sample Name 3c10r7d
Sample Type <Generic>
Lenght mm Width mm
Diameter mm Thikness 61.0 mm
Weight Kg Age dd
Max Rut depth 20.00 mm Max Number cy 10000
Test Temp 25.0 °C Wheels speed 26.0 cycle min
Time to start 1 min
Cond. cycles 5 Cycles Temp Limit. 1.0 °C
Operator

(a)



(b)

Figure 4.4 A screen-tested result (a) and typical output parameters (b) from the HWTD test.

4.4 Result and discussion

4.4.1 Indirect tensile resilient modulus

Figure 4.5 shows the relationship between tensile stress and strain of cement- and cement-NRL stabilized RCA samples at 7 days of curing. The cement stabilized RCA (3C-RCA) sample clearly indicated a higher stiffness with a smaller strain at failure (approximately 1%) than the cement-NRL stabilized RCA samples (3C5R-RCA, 3C10R-RCA, and 3C15R-RCA). The peak tensile stress and ductile behavior of cement-NRL stabilized RCA samples were found to be influenced by r/c ratio. Increasing the r/c ratio resulted in an increased tensile strain at failure of the cement-NRL stabilized RCA samples while the highest peak tensile strength was found at the optimum r/c ratio of 10%. In other words, the NRL additive can enhance the tensile strength and ductility of the cement-NRL stabilized RCA samples.

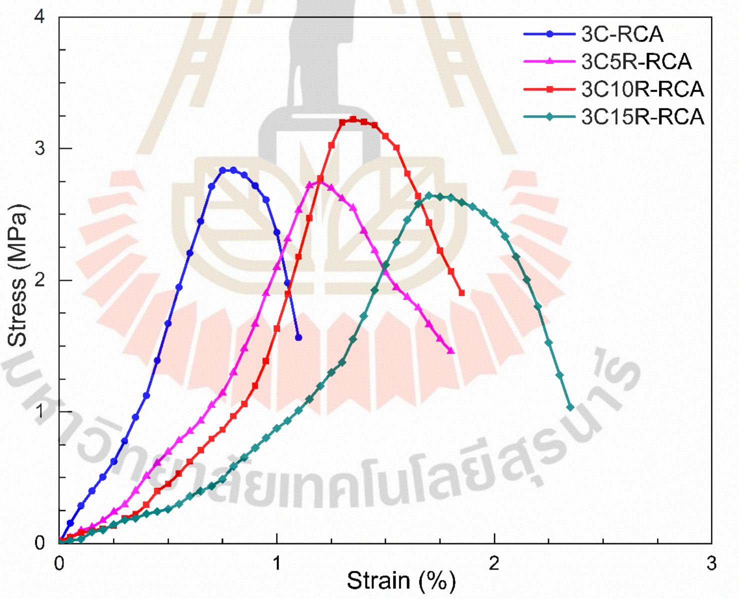


Figure 4.5 Tensile stress and strain curves of cement- and cement-NRL stabilized RCA samples.

Figure 4.6 shows the IT M_r or stiffness modulus and ITS of cement and cement-NRL stabilized RCA samples with different r/c ratios at ages of 7 and 28 days. The ITS of cement-NRL stabilized RCA depended on the r/c ratio and curing time. The

ITS of cement-NRL stabilized RCA samples increased with the increased curing time and the highest ITS was obtained at the optimum r/c ratio of 10% for both 7 and 28 days of curing. The IT M_r values of cement-NRL stabilized RCA samples varied from 7848 MPa to 9133 MPa for 7 days and from 8913 MPa to 10177 MPa for 28 days; the range of these values were found to be similar to the earlier investigations of cement stabilized granular materials (Fedrigo et al., 2018; Carthigesu et al., 2010; Jitsangiam et al., 2015; Paul & Gnanendran, 2016). Similar to ITS results, the IT M_r values of cement-NRL stabilized RCA samples depended on the r/c ratio and curing time. The IT M_r values of all cement-NRL stabilized RCA samples increased with the increased curing time. At 7 days of curing, the IT M_r values of cement-NRL stabilized RCA samples with r/c ratios of 5% and 10% are similar and were higher than that of the sample with r/c ratio of 15%. The 7-day IT M_r values of cement-NRL stabilized RCA samples with r/c ratios of 5%, 10%, and 15% were respectively about 4.2%, 4.5%, and 14.1% lower than the value of control 3C-RCA sample (r/c = 0).

Fedrigo et al. (2018) indicated that the strength and stiffness of the cement stabilized reclaimed asphalt pavement (RAP) and crushed aggregate mixtures increased with the increased cement content. Similar studies investigated on the resilient behaviors of cement stabilized C&D wastes such as RCA, RAP, and crushed brick (CB) were also demonstrated that the resilient modulus of cement stabilized RAP, RCA, and CB materials increased with the increased cement content (Mohammadinia et al., 2015, 2016). Udomchai et al. (2021) evaluated the IT M_r of cement-NRL stabilized soil and compared with cement stabilized soil (without NRL). The results indicated that the NRL additive remarkably enahnced the IT M_r of cement stabilized soil. In addition, the IT M_r values of cement-NRL stablized soil increased with increasing NRL replacement until it reached the highest value at the optium NRL replacement ratio of 20%. The same is not true for cement stabilized RCA which larger pore space and smaller fine particles.

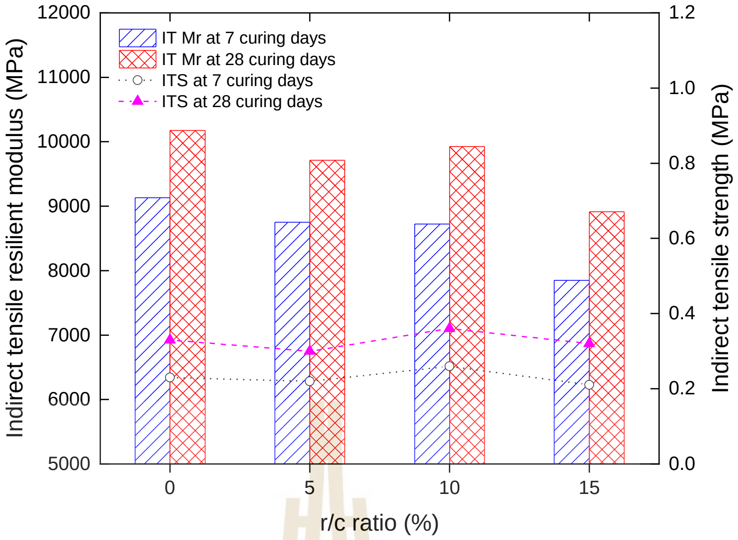


Figure 4.6 Indirect tensile resilient modulus of RCA mixtures against curing times and r/c ratios.

Resilient modulus is characterized as the ratio of deviator stress to the recoverable strain of the sample. Although it was evident from **Figure 4.6** that the ITS of cement-NRL stabilized RCA at optimum r/c ratio = 10% (3C10R-RCA) was slightly higher than that of cement stabilized RCA (3C-RCA), the IT M_r of 3C10R-RCA was slightly lower than that of 3C-RCA.

It is of interest to present the relationship between the horizontal deformation versus number of repeated load cycles of 3C-RCA and 3C10R-RCA to examine the role of NRL on improved permanent deformation resistance (**Figure 4.7**). The total horizontal deformation is the sum of recoverable deformation (elastic deformation or resilient behavior) and permanent deformation (plastic deformation or absorbing behavior). The resilient behavior is crucial for the pavement design practices (Singh & Sahoo, 2021). The accumulated permanent deformation in unbound granular aggregate base/subbase course 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 (AASHTO, 1993; Mohammad et al., 1994). **Figure 4.7** clearly indicated that for the same cyclic stress, the total deformation of cement-NRL stabilized RCA (3C10R-RCA) is greater than that of the cement stabilized RCA (3C-RCA).

The recoverable deformation of 3C10R-RCA was higher than that of 3C-RCA because the 3C10R-RCA had higher IT M_r than the 3C-RCA. However, the 3C10R-RCA exhibited lower permanent deformation than the 3C-RCA. In other words, the addition of NRL to cement stabilized RCA can improve the tensile strength and permanent deformation resistance, which lead to the improved resistance to fatigue cracking of cement-NRL stabilized RCA as a pavement base material under repeated vehicle loading.

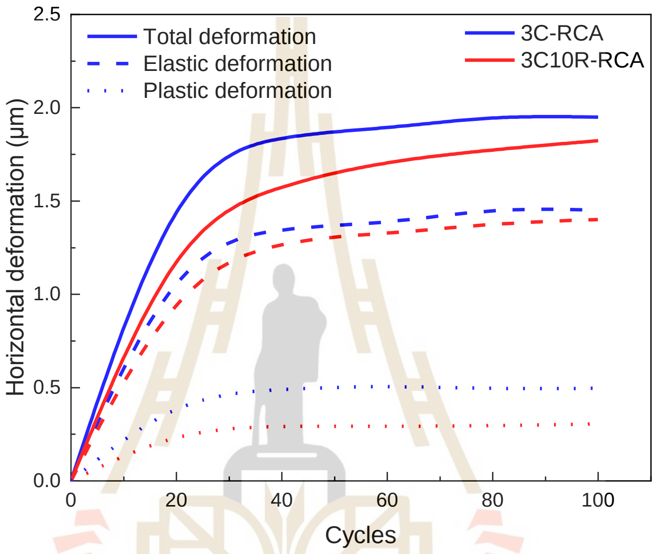


Figure 4.7 Relationship between horizontal deformation and number of load cycles.

If the properties of cement stabilized RCA are similar to tensile and compressive direction, the cement-NRL stabilized RCA would have higher resistance against the rutting than the cement stabilized RCA. In other words, the cement-NRL stabilized RCA would have lower rutting depth when benchmarked with cement stabilized RCA at the same volume of traffic load. This premise will be illustrated in the next section.

4.4.2 Indirect tensile fatigue

Figure 4.8 shows the relationship between the total deformation and the number of cycles of cement and cement-NRL stabilized RCA samples with different r/c ratios at ages of 7 and 28 days. The r/c ratio and curing time directly influenced the fatigue behavior of cement-NRL stabilized RCA. The cement-NRL stabilized RCA sample with r/c ratio of 10% (3C10R-RCA) showed better fatigue performance than the samples with r/c ratio of 5% and 15% (3C5R-RCA and 3C15R-RCA) at both ages of 7 and 28 days. The longer cured samples had superior fatigue performance to the early cured samples. The fatigue life of 3C5R-RCA and 3C15R-RCA samples was essentially the same and notably lower than that of 3C10R-RCA sample. While the 3C15R-RCA and 3C5R-RCA samples had relatively high deformation at the same number of cycles, and was higher than that of the 3C10R-RCA sample. When compared with 3C-RCA (control sample), the fatigue life of 3C-RCA was higher than that of 3C5R-RCA and 3C15R-RCA but lower than that of the 3C10R-RCA (**Figure 4.9**).

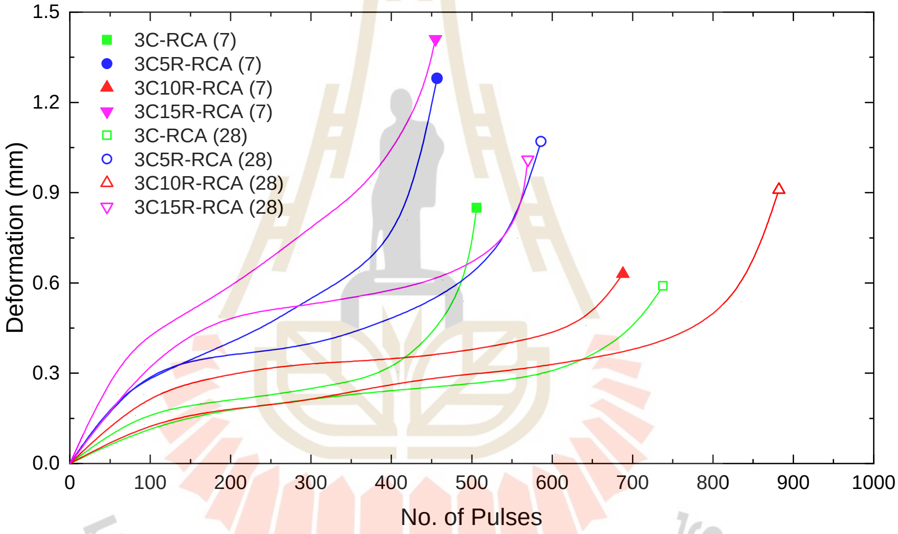


Figure 4.8 Fatigue behavior of the mixtures until structural failure.

Arulrajah et al. (2015; 2020) reported that the fatigue performance of cement stabilized recycled aggregates was dependent on the applied load and the fatigue life was reached within a few hundred loading cycles, which is similar to this study. The r/c ratio of 10% was found to be the optimum value for cement-NRL stabilized RCA. In addition, the optimum r/c ratio can significantly improve the fatigue performance of cement stabilized RCA. This is because of the NRL films can enhance the interfacial connection between RCA particles and the cement hydration products, resulting in fatigue resistance improvement (Assaggaf et al., 2021; Thomas et al., 2016).

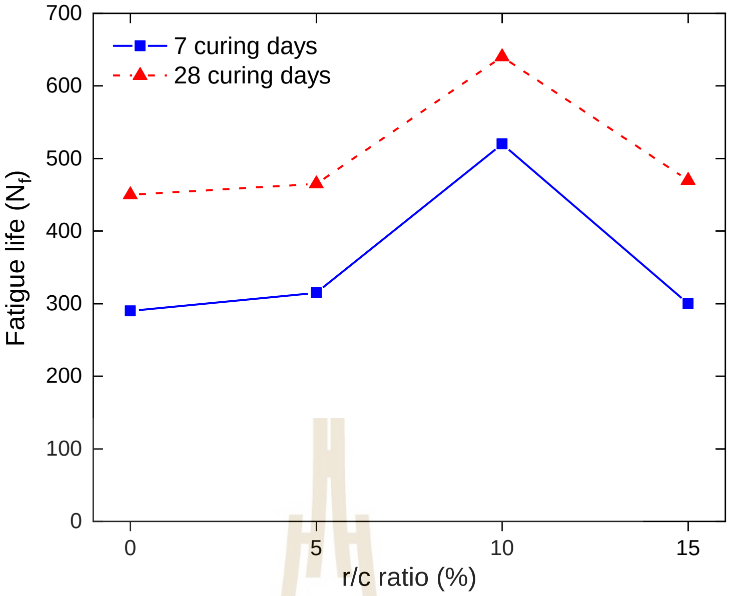


Figure 4.9 Fatigue life versus the r/c ratio of mixtures.

4.4.3 Rutting resistance

Figure 4.10 shows the relationship between the accumulative rut depth and number of wheel cycles of cement stabilized RCA (3C-RCA) and cement-NRL stabilized RCA at r/c ratios of 5%, 10%, and 15% (3C5R-RCA, 3C10R-RCA, and 3C15R-RCA) under the HWTD test. The rutting performance of 3C5R-RCA and 3C15R-RCA samples was found to be similar and their rate of increase in rut depth with the increased number of wheel cycles was higher than that of 3C10R-RCA sample. The r/c ratio of 10% was found to be the optimum for the cement-NRL stabilized RCA. With lower permanent deformation (**Figure 4.7**), the 3C10R-RCA had lower rut depth when compared with the 3C-RCA (control sample). **Table 4.3** summarizes the rutting parameters including creep slope (CS), stripping slope (SS), and stripping inflection point (SIP) determined from rutting curves in **Figure 4.10**.

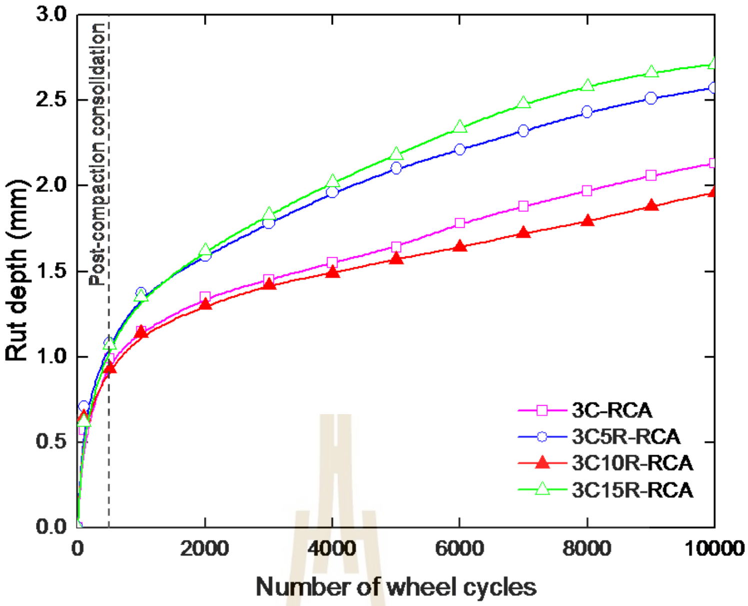


Figure 4.10 HWTD rutting curves of RCA mixtures.

Table 4.3 The rutting parameters CS, SIP, and SS for RCA mixtures.

Name of Sample	CS (mm/1000 passes)	SIP (Passes)	SS (mm/1000 passes)
3C-RCA	0.26	5,315	0.09
3C5R-RCA	0.19	4,354	0.11
3C10R-RCA	0.08	NA	0.08
3C15R-RCA	0.19	5,688	0.12

Based on **Figure 4.10** and **Table 4.3**, the rutting parameters (CS and SS) of 3C10R-RCA sample were found to be similar while the CS and SS of 3C-RCA sample were different. The 3C-RCA sample had CS and SS values slightly higher than the 3C10R-RCA sample, which indicated that the 3C10R-RCA sample had higher rutting resistance than the 3C-RCA sample due to the superior plastic flow property and moisture damage resistant of cement-NRL stabilized RCA (Fedrigo et al., 2018; Zhang et al., 2021). **Figure 4.11** shows the tested samples after 10,000 cycles of wheel tracking test and it is evident that the 3C10R-RCA sample had higher stripping resistance performance than the 3C-RCA sample.

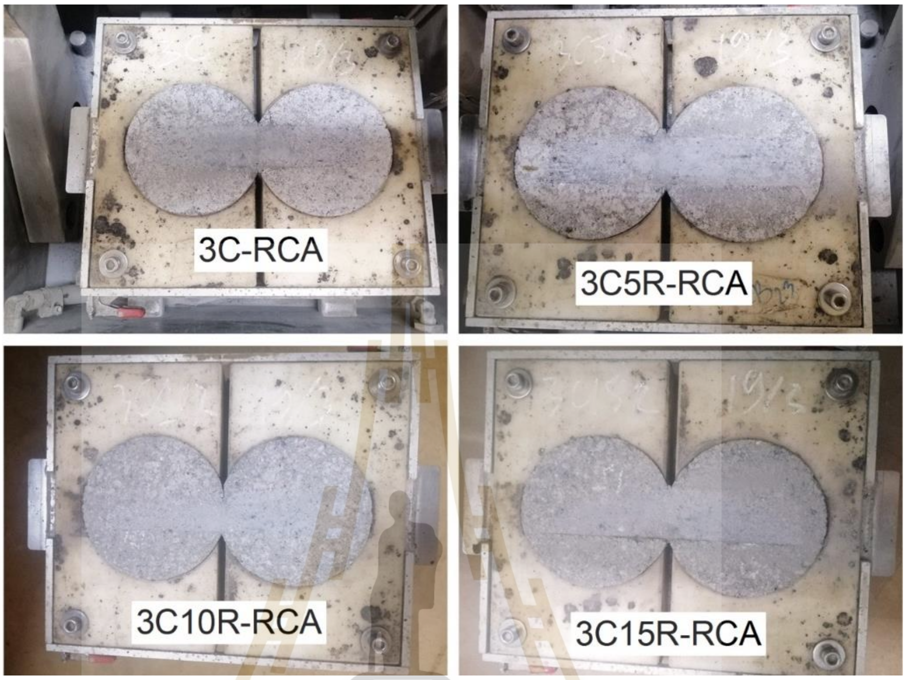


Figure 4.11 Photos of cement stabilized RCA and cement-NRL stabilized RCA samples after 10,000 load cycles of wheel tracking test.

Figure 4.12 shows the total rut depth of cement-NRL stabilized RCA at r/c ratios of 5%, 10%, and 15% compared with that of cement stabilized RCA (r/c ratio of 0%) at 5,000 and 10,000 wheel cycles. The total rut depth of 3C10R-RCA sample was about 8% lower than that of 3C-RCA sample with total rut depth of approximately 2.13 mm after 10,000 cycles. However, the total rut depth of 3C5R-RCA and 3C15R-RCA samples were approximately 20.7% and 27.2% higher than that of the 3C-RCA sample after 10,000 cycles. Several researchers reported that the addition of NRL at optimum content can improve the flexural/tensile strength and durability of the cement stabilized materials because the bonding strength of aggregates were enhanced by NRL films (Buritatum et al., 2021; and 2020; Sukmak et al., 2020; Vo & Plank, 2018; Yaowarat et al., 2021). On the dry side of optimum r/c ratio, the bonding strength is low because of the flocculation process of NRL polymeric material.

However, on the dry side of optimum r/c ratio, the thick NRL films prevent the cement hydration, which make stabilized materials more irrecoverable deformation under wheel loading (Ismail et al., 2009; Nagaraj et al., 1988; Subash et al., 2021).

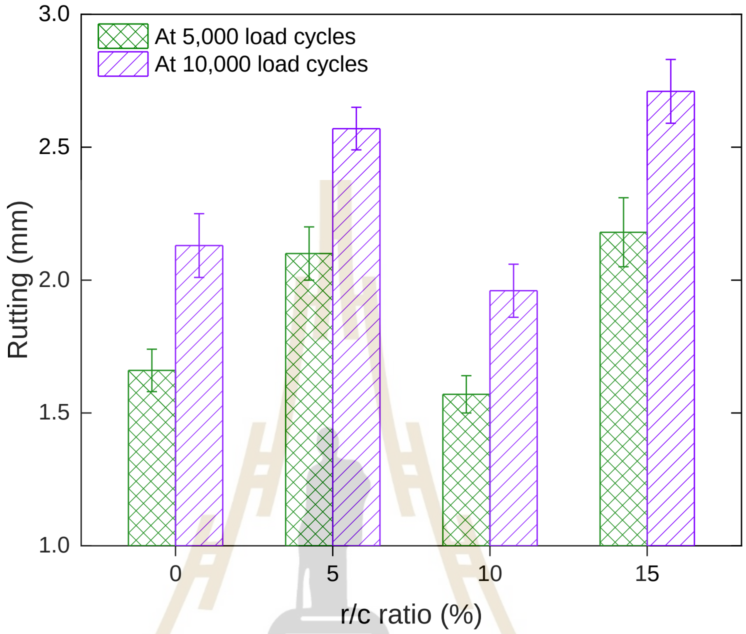


Figure 4.12 Correlation between rutting evolution and r/c ratio.

From the rutting and indirect tensile fatigue test results, the rutting resistance and fatigue life of cement stabilized RCA can be improved by the NRL replacement at the optimum r/c ratio. As a result, the durability of the pavement and its service life can be enhanced by reducing the distresses under the cyclic traffic loading.

4.5 Conclusions

This research investigates the performance of 3% cement stabilized RCA (3C-RCA) and 3% cement-NRL stabilized RCA with different r/c ratios of 5%, 10%, and 15% (3C5R-RCA, 3C10R-RCA, 3C15R-RCA) as pavement base under a cyclic loading. The performance evaluation was carried out through the advanced experimental program:

IT Mr test, ITF test, and rutting susceptibility test using Hamburg wheel tracking device (HWTD).

The r/c ratio of 10% was found to be the optimum for cement-NRL stabilized RCA in term of ITS, ITF, and rutting resistance. The cement-NRL stabilized RCA at the optimum r/c ratio (3C10R-RCA) exhibited higher ITS and ITF than the cement stabilized RCA. This implied that the presence of NRL film can enhance interfacial connection between RCA particles and the cement hydration products, which lead to the improved fatigue cracking failure of the cement stabilized RCA as pavement base. All of the longer aged cement-NRL stabilized RCA samples had superior fatigue performance to the early aged samples.

Even though the IT M_r of 3C10R-RCA was lower than the 3C-RCA, the permanent deformation under indirect tensile fatigue test was found to be lower. Similar to the compressive cyclic loading condition under wheel tracking test, the rut depth of 3C10R-RCA was approximately 8% lower than 3C-RCA after 10,000 cycles. In other words, the NRL additive optimim r/c ratio could improve permanent deformation in both compressive and tensile directions. However, the rut depths of 3C5R-RCA and 3C15R-RCA were approximately 20.7% and 27.2% higher than the rut depth of 3C-RCA after 10,000 cycles. On the dry side of r/c ratio, the adhesive strength of the mixtures is low because the flocculation process of NRL polymeric material coagulates the mixtures, which reduces the bonding strength of the sample. However, on the wet side of optimum r/c ratio, the thick NRL films prevent the cement hydration and make mixture more unrecoverable deformation under wheel loading.

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CHAPTER V

INFLUENCE OF WETTING - DRYING CYCLES ON MECHANICAL PROPERTIES AND MICROSTRUCTURE OF CEMENT - NATURAL RUBBER LATEX STABILIZED RECYCLED CONCRETE AGGREGATE

5.1 Statement of the problem

Wetting-drying (w-d) cycles cause the formation of cracks that may lead to the damage of pavement infrastructures, especially in tropical climate areas where have high temperatures in the dry season and a long wet season (Hoy et al., 2016; Nabil et al., 2020; Neramitkornburi et al., 2015). In the last decades, recycled concrete aggregate (RCA) has become a popular material in pavement applications due to societal awareness of the need to conserve natural resources and reduce construction costs. In addition, cement stabilized RCA has been recommended as a suitable base material for pavement construction (Bestgen et al., 2016; S Chakravarthi et al., 2019; Sarella Chakravarthi & Shankar, 2021; Ebrahim Abu El-Maaty Behiry, 2013a; Gabr et al., 2013; Haider et al., 2014; Mohammadinia et al., 2015; Xuan et al., 2015; Zhang et al., 2020).

In tropical countries such as Thailand, the pavement layers annually suffer from drought in the dry season and flood in rainy season, which cause the degradation of the pavement materials (Buritatun et al., 2020). Moisture damage resistance is vital to the success of the use of recycled materials as a green pavement material (Zou et al., 2020). According to Mathanraj (2015), seasonal changes in moisture content and temperature are reduced the bearing capacity of pavement materials. Therefore, the research on pavement material deterioration and prolonging their service life under w-d cycles have received much attention (Mamlouk et al., 2018).

Although cement stabilized RCA shows good physical and mechanical characteristics for the pavement base applications. It exhibits brittle behavior, extremely low flexibility and sensitivity to moisture changes during the w-d cycles which may cause the loss in interparticle bonding strength and propagation of microcracks (Buritatum et al., 2021a). When passed through w-d cycles, steady cracks may propagate and generate external surface fractures in cement stabilized RCA (Neramitkornburi et al., 2015) (Chakradhara Rao et al., 2012) (Donrak et al., 2018) (Udomchai et al., 2021a) (Suddeepong et al., 2018).

Natural rubber latex (NRL) is a green polymer that has the ability to form homogeneous and flexible films upon dehydration. Rubber film acts as a substrate to enhance cohesion and adhesion properties (Vo & Plank, 2018). The previous study (Duong Vinh et al., 2021) focused on the utilization of NRL to improve the geotechnical engineering properties of cement stabilized RCA. The dry rubber to cement (r/c) ratio of 5%, 10%, and 15% and the cement content of 3%, 5%, and 7% were chosen to stabilize RCA. The results indicated that cement stabilized RCA with optimum r/c ratio could significantly improve the compressive strength, stress-strain relationship, and toughness compared to control mixtures.

In this study, the cement content was kept constant at 3%, and the r/c was varied at 5%, 10% and 15% based on the results from previous study (Duong Vinh et al., 2021). The long-term pavement performance of cement- and cement-NRL stabilized RCA against w-d cycles was evaluated in order to understand the response of the studied mixtures to w-d process. The cement- and cement-NRL stabilized RCA mixtures were tested to determine the compressive strength at various w-d cycles (0, 1st, 3rd, 6th, 9th, and 12th). Besides, the FESEM was conducted to analyze the microstructural deterioration corresponding to the test cycle. The outcome of this research will address the knowledge gap about resistance to w-d deterioration of cement-NRL stabilized RCA and encourage the use of NRL in pavement base applications.

5.2 Materials and sample preparation

5.2.1 Materials

The recycled concrete aggregate (RCA) was obtained from demolished waste concrete and crushed by a crusher machine for the nominal maximum size of 20 mm. **Figure 5.1** presents the particle size distribution curve of RCA compared to the specified limits of Thailand’s Department of Highways (DOH) and ASTM standards.

The geotechnical properties of RCA are summarized in **Table 5.1**; the results indicate that there are an appropriate to the typical values. The chemical compositions of ordinary Portland cement (OPC) are shown in **Table 5.2**. In this study, the specific density of OPC is 3.15 g/cm^3. The NRL sample was supplied by the Rubber Authority of Thailand and the dry rubber content in latex is 30.79 (wt %). The NRL is deproteinized using sodium dodecyl sulfate (SDS).

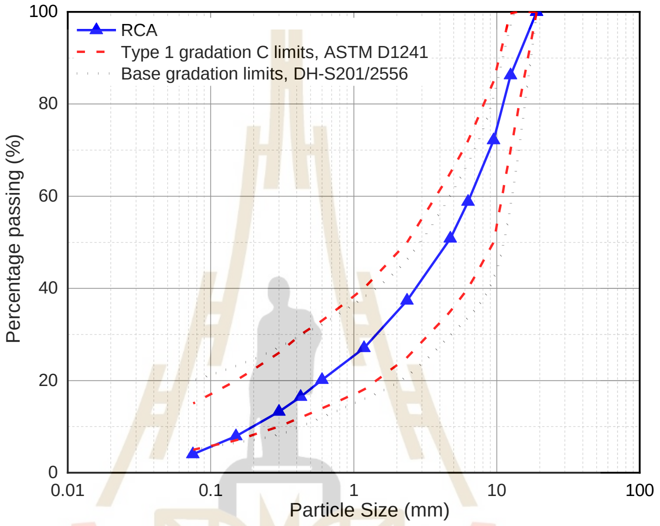


Figure 5.1 Particle size distribution curve of studied RCA.

Table 5.1 Geotechnical properties of RCA (Duong Vinh et al., 2021).

Properties	Standard Method	Values	Typical values (Verian et al, 2013)
Specific gravity - coarse	ASTM C127	2.30	> 2
Specific gravity - fine	ASTM C128	2.17	> 2
Water absorption - coarse (%)	ASTM C127	6.32	< 10
Water absorption - fine (%)	ASTM C128	7.95	< 10
Organic content (%)	ASTM D2974	2.56	< 5
Fine content (%)	ASTM D422	4.0	< 10
Sand content (%)	ASTM D422	46.8	-

Table 5.1 Geotechnical properties of RCA (Duong Vinh et al., 2021). (Continued)

Properties	Standard Method	Values	Typical values (Verian et al, 2013)
Gravel content (%)	ASTM D422	49.2	-
Coefficient curvature (C_c)	ASTM D2487	1.65	-
Coefficient uniformity (C_u)	ASTM D2487	34.0	-
Soil classification	ASTM D2487	GW	GW, GS
Flakiness index	BS 812:105.1	15.6	< 35
Los Angeles abrasion loss	ASTM C1311	38.1	< 40
pH	ASTM D4972	12.2	7 - 12
Maximum dry density (Mg/m^3)	ASTM D1557	1.89	> 1.8
Optimum moisture content (%)	ASTM D1557	11.7	8 - 15

Table 5.2 Chemical compositions of OPC (Duong Vinh et al., 2021).

Composition	SiO_2	CaO	Al_2O_3	Fe_2O_3	MgO	SO_3	LOI
Content (%)	20.1	65.0	4.7	3.2	2.6	3.3	0.9

5.2.2 Sample preparation

RCA mixed with cement at a cement content of 3% by weight of the RCA and NRL at r/c ratios of 5%, 10%, and 15%, respectively. The liquid content is required to achieve the optimum liquid content (OLC) including the water in NRL additive and the free water as predetermined from modified Proctor compaction test results (Duong Vinh et al., 2021). **Table 5.3** shows the results of maximum dry density (MDD) and OLC of cement- and cement-NRL stabilized RCA mixtures at different r/c ratios.

Table 5.3 Compaction test results at 3% cement content and different r/c ratios.

r/c (%)	0	5	10	15
Name	3C-RCA	3C5R-RCA	3C10R-RCA	3C15R-RCA
OLC (%)	12.0	11.9	11.5	10.6
MDD (kg/m^3)	1937	1906	1828	1824

The mixtures were produced according to the two-stage mixing approach (TSMA) (Tam et al., 2005). First, the RCA surface was wetted by 1/2 mixing water and then mixing for 30 seconds by hand. Next, 3% of cement by weight of RCA was added for another 30 seconds. The last 1/2 mixing water was added and continued the mixing for 60 seconds to produce the cement stabilized RCA sample. For cement-NRL stabilized RCA, the rubber latex was added to the mix and stirred for 60 seconds after adding water. The cement-NRL stabilized RCA samples were compacted in 5 layers (25 blows per layer) to attain the target MDD, according to ASTM D558 (2004). The dimensions of compaction molds are 101.6 mm diameter and 116.8 mm height. The compacted samples were kept in the mold for 24 hours before demolded, and then wrapped with a plastic sheet.

A total of 72 cylindrical samples were prepared and cured for 28 days at room temperature 25±2°C before being subjected to w-d process. Since the cement hydration reaches more than 75% after 28 days (Buritatum et al., 2021b; Jha & Sharma, 2021; N. N. Khoury & Zaman, 2002; N. Khoury & Zaman, 2007), the growth of cement hydration products does not affect the strength changes during the test.

5.3 Laboratory experimental programs

5.3.1 Wetting and drying cycles

The w-d cycles tests were conducted to investigate the long-term performance and the durability against the effect of weather changes of cement-NRL stabilized RCA in accordance with ASTM D559 (2011). The w-d cycling test is explained as follows: The 28 days cured samples were removed the plastic sheets and determined its weight. After that, the samples were immersed into a water tank for 5 hours (wetting stage) to absorp water freely. Finally, the samples were put into an oven and kept in constant temperature at 70°C for 42 hours (drying stage) (Udomchai et al., 2021b). The experimental process of wetting and drying stages are shown in **Figure 5.2**. The variation in weights of samples was recorded at the end of each iteration. In this study, the w-d process was set for 12 cycles and the mixtures were tested at 0, 1st, 3rd, 6th, 9th, and 12th cycle (as seen in **Table 5.4**). At least three samples per mixture were prepared for each w-d cycling test to ensure the test result is reliable.

Table 5.4 Process of w-d cycles.

Cycles	0	1st	2nd	3rd	4th	5th	6th	7th	8th	9th	10th	11th	12th
Wet	-	1	3	5	7	9	11	14	15	17	19	21	23
Dry	-	2	4	6	8	10	12	14	16	18	20	22	24
Testing	✓	✓		✓			✓			✓			✓

(a) Drying samples (b) Wetting sample

Figure 5.2 Part of a w-d experimental process.

5.3.2 Unconfined compression test

The unconfined compressive strength (UCS) test is commonly used to evaluate the material strength to categorize the class of roads (Baghini et al., 2015).

The UCS test was conducted according to ASTM D1633 (2017) at a compression rate of 1 mm/min. The stress-strain relationships were automatically recorded using a software. Secant modulus of elasticity (E_{50}) or elastic stiffness of cement- and cement-NRL stabilized RCA samples were determined from the recorded stress-strain relationships by measuring the slope between origin and 1/2 UCS coordinately.

5.3.3 Microstructural morphology by FESEM/EDS

The micro-structural images were obtained from a FESEM/EDS microscope with a magnification range from 5,000 to 20,000× (**Figure 5.3**). FESEM was also used to observe the deterioration and the process of mini-crack initiation in the samples under the wetting-drying cycles.

Figure 5.3 Field emission scanning electron microscope (FESEM/Zeiss AURIGA model).

5.4 Result and discussion

5.4.1 Effect of wetting-drying cycles on the weight change

The total weight changes of cement- and cement-NRL stabilized RCA mixtures compared to the initial weight (i.e., zero cycle) are shown in **Figure 5.4**. The weight of samples reduced with the increased w-d cycles and the reduction in weight became more stable after 5th cycle. As can seen from **Table 5.5**, the average weight loss at 12th cycle of the control mixture (3C-RCA) was 0.98%, which was lower than that of 3C5R-RCA (1.05%), but higher than those of 3C10R-RCA (0.91%) and 3C15R-RCA (0.85%). This finding indicated that increasing the r/c ratio improves resistance to weight loss versus w-d cycles. The role of NRL on weight change can be explained by the rheological behavior of NRL, which enhanced the bond strength between the particles (Cornish & Brichta, 2002; Peethambaran et al., 1990).

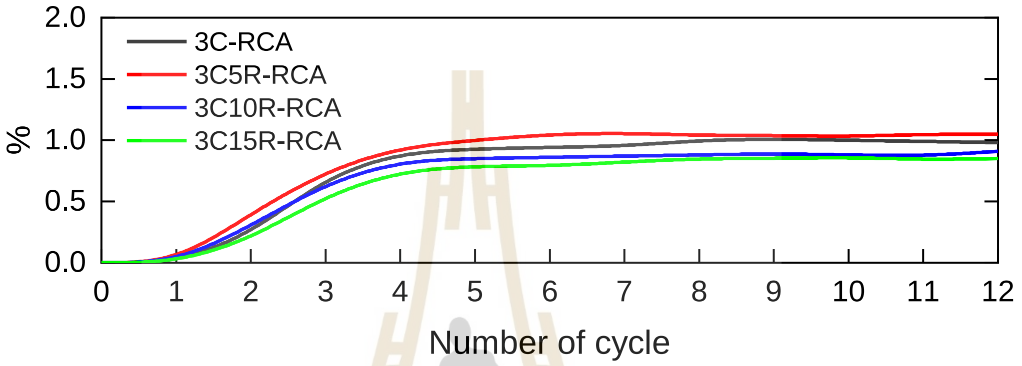


Figure 5.4 Weight changes of cement- and cement-NRL stabilized RCA over 12 w-d cycles.

Table 5.5 Summary of test results for w-d durability.

Mixture name	Orginal weight (g)	Received weight (g)	W-D cycle completed	Weight change (%)
3C-RCA	1823.0	1805.1	12	0.98
3C5R-RCA	1793.6	1774.8	12	1.05
3C10R-RCA	1751.0	1735.1	12	0.91
3C15R-RCA	1738.7	1723.9	12	0.85

5.4.2 Effect of wetting-drying cycles on unconfined compressive strength

Figure 5.5 shows the relationship between UCS values and the number of w-d cycles. It can be seen that the higher number of w-d cycle, the lower UCS value. The 3C10R-RCA has the best in compressive strength value when compared with other cement-NRL stabilized RCA mixtures (3C5R-RCA, 3C15R-RCA) and cement stabilized RCA mixture (3C-RCA). When the number of w-d cycles was 0, 1st, 3rd, 6th, 9th, and 12th, the percentage decrease in the UCS value of 3C10R-RCA was 0, 3.9, 9.8, 15.0, 17.8 and 23.0% respectively, while the proportion of 3C-RCA was 0, 9.8, 18.9, 27.1, 31.9 and 39.1% respectively (**Figure 5.6**). The results indicated that rubber latex additive helped to reduce the UCS deterioration of stabilized mixture, this effect may explained the optimum r/c ratio improved the interparticle bonding strength (Duong Vinh et al., 2021). The UCS of all samples after 12 w-d cycles was found to be satisfied with the minimum requirement of 1.724 MPa for pavement base material (DOH, Thailand).

Figure 5.7 illustrates an effect of r/c ratios and the number of w-d cycles on the UCS values of cement- and cement-NRL stabilized RCA mixtures. For the initial condition (zero w-d cycle), adding r/c ratio to cement stabilized RCA improved the UCS, but excessive the optimum r/c ratio caused retardation of cement hydrates, leading to reduced strength. When the number of w-d cycles increased, the UCS value decreased. During the w-d process, the mixture with added NRL tended to decline lower than without additive.

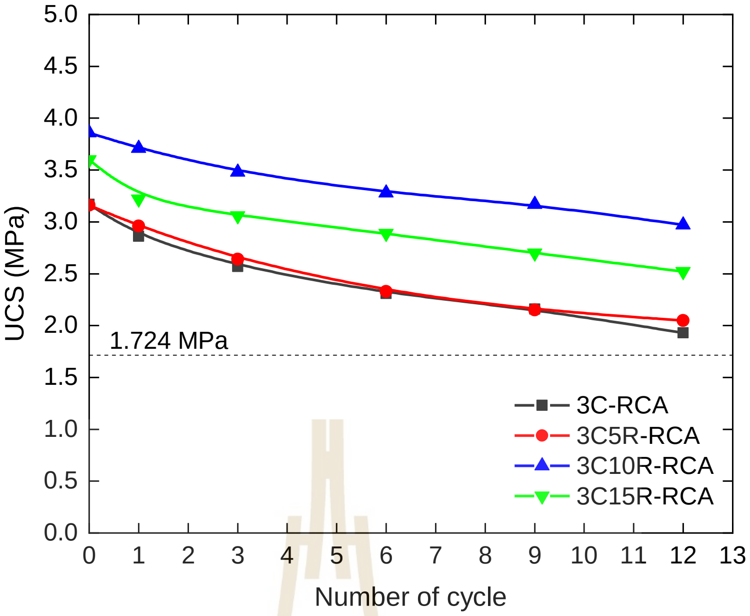


Figure 5.5 UCS values at each w-d cycle.

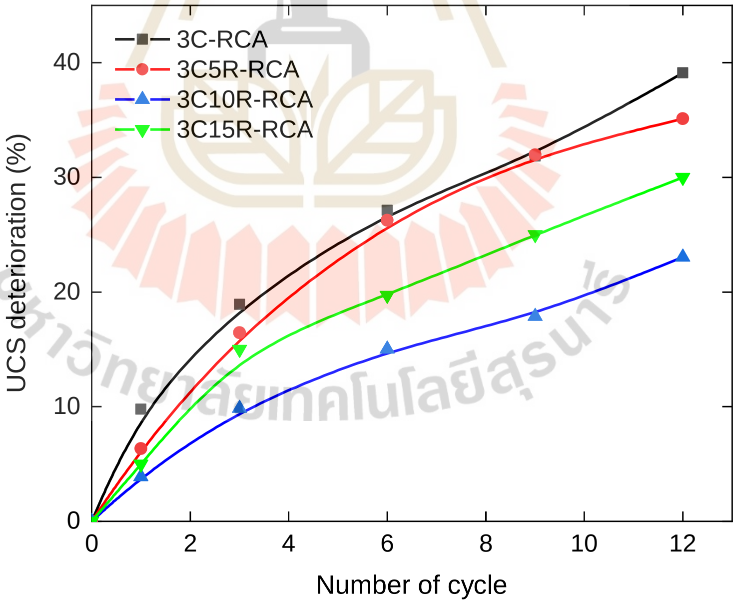


Figure 5.6 The amount of w-d cycles influence the rate of UCS deterioration.

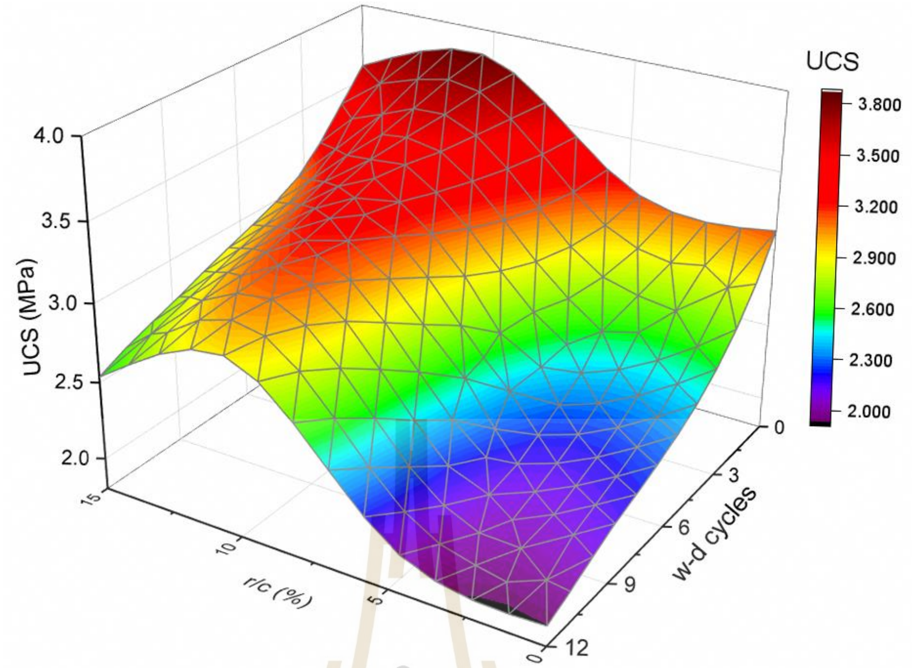


Figure 5.7 Effect of r/c ratio and w-d cycles on UCS values.

5.4.3 Effect of wetting-drying cycles on the stress-strain relationship

The stress-strain relationships of cement- and cement-NRL stabilized RCA mixtures at 28 days of curing are shown in **Figure 5.8**. The result demonstrated that the NRL additive improved the tensile stresses and strains of cement stabilized RCA samples. The r/c ratio of 10% (3C10R-RCA) exhibited the highest stress because it contained the optimum r/c ratio. The compressive stress of 3C10R-RCA was 21.8% higher than that of 3C-RCA (control mixture). In comparison, the r/c ratio of 15% (3C15R-RCA) had the largest failure strain at peak stress. This indicates that the rubber films have significant effects on the elastic behavior of mixture and interparticle forces (Duong Vinh et al., 2021). As a result, the toughness or the ability to absorb energy without fracture of cement-NRL stabilized RCA mixtures was observed to be better than those without NRL additive.

Figure 5.9 shows the stress-strain relationships of studied samples over 12 w-d cycles. The w-d cycles of mixtures show a similar trend in that there is a reduction in peak stresses with the increase in w-d cycles. In addition, the compressive strength of mixtures decreases as the number of cyclic w-d cycles increases. This phenomenon may be explained by the hydrophilic character (water absorption) of stabilized RCA that influences the bond strength and shrinkage cracks gradually increases with w-d cycles (Assaad & Daou, 2017; Ebrahim Abu El-Maaty Behiry, 2013b; Li & Hu, 2020; Qiu et al., 2014).

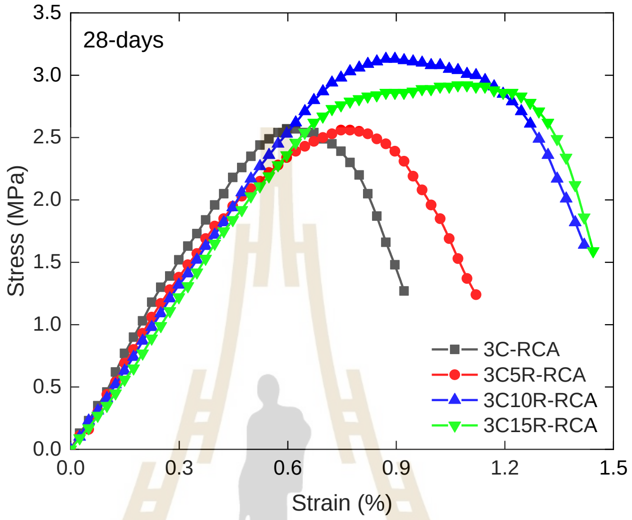


Figure 5.8 Stress-strain from UCS testing resuts in 28 days cured sample.

Figure 5.8 shows the stress-strain relationships of studied samples over 12 w-d cycles. Wetting and drying cycles show similar trends in that the reduction in peak strength decreased with the increased w-d cycles while the stiffness of the samples slightly reduced. It means that the compressive strength of mixtures decreases as the number of cyclic w-d cycles increases. However, the strain at failure of the wetting stage is at a lower rate than that of the drying stage, which is mainly associated with the rapidly decreasing weak bonding of stabilized RCA through hydrophilic character (water absorption) (Assaad & Daou, 2017; Ebrahim Abu El-Maaty Behiry, 2013b; Li & Hu, 2020; Qiu et al., 2014).

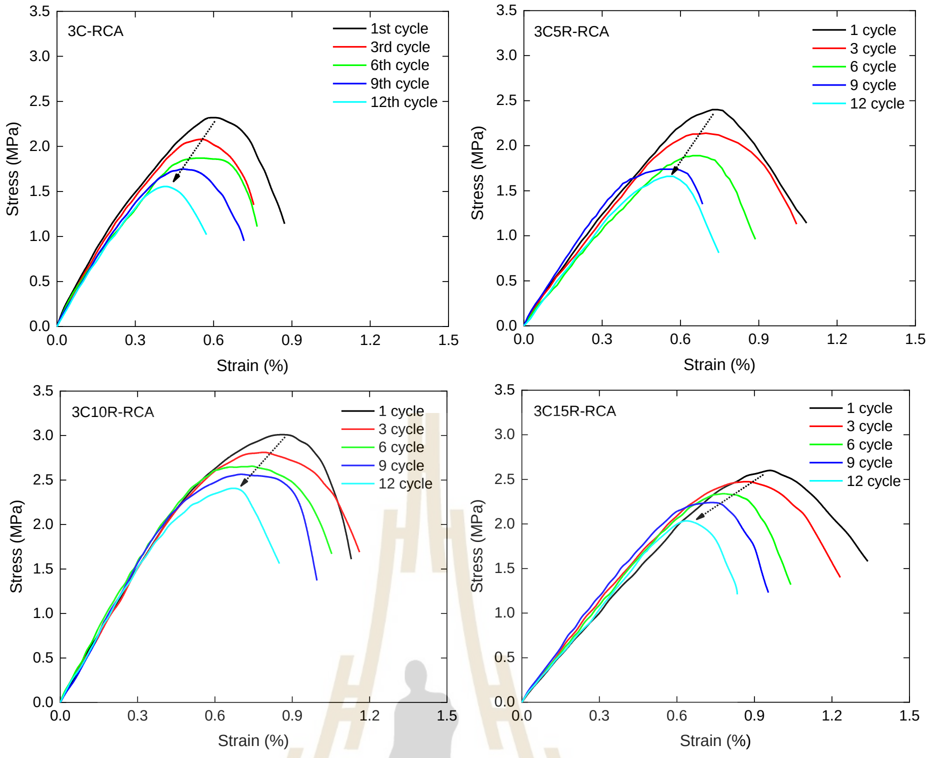


Figure 5.9 Stress-strain relationships with the number of w-d cycles.

5.4.4 Effect of wetting-drying cycles on elastic modulus

The variation of secant Young modulus with the number of w-d cycles for cement- and cement-NRL stabilized RCA mixtures is presented in **Figure 5.10a**. Young modulus discussed in this study refers to the secant modulus, which is determined from the linear portion (i.e., at 50% of the peak stress) of the examined stress-strain curve. Similar to the results of UCS, Young modulus was found to decrease with the increase of w-d cycles. Young modulus of the 3C10R-RCA had the highest value compared to other mixtures in a similar w-d cycle. The linear regression analyses were employed to develop the relationship between the number of w-d cycles and Young modulus (E_{50}) of mixtures as follows:

$$E_{50} = -0.04 \times N + 3.79,\ R^2 = 0.89 \qquad \text{for 3CRCA} \tag{5.1}$$

$$E_{50} = -0.05 \times N + 3.77,\ R^2 = 0.93 \qquad \text{for 3C5R-RCA} \tag{5.2}$$

$$E_{50} = -0.03\times N + 3.78,\ R^2 = 0.92 \qquad \text{for 3C10R-RCA} \qquad (5.3)$$

$$E_{50} = -0.05\times N + 3.69,\ R^2 = 0.95 \qquad \text{for 3C15R-RCA} \qquad (5.4)$$

where N is the number of w-d cycles.

Figure 5.10b illustrates the relationship between Young modulus (E_{50}) and UCS. It can be seen that Young modulus increases with UCS values increase. The relationship between UCS and Young modulus can be expressed using the following equations:

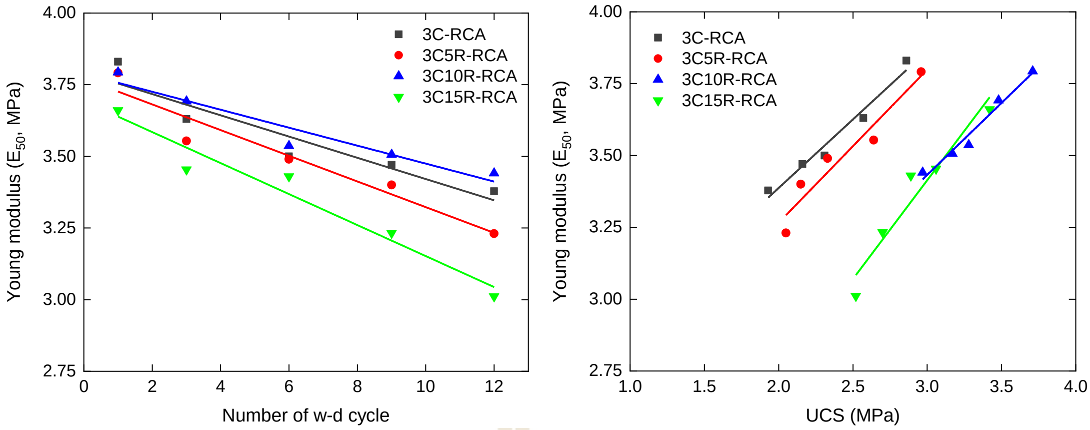
$$E_{50} = 0.48\times UCS + 2.43,\ R^2 = 0.97 \qquad \text{for 3CRCA} \qquad (5.5)$$

$$E_{50} = 0.53\times UCS + 2.20,\ R^2 = 0.93 \qquad \text{for 3C5R-RCA} \qquad (5.6)$$

$$E_{50} = 0.50\times UCS + 1.93,\ R^2 = 0.97 \qquad \text{for 3C10R-RCA} \qquad (5.7)$$

$$E_{50} = 0.69\times UCS + 1.35,\ R^2 = 0.94 \qquad \text{for 3C15R-RCA} \qquad (5.8)$$

The coefficient of determination (R^2) obtained from Eq. (1) to (8) has shown high values of 0.89 ÷ 0.97. These results indicated that Young modulus of mixtures has a close relationship with UCS values and the number of w-d cycles.



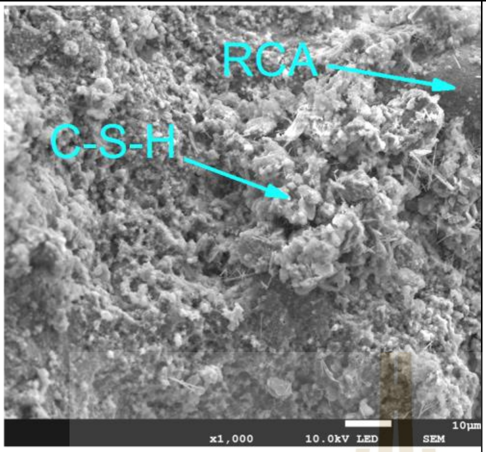
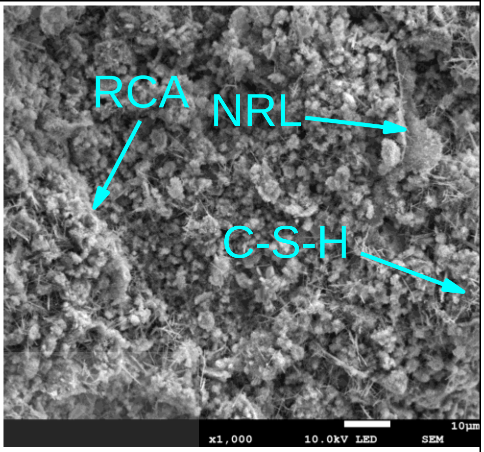
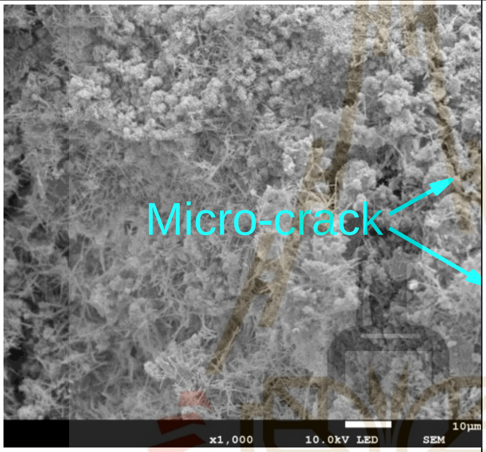
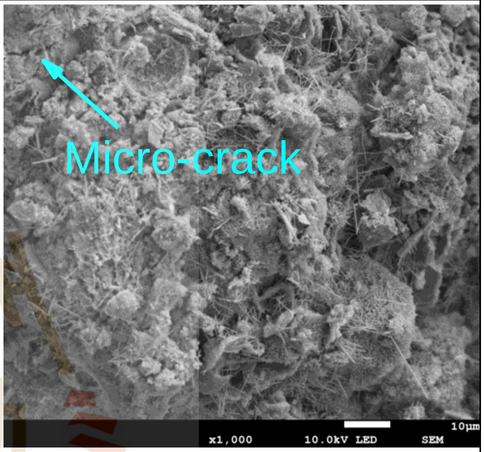
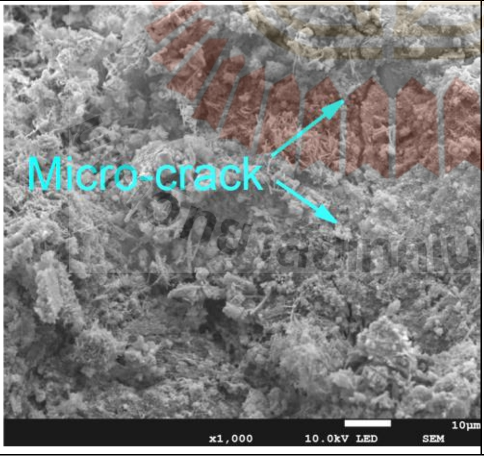
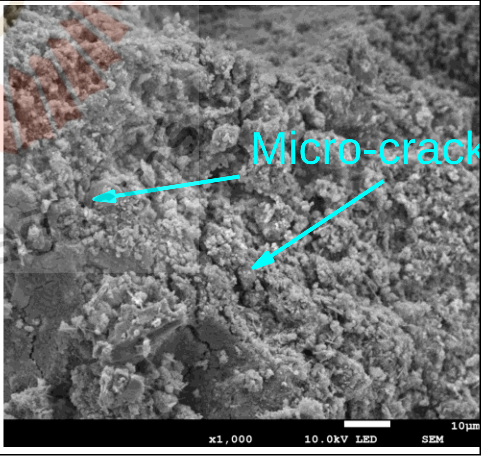
(a) (b)

Figure 5.10 Secant Young modulus E_{50} versus w-d cycles (a) and UCS values (b).

5.4.5 Effect of wetting-drying cycles on microstructure and crack propagation process

Figure 5.11 provides SEM images of cement stabilized RCA (3C-RCA) and cement-NRL stabilized RCA at optimum r/c ratio (3C10R-RCA) for different w-d cycles. Previous study (Duong Vinh et al., 2021) detected some microcracks inside the samples before the w-d process (zero w-d cycle). After the 1st w-d cycle, cementitious products (C-S-H) and rubber films showed a dense matrix between the RCA with small pores and tiny cracks. During 1st to 12th w-d cycle, the increase of micro-crack networks and detachment in structure were observed. Mamlouk et al. (2018) determined the cracks that developed during the w-d process were the result of drying shrinkage. Cracks occurred continually as the number of w-d cycles increased, the sample is weakened the structure and loses its strength.

Figure 5.12 illustrates the evolution of microstructures throughout w-d cycles. After w-d cycles of different times, micro-cracks might enlarge into macro-cracks. These outcomes are similar to those of previous studies on volumetric shrinkage and expansion during w-d process (Chethan & Ravi Shankar, 2021; Rosone et al., 2018; Xu et al., 2020; Zhao et al., 2021).

Cycles	3C-RCA	3C10R-RCA
1st		
3rd		
6th		

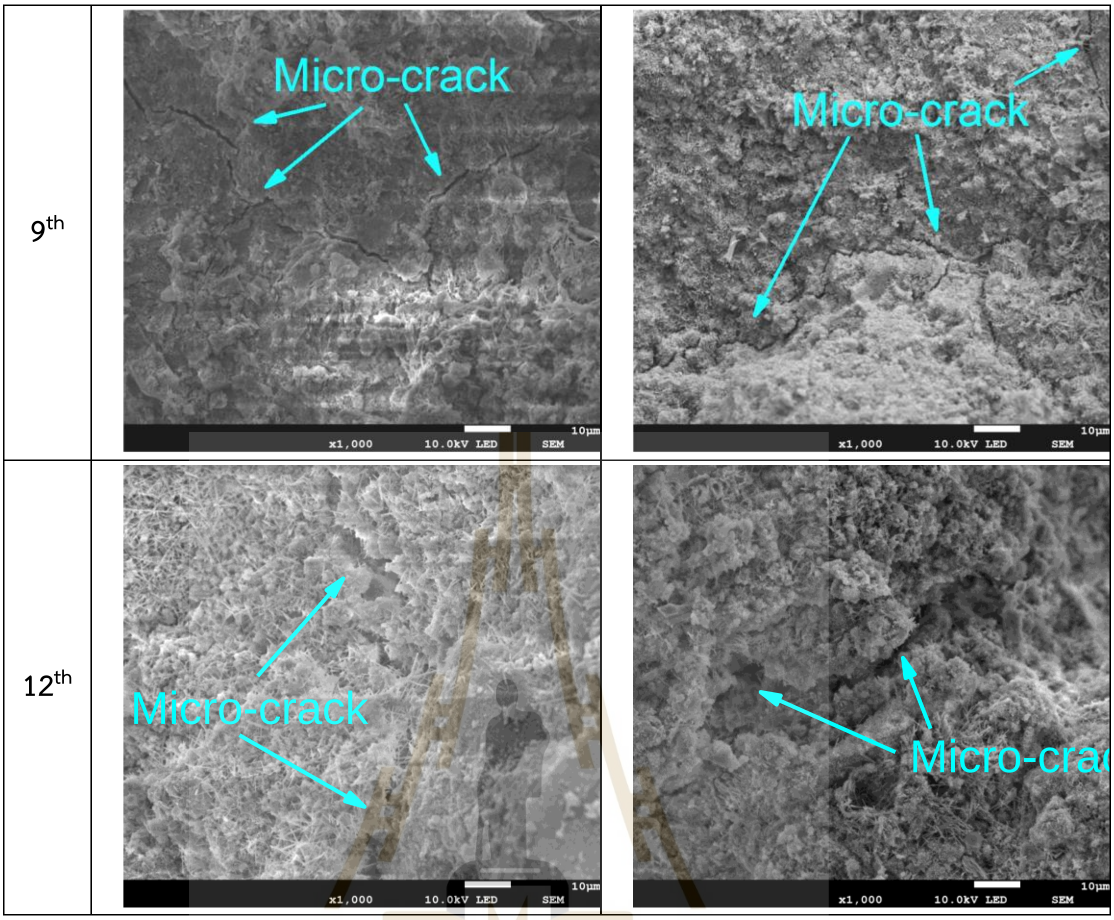


Figure 5.11 The deterioration morphology of mixtures under w-d cycles.

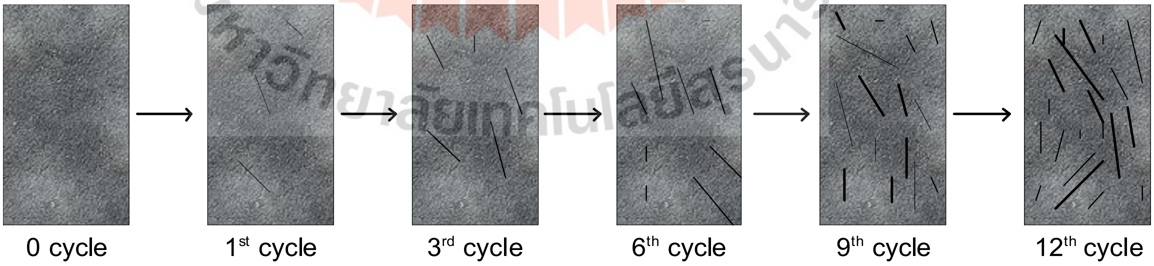


Figure 5.12 Schematic diagram of w-d cycles mechanism.

5.5 Conclusions

In this study, the total 12 w-d cycles tests were carried out on cement- and cement-NRL stabilized RCA samples to investigate the durability against cyclic wetting and drying. The weight loss, compressive strengths, deterioration rates, Young modulus and microstructural changes were examined by laboratory experimental programs. The test results have been analyzed, and the main findings of this study may be summarized as follows:

- With the increase of w-d cycles, the weight loss of mixtures increases from 0.85% to 1.05% after 12 w-d cycles. Because the presence of rubber films increased the adhesion performance of cement-NRL stabilized RCA, the weight changes were reduced by adding NRL.

- The UCS tends to reduce the value due to the cyclic wetting and drying test. After 12 w-d cycles, the UCS of all samples had a higher value than the minimum requirement for the pavement base material of 1.724 MPa.

- As the w-d cycle increases, the peak stress tends to decrease owing to structural weakening. The rate of UCS reduction of the cement stabilized RCA was higher than that of the cement-NRL stabilized RCA mixtures.

- Microstructure investigation revealed the extension of micro-cracks or crack propagation as a result of drying shrinkage through w-d process. As the number of w-d cycles increases, the number of cracks in the sample trends to be increasing.

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CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

6.1 Introduction

Recycled concrete aggregate (RCA) is the most significant part of construction and demolition (C&D) waste. Recently, due to the preservation of natural resources, protecting the environment, benefit the economic costs, etc., there has been a wide approach to the C&D sector. Therefore, RCA is highly recommended for pavement constructions consisting of the base layer. Furthermore, cement stabilized RCA material has been used for pavement base application due to its various advantages compared to natural aggregates. Because cement stabilized RCA mixture has shown brittle behavior and low flexural strength, that can lead to premature cracking failure due to the dynamic loading by traffics. The fundamental objective of this study is to employ natural rubber latex (NRL) as an additive polymer by integrating it with cement for stabilizing RCA material. In order to accomplish the main purpose, three distinct objectives were investigated. The first objective is to identify the basic geotechnical properties of RCA, the stabilized RCA mixtures with/without NRL additive. Based on the results obtained, the list of samples was prepared and tested to determine the compressive strength, indirect tensile strength, and microstructural characteristics. The second objective of this study is to evaluate the influence of repeated loading of traffic on the indirect tensile resilient modulus, indirect tensile fatigue, and rutting susceptibility of RCA mixture based on the outcomes of the first objective. Finally, the permanent performance of cement- and cement-NRL stabilized RCA mixtures undergo cracking problems and premature pavement distress due to seasonal wetting and drying are examined.

In this study, the cement content of 3%, 5%, and 7% based on the mass of RCA was chosen. In addition, the ratio of dry rubber latex to cement content (r/c) of 5%, 10%, and 15% was also selected based on the literature review. The samples are compacted in a modified proctor test at maximum dry density value and optimum liquid content. The samples are cured at room temperature of 25 ± 2^{o}C for 7 and 28 days before being subjected to the tests.

Earlier, at the end of each chapter, conclusions were drawn that were more particular to the chapter topics. This chapter presents the key findings of the study on cement-NRL stabilized RCA.

6.2 Conclusions

The primary findings of this thesis may be summed up in three categories:

6.2.1 Natural rubber latex as a polymer to improve the mechanical properties of cement stabilized RCA for pavement base application

The test results have shown that the maximum dry density and optimum liquid content of cement-NRL stabilized RCA decreased with increasing the r/c ratio for all cement contents because the excessive solid phase of NRL causes the decrease of compressibility of the mixtures, while hydrophobic molecules and surface of NRL repel water absorption. The optimum r/c ratios providing the highest unconfined compressive strength (UCS) and indirect tensile strength (ITS) of cement-NRL stabilized RCA were found to be 10%, 5%, and 5% for 3%, 5%, and 7% cement content, respectively. The UCS and ITS values of 3C10R-RCA < 5C5R-RCA < 7C5R-RCA. Beyond the optimum r/c ratios, the UCS and ITC values of mixtures decreased although all UCS values of cement-NRL stabilized RCA were greater than the minimum requirement (UCS > 1.724 MPa) for pavement base material specified by Department of Highways, Thailand. In addition, NRL additive can enhance the ductility of cement stabilized RCA mixture and significantly improve the toughness between 5 and 10%. The XRD and SEM analyses indicated that at optimum r/c ratio of cement-NRL stabilized RCA, the cement hydration products were remarkably increased while the rubber films improved the adhesion of RCA particles, leading to the higher bond between the RCA aggregates and resulting in UCS and ITS development. However, the excessive NRL additive over the optimum r/c ratio retarded the cement hydration and resulted in low UCS and ITS development of cement-NRL stabilized RCA.

6.2.2 Natural rubber latex is used as an additive to enhance the dynamic mechanical properties of cement stabilized RCA

Cement content of 3% by mass of RCA and the dry rubber content in NRL to cement (r/c) ratios of 5%, 10%, and 15% were used for evaluating the stiffness and mechanical performance (rutting resistance, fatigue life) of cement-NRL stabilized RCA under cyclic loading. The performance evaluation of cement-NRL stabilized RCA mixtures was carried out through the experimental program consisting of indirect tensile resilient modulus test (IT Mr), indirect tensile fatigue test (ITF), and Hamburg wheel tracking device (HWTD). The test results indicated that the r/c ratio of 10% was the optimum percentage of NRL for improving the characteristics of cement stabilized RCA. At optimum r/c ratio (3C10R-RCA), cement-NRL stabilized RCA has enhanced the resistance to both fatigue cracking and rutting properties compared to the control mixture. The fatigue life of 3C10R-RCA was found to be 79.3% greater than that of 3C-RCA, while the rut depth was found to be 8.0% lower. Moreover, the brittle behavior of the cement stabilized RCA mixture has been improved due to the plasticizing effect of the NRL additive. The results revealed that NRL could enhance the cyclic performance of cement stabilized RCA for use as a pavement base material.

6.2.3 Natural rubber latex strengthens the durability against cyclic wet and dry seasons of cement stabilized RCA

The characteristics of cement-natural rubber latex (NRL) stabilized recycled concrete aggregate (RCA) under the influence of wetting-drying (w-d) cycles were investigated. The results showed that the UCS values decreased with the increased w-d cycles and the dry strength was higher than that of the wet strength on a similar w-d duration. The peak curves were found to diminish as the number of w-d cycles gradually increased. This study also proposed the Young modulus at various w-d cycles and the linear relationship with the UCS values. As the number of w-d cycles increases, cracks continually form in the samples due to the volumetric shrinkage and expansion accompanying the wetting and drying processes. Consequently, after each cyclic wetting and drying process, some micro-cracks could become macro-cracks.

6.3 Recommendations for future work

The effect of natural rubber latex on the performance of cement-NRL stabilized RCA has been investigated in this thesis. Due to the presence of NRL additive, cement-NRL stabilized RCA mixtures revealed good mechanical performances under static and cyclic loading conditions. Besides, the rubber latex helped reduce the influence of moisture damage on wetting-drying cycle conditions. However, some issues need to be studied in future work, summarised as:

- This study used only the dry rubber in latex of 5%, 10%, and 15% with a cement content of 3%, 5%, and 7%, respectively. The various r/c ratios and cement contents may be investigated further.
- This study demonstrated that NRL might enhance the cyclic performance of cement stabilized RCA when used as a pavement base material. In addition, more studies must be done to determine the impact of NRL on the durability performance of cement-stabilized RCA under different environments, such as moisture and temperature susceptibility.
- Further study is necessary to analyze the impact of rubber latex addition to cement stabilized RCA mixture utilizing repeated load triaxial test to determine the resilient modulus under confining pressure.
- It is very recommended to meet industrial needs by developing a model or finite element analysis to evaluate the engineering properties of cement-NRL stabilized RCA and predict the pavement distresses.

APPENDIX A

PUBLICATIONS

List of Publications

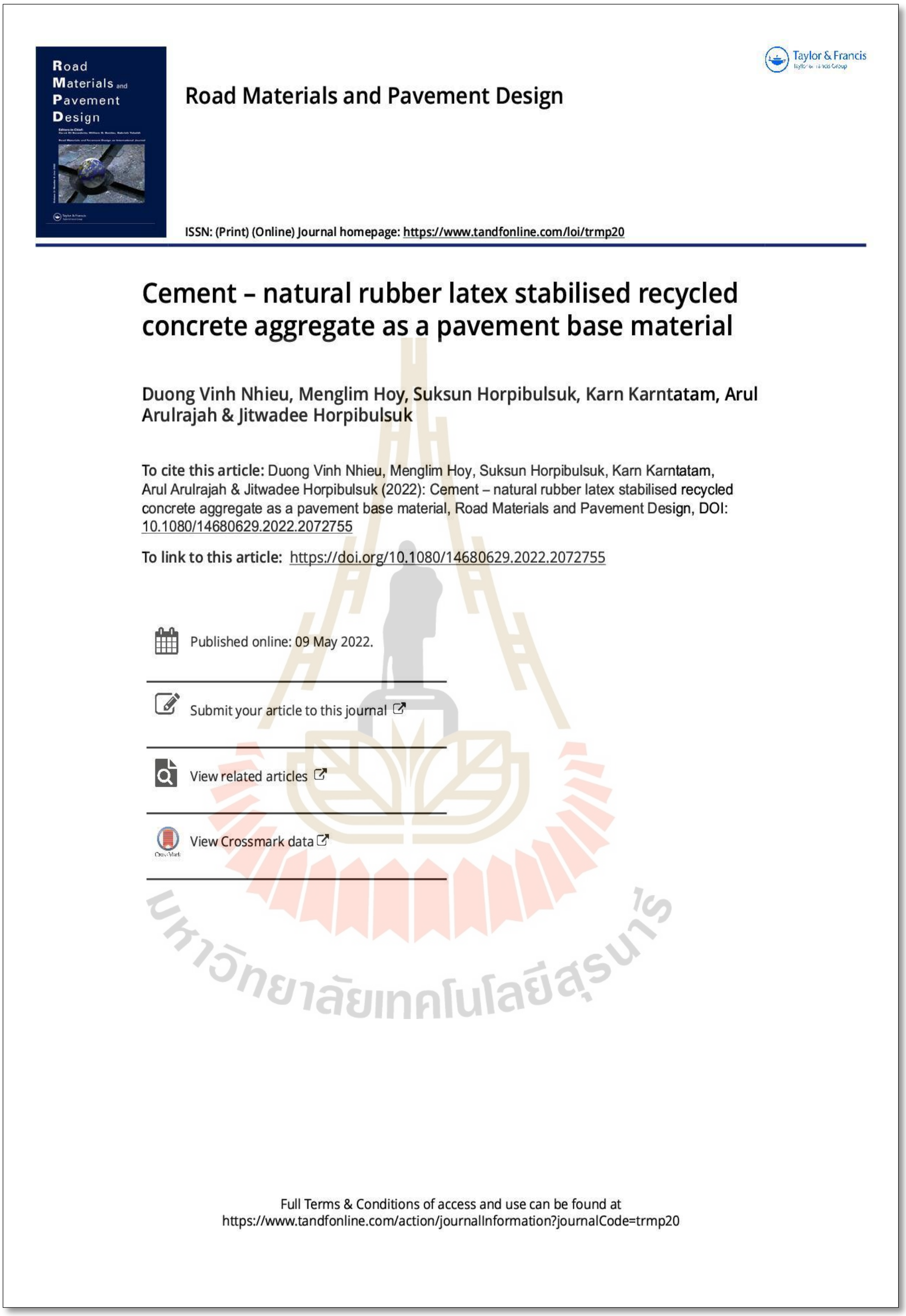
INTERNATIONAL JOURNAL PAPERS

Duong Vinh Nhieu, Menglim Hoy, Suksun Horpibulsuk, Karn Karntatam, Arul Arulrajah, and Jitwadee Horpibulsuk (2022). **“Cement-natural rubber latex stabilized recycled concrete aggregate as a pavement base material”**. Journal of Road Materials and Pavement Design. Doi: 10.1080/14680629.2022.2072755

Menglim Hoy, Duong Vinh Nhieu, Apichat Suddeepong, Suksun Horpibulsuk, Arul Arulrajah, and Yongfeng Deng (2022). **“Cement-natural rubber latex stabilized recycled concrete aggregate as a pavement base material”**. Journal of Construction and Building Materials (Under Review).

INTERNATIONAL CONFERENCE PAPERS

Duong Vinh Nhieu, Menglim Hoy, and Suksun Horpibulsuk (2022). **“Natural rubber latex as a polymer additive modified cement stabilized recycled concrete aggregate for base pavement application”.** The 7th International Young Geotechnical Engineers Conference (ISSMGE) in Sydney, Australia.



Road Materials and Pavement Design

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ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/trmp20

Cement – natural rubber latex stabilised recycled concrete aggregate as a pavement base material

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To cite this article: Duong Vinh Nhieu, Menglim Hoy, Suksun Horpibulsuk, Karn Karntatam, Arul Arulrajah & Jitwadee Horpibulsuk (2022): Cement – natural rubber latex stabilised recycled concrete aggregate as a pavement base material, Road Materials and Pavement Design, DOI: 10.1080/14680629.2022.2072755

To link to this article: https://doi.org/10.1080/14680629.2022.2072755

ROAD MATERIALS AND PAVEMENT DESIGN
https://doi.org/10.1080/14680629.2022.2072755

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Cement – natural rubber latex stabilised recycled concrete aggregate as a pavement base material

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ABSTRACT

This research investigated the influence of natural rubber latex (NRL) on the performance of cement stabilised recycled concrete aggregate (RCA) as a pavement base material. The influence factors studied included different cement at contents and dry rubber to cement (r/c) ratios. The NRL replacement enhanced the unconfined compressive strength (UCS) and indirect tensile strength (ITS) of cement stabilised RCA. The highest UCS and ITS of cement-NRL stabilised RCA were found at the optimum r/c ratios. Beyond these optimum r/c ratios, the UCS and ITC values decreased although all UCS values were still greater than the minimum requirement for base material. Microstructural analyses indicated the detected cement hydration products and NRL films, which NRL films were found to improve the adhesion and interparticle bonds of RCA particles. However, the excessive NRL additive retarded the cement hydration, whereby the UCS and ITS development was low when the r/c was greater than the optimum value.

ARTICLE HISTORY
Received 30 June 2021
Accepted 25 April 2022

KEYWORDS
Ground improvement; natural rubber latex; soil-cement; recycled materials; mechanical strength

Introduction

The construction of roads requires a vast amount of high-quality aggregates for pavement structures, such as the base and subbase courses. The innovative road construction methods by using construction and demolition (C&D) materials as aggregates to replace the natural crushed aggregate (NCA) have been placed as a priority construction material for pavement authorities (Arshad & Ahmed, 2017; Ebrahim Abu El-Maaty Behiry, 2013). This is due to the high demand for virgin aggregates resulting in increased construction costs and environmental concerns. Recycled concrete aggregate (RCA), containing cement and aggregate, is a C&D material, which is abundantly obtained from demolished concrete structures. Due to the inferior properties of RCA, cement stabilisation is practically adopted for the road base layer (Ebrahim Abu El-Maaty Behiry, 2013; Verian et al., 2013). One of the advantages of cement stabilised RCA material is its high compressive strength, which meets the local road-authority requirements for stabilised pavement base. However, cement stabilised RCA often exhibits brittle behaviour and leads to low tensile and flexural strength, which results in the reduced

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service life of roads (Chakravarthi et al., 2019; Sukmak et al., 2020; Yaowarat et al., 2022). To solve this shortcoming, several research studies have attempted to improve the performance of cement stabilised RCA by mixing RCA with fibres, synthetic polymers and geopolymers (Arulrajah et al., 2017; Mohammadinia et al., 2016; Sukprasert et al., 2021; Yaowarat et al., 2022; 2018).

Natural rubber latex (NRL) obtained from rubber tree plants (*Hevea Brasiliensis*) contains approximately 30% to 35% of dry rubber content which can be used as alternative additive to fibres, synthetic polymers and geopolymer in pavement application (Sukmak et al., 2020).

Previous research works indicated that NRL improved the tensile and flexural strengths of concrete structure (Buritatun et al., 2020; Nagaraj et al., 1988; Sukmak et al., 2020) and improved the tensile strength and toughness of the cement pastes but reduced compressive strength (Sukmak et al., 2020). Several recent studies have focused on the compatibility between NRL and cement with natural soil in pavement base/subbase (Buritatum et al., 2021; 2020) and pavement concrete (Yaowarat et al., 2021). NRL can improve the cyclic properties, moisture resistance properties and durability against wetting and drying of cement stabilised soils and hence usage of NRL can increase the service life of pavement structure (Buritatum et al., 2021; 2022; Udomchai et al., 2021).

To the best of authors' knowledge, there is a lack of research on the usage of NRL as a polymer, to improve the mechanical properties of cement stabilised recycled aggregate as pavement materials. This research aims to evaluate the possibility of using NRL as a potential green polymer, to enhance the tensile and flexural strengths of cement stabilised RCA. Influence factors including cement content by total weight of RCA and dry rubber content in NRL to cement content (r/c) ratio were studied. The outcomes of this research will facilitate the efficient utilisation of NRL in cement stabilised RCA as a pavement base material.

Materials and sample preparation

Materials

The grain size distribution of RCA sample was implemented in accordance with ASTM D422 (ASTM-D422, 2007) (Figure 1), which was within the boundary gradation for pavement base material specified by the Department of Highways (DOH), Thailand (DH-S201/2556) (DH-S201/2556, 1996) (similar to ASTM D1241 (ASTM-D1241, 2016) or AASTHO M 147 (AASHTO-M-147, 2017)). The basic and engineering properties of RCA was illustrated in Table 1. Since RCA contained the amount of concrete mortar, the water absorption of RCA is higher than the NCA [21]. Table 2 shows the chemical compositions of ordinary Portland cement type I while the main components of NRL are summarised in Table 3. A surfactant sodium dodecyl sulphate (SDS) was added into NRL to remove the protein and to stabilise the colloidal dispersion of the latex.

Sample preparation

The cement stabilised RCA samples were the mixtures of RCA with different cement contents of 3%, 5% and 7% (by mass of RCA), namely 3C-RCA, 5C-RCA and 7C-RCA. Cement content of 3–7% by weight is typically used in road construction (Buritatum et al., 2021; Ebrahim Abu El-Maaty Behiry, 2013; Faysal et al., 2016; Mohammadinia et al., 2015). The cement-NRL stabilised RCA samples were the mixtures of RCA, cement and NRL, whose r/c ratios were 5%, 10% and 15% (by mass of cement). This range of r/c ratios with 5% interval was recommended based on a previous study for determining the optimum r/c ratio, providing the best mechanical properties (Mohammadinia et al., 2015). The ingredient and labels of the studied mixtures are summarised in Table 4.

The samples were mixed based on a two-stage mixing approach (Tam et al., 2005), which is suitable for recycled materials. The sample preparation of cement stabilised RCA commenced by mixing RCA with half of the required water for 30 s and followed by cement for 30 s, which was followed by the addition of a final half of water for another 30 s. The sample was thoroughly mixed for another 60 s

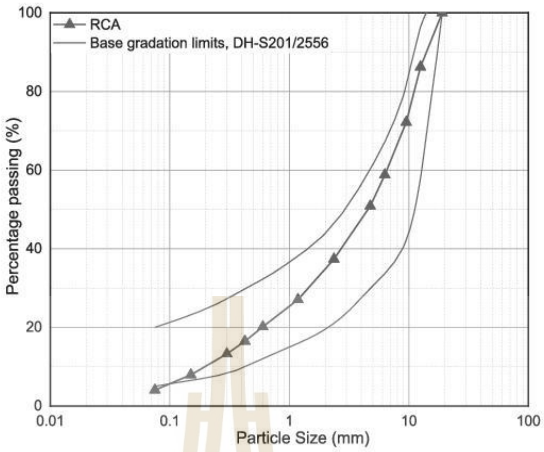

Figure 1. Particle size distribution curve of RCA.

Table 1. Geotechnical properties of RCA.

Properties	Values	Typical values [5]	Standard Method
Specific gravity - coarse	2.30	> 2	ASTM C127
Specific gravity - fine	2.17	> 2	ASTM C128
Water absorption - coarse (%)	6.32	< 10	ASTM C127
Water absorption - fine (%)	7.95	< 10	ASTM C128
Organic content (%)	2.56	< 5	ASTM D2974
Fine content (%)	4.0	< 10	ASTM D422
Sand content (%)	46.8	–	ASTM D422
Gravel content (%)	49.2	–	ASTM D422
Coefficient curvature (C_c)	1.65	–	ASTM D2487
Coefficient uniformity (C_u)	34.0	–	ASTM D2487
Soil classification	GW	GW, GS	ASTM D2487
Flakiness index	15.6	< 35	BS 812:105.1
Los Angeles abrasion loss	38.1	< 40	ASTM C1311
pH	12.2	7–12	ASTM D4972
Maximum dry density (Mg/m^3)	1.89	> 1.8	ASTM D1557
Optimum moisture content (%)	11.7	8–15	ASTM D1557

Table 2. Chemical compositions of cement.

Composition	Content (%)
SiO_2	20.1
CaO	65.0
Al_2O_3	4.7
Fe_2O_3	3.2
MgO	2.6
SO_3	3.3
LOI	0.9

to ensure the homogenous mixture. The same procedure was used to produce the cement-NRL stabilised RCA samples, while the desired NRL content was added and mixed for another 30 s prior to the final stage. The mixed liquid content was the additional water and liquid rubber content, which was measured by mass of the solid phase (RCA, cement and dry rubber content).

Table 3. Properties of natural rubber latex.

Property	Value
Total solid contents (% by weight)	33.06
Dry rubber contents (% by weight)	30.79
Sludge content (% by weight)	2.46
Coagulum content (% by weight)	0.024
Specific gravity (Gs)	0.96
pH	8

Table 4. The mix design in this study.

Mixture ingredient	Mixture name
100% RCA	100RCA
100% RCA + 3% Cement	3C-RCA
100% RCA + 3% Cement + 5% Dry Rubber	3C5R-RCA
100% RCA + 3% Cement + 10% Dry Rubber	3C10R-RCA
100% RCA + 3% Cement + 15% Dry Rubber	3C15R-RCA
100% RCA + 5% Cement	5C-RCA
100% RCA + 5% Cement + 5% Dry Rubber	5C5R-RCA
100% RCA + 5% Cement + 10% Dry Rubber	5C10R-RCA
100% RCA + 5% Cement + 15% Dry Rubber	5C15R-RCA
100% RCA + 7% Cement	7C-RCA
100% RCA + 7% Cement + 5% Dry Rubber	7C5R-RCA
100% RCA + 7% Cement + 10% Dry Rubber	7C10R-RCA
100% RCA + 7% Cement + 15% Dry Rubber	7C15R-RCA

Laboratory experimental programmes

Modified Proctor compaction tests were conducted to determine the maximum dry density (MDD) and optimum liquid content (OLC) of RCA, cement stabilised RCA, and cement-NRL stabilised RCA based on ASTM D1557 (ASTM-D1557, 2012). The amount of RCA, cement, NRL and water content was then prepared for unconfined compressive strength (UCS) and indirect tensile strength (ITS) tests once the MDD and OLC were obtained.

UCS and ITS tests were conducted in accordance with the ASTM D1633 (ASTM-D1633, 2017) and ASTM D6931 (ASTM-D6931, 2017), respectively. UCS samples (diameter of 101.6 mm and a height of 116.8 mm) were compacted in five layers under modified compaction effort with 25 blows per layer to attain the target MDD at OLC. While the ITS test samples with a diameter of 101.6 mm and a height of 78 mm were compacted in three layers with 28 blows per layer to attain the MDD and OLC values. Both UCS and ITS samples were demolded after 24 h and then wrapped with a plastic sheet and cured for 7 and 28 days at the curing room temperature (25 ± 2°C) prior to the UCS and ITS test. The mean results of at least three samples for each mixture were reported.

The scanning electron microscope (SEM) was performed on the samples obtained from the middle parts of the tested UCS samples. Small pieces of each sample were frozen after UCS testing at 28 days of curing by soaking in liquid nitrogen at −195°C, afterward broken to satisfactory dimension for identifying the internal structure. The samples were coated with gold for about 60 s before SEM analysis. The current and operating distance of 15 kV and 15 mm were, respectively, selected for sample morphological analysis. X-ray diffraction (XRD) analyses were conducted on cement- and cement-NRL stabilised RCA powders to investigate its mineralogical development. A D2-PHASER diffractometer with Cu-Kα radiation equipped with a sensitive detector was used. The XRD pattern was obtained by scanning from 5° to 65° at an angle of 2θ, and the scan increment size is 0.02.

Results and discussion

Compaction characteristics

Figure 2 presents the compaction test result of the studied mixtures. When compared with the unstabilised RCA sample, the MDD values of cement stabilised RCA samples were increased by 1.9%, 2.0% and 2.2% with increasing 3%, 5% and 7% cement content, respectively.

At a particular cement content, the cement stabilised RCA samples had higher MDD values than the cement-NRL stabilised RCA samples for all r/c ratios. Although the MDD values of the 3%, 5% and 7% cement stabilised RCA samples decreased with increasing r/c ratios, the samples with higher cement contents had lower rates of MDD reduction with increasing r/c ratios. Initially, the higher cement content led to a higher MDD of cement stabilised RCA samples because the compactability of RCA particles is improved by the cation exchange and cementitious products. Consequently, the matrix between the RCA particles is denser with the addition of cement content; similar observations were also reported by Chakravarthi et al. (2019). However, with the NRL additive, the solid phase of NRL within the RCA-cement matrix caused the decrease of compressibility of the mixtures. Buritatun et al. (2020) and Baghini et al. (2015) also indicated that the NRL additive reduced MDD of cement stabilised soil. Meanwhile, the OLC values of cement stabilised RCA samples were also slightly increased with increasing the cement content. This is because a higher cement content caused a higher water absorption (Bekhiti et al., 2019).

On the other hand, at a particular cement content, the OLC value of cement-NRL stabilised RCA shown in Figure 2 decreased when increasing the r/c ratio. In general, the OLC value was reduced by about 1%, 4% and 10% for r/c ratios of 5%, 10% and 15%, respectively. Jose and Kasthurba (2021) reported that the decrease in OLC is due to the hydrophobic behaviour of rubber. Furthermore, the MDD of cement-NRL stabilised RCA samples decreased with increasing r/c ratio. In other words, less cement content with higher r/c ratio resulted in lower OLC.

Unconfined compressive strength

Figure 3 shows the 7-day and 28-day UCS values of the studied mixtures. It is evident that the unstabilised RCA had a very low UCS value, similar to that reported in previous works (Baghini et al., 2015) while the UCS of cement stabilised RCA samples was found to meet the minimum requirement. In addition, UCS values of cement stabilised RCA increased with increasing the cement content and/or curing time (Figure 3), which is typical for cemented materials.

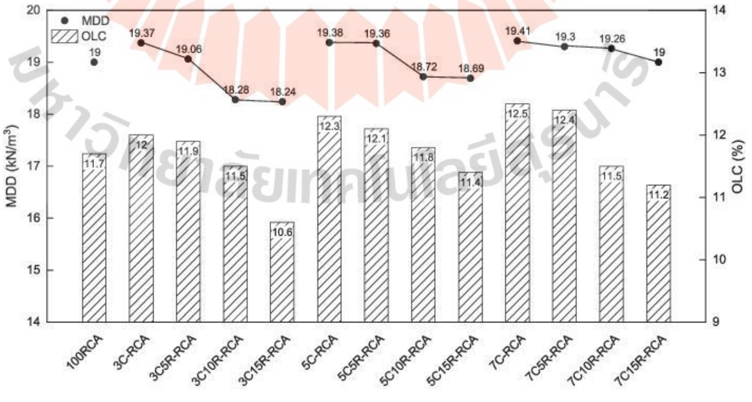

Figure 2. Compaction test result of RCA, cement- and cement-NRL stabilised RCA.

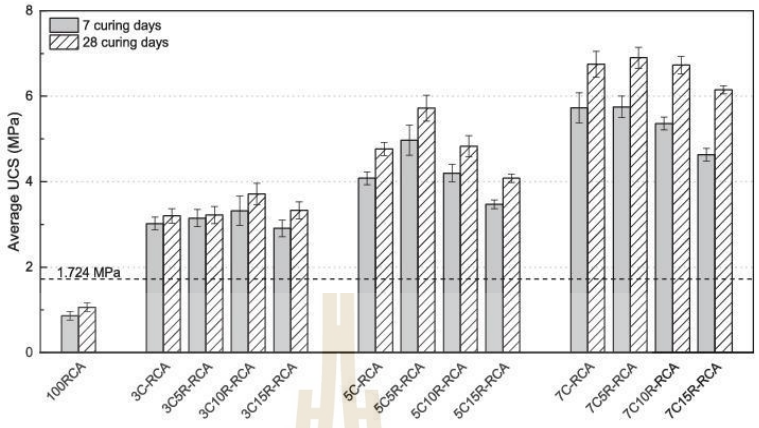

Figure 3. Unconfined compressive strength of RCA, cement- and cement-NRL stabilised RCA.

Figure 3 also indicates that the NRL additive can improve the UCS of cement stabilised RCA. The highest UCS values were found at the optimum r/c ratios of 10%, 5% and 5% for 3%, 5% and 7% cement, respectively. Since the r/c ratio interval was 5%, the highest UCS might fall between the studied r/c values. The r/c ratio at the highest UCS value is herein designated as optimum r/c ratio. At the optimum r/c ratio, the 7-day UCS values of 3C10R-RCA, 5C5R-RCA and 7C5R-RCA were improved by up to 9.9%, 21.8% and 0.3% higher than UCS values of 3C-RCA, 5C-RCA and 7C-RCA, respectively. The degree of improvement was the highest for 5% cement with 5% dry content. This result implies that the strength improvement by NRL is dependent upon the cement content. The percent of improvement increased with cement content up to the optimum cement content of 5% and then decreased. Generally, the strength development over time of a cemented material with various cement contents is unique (Chaidachatorn et al., 2019). Therefore, the relationship between 7-day and 28-day UCS of cement- and cement-NRL stabilised RCA was plotted and is shown in Figure 4 to investigate the role of NRL additive. All test data could be represented by a unique function. This implied that NRL has no effect on the UCS development over time of cement stabilised RCA even though it affects the UCS at a particular curing time.

Indirect tensile strength

The ITS results (Figure 5) demonstrated that the ITS of cement stabilised RCA can be enhanced by NRL additive. The highest ITS of cement-NRL stabilised RCA was found at the optimum r/c ratio. The ITS of cement-NRL stabilised RCA also increased with increasing the cement content. The optimum r/c ratios were found to be the same for both UCS and ITS. The 7-day ITS values of 3C10R-RCA, 5C5R-RCA and 7C5R-RCA were up to 12.5%, 13% and 1.3% higher than those of 3C-RCA, 5C-RCA and 7C-RCA, respectively. The 5C5R-RCA had the highest percent improvement of both UCS and ITS when compared with the other ingredients. Similar to UCS, at a particular cement content, ITS of cement-NRL stabilised RCA decreased when the r/c ratios were beyond the optimum value. It is interesting to note that the influence of NRL on UCS and ITS of cement-NRL stabilised RCA was found to be similar in this study.

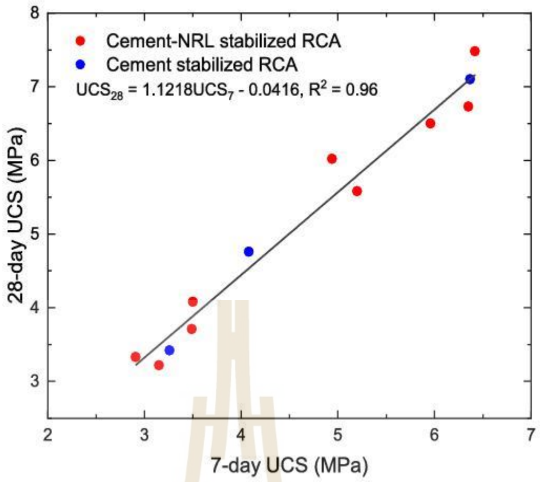

Figure 4. Relationship between 28-day and 7-day UCS of cement- and cement-NRL stabilised RCA.

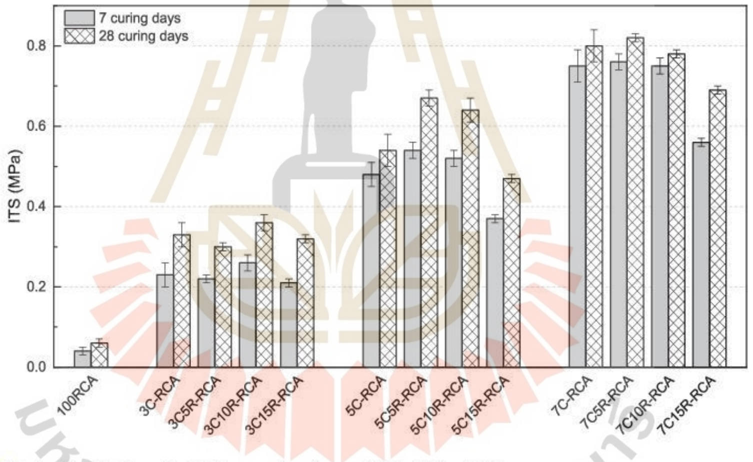

Figure 5. Indirect tensile strength of RCA, cement- and cement-NRL stabilised RCA.

Stress–strain and toughness characteristics

Figure 6 illustrates the tensile stress and strain curves of RCA, cement- and cement-NRL stabilised RCA samples at 7 days of curing. Cement stabilised RCA samples for all the cement contents demonstrated brittle behaviour with small strain at failure (around 1%), similar to previous research (Buritatun et al., 2020). The NRL additive improved the peak tensile stress and ductility of cement stabilised RCA samples. The previous research on polymer-modified concrete and NRL stabilised lateritic soil also indicated this similar finding (Baghini et al., 2015; Yaowarat et al., 2022).

The maximum strain values at failure of all cement-NRL stabilised RCA samples were found at the highest r/c ratios for all cement contents due to the highest elastic properties. Chakravarthi et al. (2019) reported that the larger area under the stress–strain curve represents the more energy stored in the

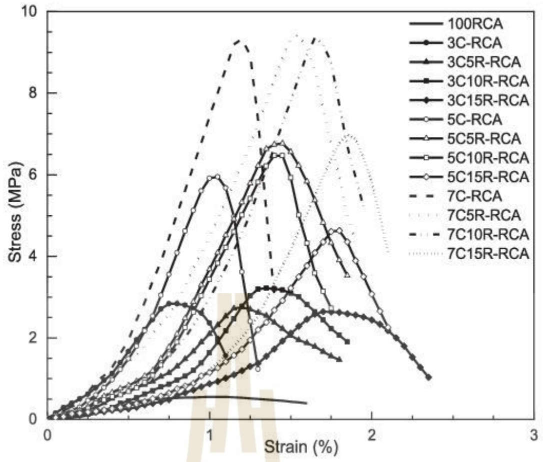

Figure 6. Stress–strain curves of RCA, cement- and cement-NRL stabilised RCA.

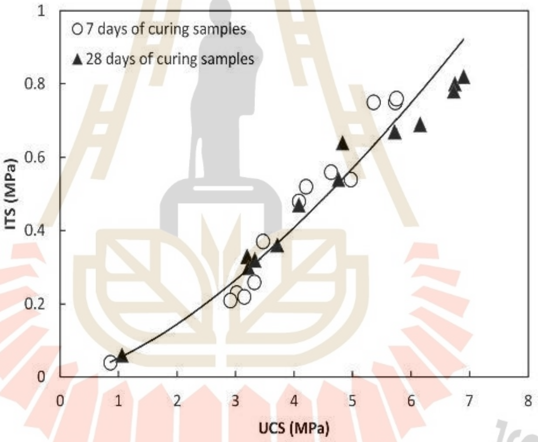

Figure 7. Relationship between UCS and ITS of cement- and cement-NRL stabilised RCA.

sample. The NRL additive might improve the resilient characteristic of the cement-NRL stabilised RCA and, its durability under traffic loading when used as a pavement base material.

In general, the UCS test is found to be more convenient and time-saving than the ITS test. Since the UCS and ITS of cement-NRL stabilised RCA samples yield the highest values at the same r/c ratios for all cement contents, it is logical to develop a relationship between ITS and UCS for pavement engineering design as shown in Figure 7 and the following equation:

$$\mathrm{ITS} = 0.0514(\mathrm{UCS})^{1.4945}(R^2 = 0.97) \tag{1}$$

The equation is very useful to predict the ITS at any curing times, cement contents and NRL replacement ratios once the corresponding UCS is known. The ITS was found to be directly related to the resilient modulus, a prime parameter for pavement design (Udomchai et al., 2021). This relationship

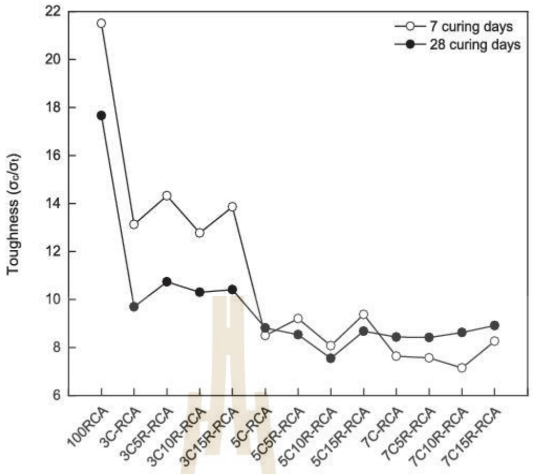

Figure 8. Toughness characteristic of RCA, cement- and cement-NRL stabilised RCA.

was developed based on the studied soil and NRL; however, it can be used as a reference and be refined with more test data by pavement geotechnics researchers.

Toughness is an essential factor when evaluating the ability of the material to absorb energy before rupture (Wang et al., 2005). The toughness of cement- and cement-NRL stabilised RCA samples was estimated by the ratio of compressive strength to tensile strength (σ_c/σ_t); the results were presented in Figure 8. The lower σ_c/σ_t ratio indicates the higher toughness of the sample (Wang et al., 2005).

From Figure 8, the σ_c/σ_t ratios of cement- and cement-NRL stabilised RCA samples at 3% and 5% cement content after 28 days of curing were lower than those after 7 days of curing. In other words, the samples at age of 28 days had higher toughness than the samples at age of 7 days. This indicated the toughness improvement over time. On the other hand, the σ_c/σ_t ratios of the 7% cement samples after 7 days of curing were lower than those after 28 days of curing for all r/c ratios. This implies that the rate of compressive strength development is higher than the rate of tensile strength development at an early age for the 7% C sample, leading to a rapid acceleration of cement hydration and brittle behaviour. The toughness of cement- and cement-NRL stabilised RCA samples at 3% cement content after 28 days of curing was remarkably higher than that samples after 7 days of curing. Whereas the cement- and cement-NRL stabilised RCA samples at 5% cement content after 28 days of curing had slightly higher toughness than the samples after 7 days of curing. This demonstrates that the 3% cement samples required longer curing time for tensile strength development.

Microstructural analysis

Figure 9 illustrates the XRD patterns of cement- and cement-NRL stabilised RCA samples with 3% and 5% cement contents and with various r/c ratios at age of 28 days. The XRD patterns of cement-NRL stabilised RCA samples with 3% and 5% cement contents were similar, whose major phases were calcite, quartz, dolomite, portlandite, gypsum, ettringite and Rosenhahnite.

Based on the major peak value, the quartz (SiO_2) and calcite ($CaCO_3$) phases appeared in high volume fraction. The presence of these crystalline phases showed significant changes in the composition due to the carbonation of cement hydrates in the cement paste adhering to RCA particles, consisting mainly of portlandite ($Ca(OH)_2$) and C–S–H ($CaO–SiO_2–H_2O$). These phases are carbonated in the way

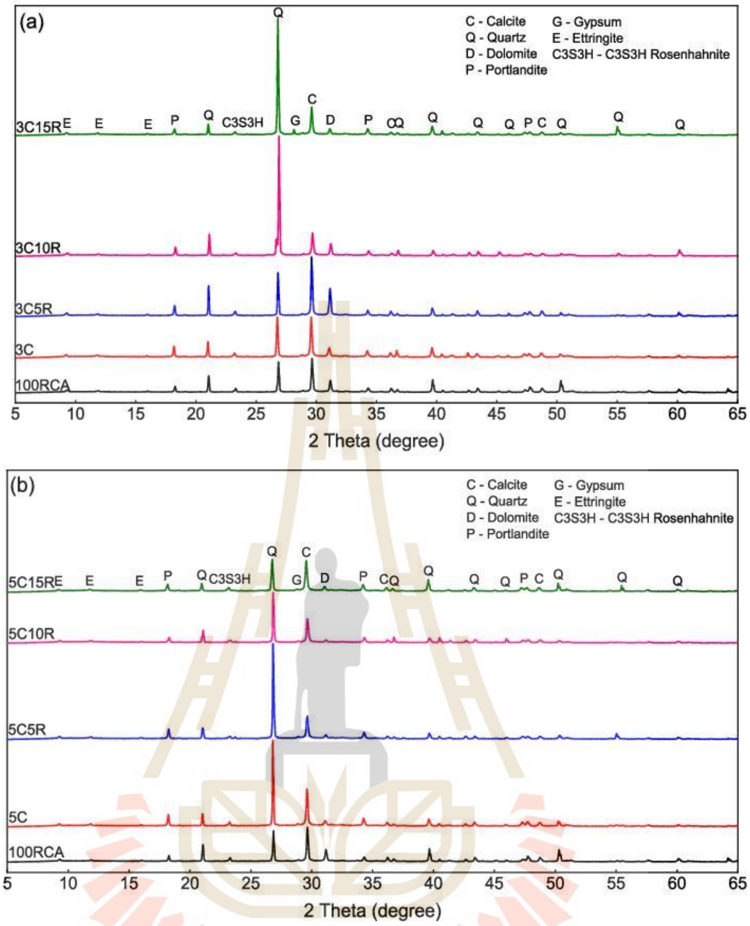

Figure 9. XRD patterns of RCA, cement- and cement-NRL stabilised RCA at 28 days of curing.

described in Equations (2) and (3) as follows (Moreno-Pérez et al., 2018):

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \tag{2}$$

$$C\text{–}S\text{–}H + CO_2 \rightarrow CaCO_3 + SiO_2 \cdot nH_2O \tag{3}$$

When compared with cement-stabilised RCA samples, it was observed that the peak intensity of quartz increased while calcite decreased in the cement-NRL stabilised RCA at the optimum r/c ratios. In contrast, beyond the optimum r/c ratios, the quantity of quartz decreased, while the quantity of calcite increased. This indicated that NRL additive significantly affected the cement hydration and therefore influenced the strength development of cement-NRL stabilised RCA samples, which is similar to the previous findings by Diab et al. (2013).

Kunther et al. (2017) examined the effect of Ca/Si ratio on the UCS of cemented samples and found that the lower Ca/Si ratio resulted in the highest strength for all studied hydration times of the samples.

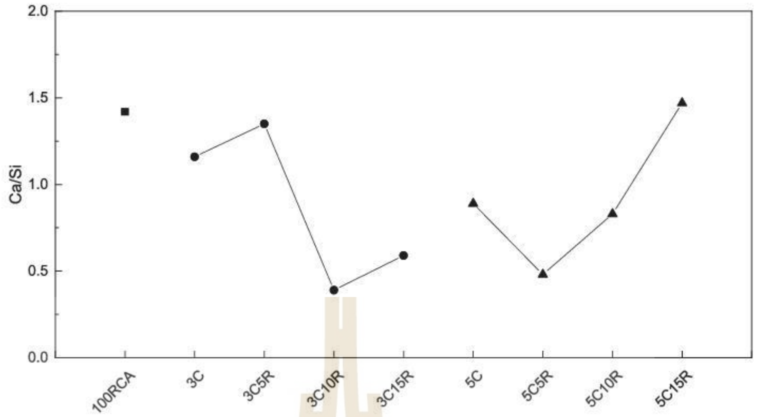

Figure 10. Ca/Si ratio of RCA, cement- and cement-NRL stabilised RCA.

Figure 10 shows that the lowest Ca/Si ratios were found at the optimum r/c ratios for both cement-NRL stabilised RCA at 3% cement (3C10R-RCA) and 5% cement (5C5R-RCA). The XRD analyses and Ca/Si ratio results clearly confirmed the influence of NRL additive on the UCS and ITS development of cement-NRL stabilised RCA, in which the highest UCS and ITS values were found at the same optimum r/c ratio for a particular cement content (see Figure 3 and 5).

The SEM images of 5C-RCA, 5C5R-RCA and 5C15R-RCA samples after 28 days of curing are displayed in Figure 11. The cement hydration products of 5C-RCA sample detected by SEM analysis were calcium hydroxide (CH), as the large hexagonal plate crystals, needle-like crystals of ettringite form and C–S–H phase, which indicated a common reticular form, honeycomb shape or resemblance to the crystalline minerals of tobermorite (Chen et al., 2004). The existence of C–S–H, ettringite and CH forms fills the gaps (air voids) in the cement paste and enhances the bonding strength between the RCA particles, thus improves the strength development of the mixture (Horpibulsuk et al., 2010).

Figure 11(b) shows the SEM image of cement-NRL stabilised RCA at the optimum r/c ratio (5C5R-RCA). It was noted that rubber films were intermingled and intergrown inside the cement hydrates, which covered the C–S–H phase and ettringite needles at the air void surface between the particles. The rubber films act as the bridges to connect the cement hydration products, serving as an additional interparticle forces to bond the RCA particles together. Bean and Husbands (1986) similarly indicated that the polymer matrix acts as a barrier that helps retain the high degree of internal moisture (preventing moisture removal due to evaporation) for the progress of cement hydration. Therefore, the existing amount of C–S–H and ettringite crystals with rubber films generated by NRL additive at the optimum r/c ratio resulted in the highest UCS and ITS development of cement-NRL stabilised RCA.

Figure 11(c) shows the SEM image of cement-NRL stabilised RCA with r/c ratio of 15% (> optimum r/c ratio) (5C15R-RCA). The excessive volume fraction of NRL created continuous NRL films, which abundantly covered the hydrating cement grains and the RCA aggregates. In other words, the formation of thicker rubber film was widely distributed over the particle surface, which generated the jelly-like surface and retarded the cement hydrations (Buritatun et al., 2020). Consequently, the UCS and ITS values were low.

The influence of NRL on UCS and ITS development was found to be dependent upon cement content (Figures 3 and 5). Based on the present and previous microstructural analysis results, although the NRL films enhanced the cohesion in the matrix, they retarded the cement hydration. At low amount of C, the cement hydration has a little effect on the strength development, while the NRL films have more dominant to improve the bonding strength than the retardant effect. On the contrary, the retardant

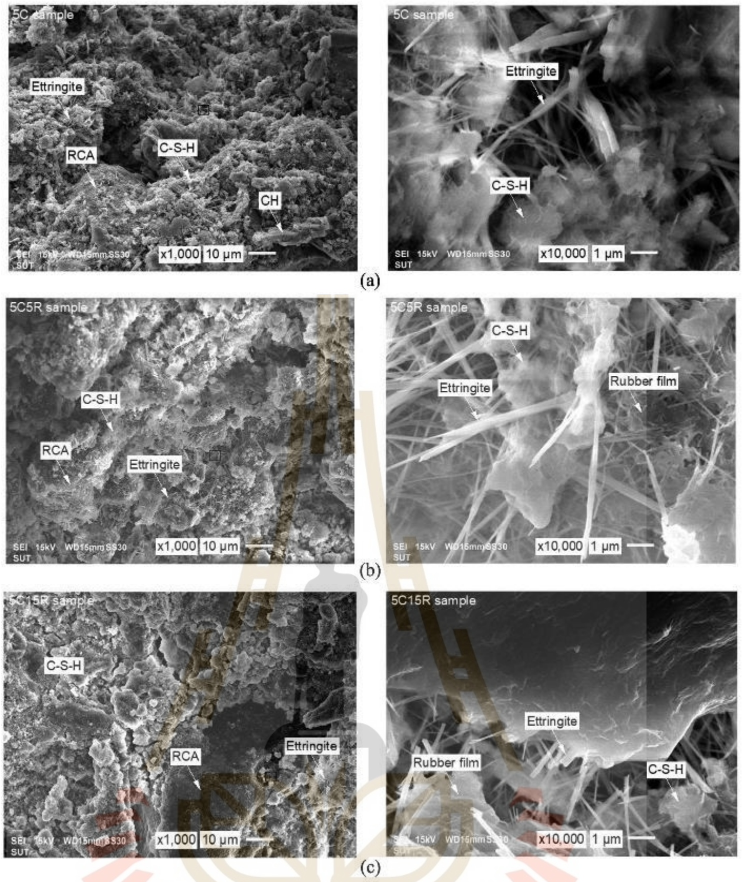

Figure 11. SEM images of: (a) 5C-RCA, (b) 5C5R-RCA, (c) 5C15R-RCA.

effect was more dominant at a high cement content (Buritatum et al., 2021; 2022). As such, the optimum r/c ratio decreased with the increased cement content. For instance, at 3% cement content, the highest UCS values were obtained at the optimum r/c ratio of 3% while the highest UCS values were found at the optimum r/c ratio of 5% for 5% and 7% cement content.

Conclusions

This research investigated the possibility of NRL as a promising green additive to enhance the UCS and ITS of cement stabilised RCA as a pavement base material. The significant conclusions can be drawn as follows:

(1) When compared with cement stabilised RCA, theMDD and the OLC of cement-NRL stabilised RCA decreased with increasing r/c ratios for all cement contents. This is because the solid phase of NRL within the RCA-cement matrix causes the decrease of compressibility of the mixtures while the hydrophobic molecules and surfaces of rubber repel water absorption.

(2) The UCS and ITS values of both cement- and cement-NRL stabilised RCA were increased with increasing the cement content and curing time. At a particular cement content, the UCS and ITS values of cement-NRL stabilised RCA at the optimum r/c ratios were higher than that of cement stabilised RCA. The optimum r/c ratios providing the highest UCS and ITS of cement-stabilised RCA were the same, which were 10%, 5% and 5% for 3%, 5% and 7% cement content, respectively. The UCS and ITS values of 3C10R-RCA $<$ 5C5R-RCA $<$ 7C5R-RCA. Although the UCS and ITS values of cement-NRL stabilised RCA decreased when the r/c ratios were beyond the optimum values, all UCS values were greater than the minimum requirement specified by DOH, Thailand (i.e. UCS $>$ 1.724 MPa) for base material.

(3) The maximum strain values at failure of all cement-NRL stabilised RCA samples were at the highest r/c ratios for all cement contents. It implies that the higher r/c ratio can enhance the soft hardening behaviour of cement stabilised RCA. The toughness of cement- and cement-NRL stabilised RCA at 3% and 5% cement contents improved over time.

(4) The XRD and SEM analyses indicated that at optimum r/c ratios, the cement hydration products were remarkably high while the NRL films can enhance the adhesion, leading to the increased interparticle bonds between RCA particles and UCS and ITS development. In addition, NRL films can enhance the plastic strain, the overall stress–strain behaviour and toughness of the cement-NRL stabilised RCA. However, the excessive NRL additive over the optimum r/c ratio retarded the cement hydration and resulted in low UCS and ITS development.

The outcomes of this research will facilitate the efficient utilisation of NRL in cement stabilised RCA as a pavement material, which provides advantages to traditional cement stabilised recycled material in terms of compressive, tensile, ductility and toughness properties. Furthermore, other properties such as moisture resistance, resistance to cracking, resistance against freeze–thaw or wetting–drying cycles, and resistance to rutting and fatigue cracking, which are important in pavement material design were recommended for further investigation to ensure the long-term performance of the cement-NRL stabilised RCA.

Acknowledgements

This work was financially supported by the National Science and Technology Development Agency under the Chair Professor program [grant number P-19-52303], Suranaree University of Technology and Thailand Science Research and Innovation (TSRI).

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by National Science and Technology Development Agency [grant number P-19-52303]; Suranaree University of Technology.

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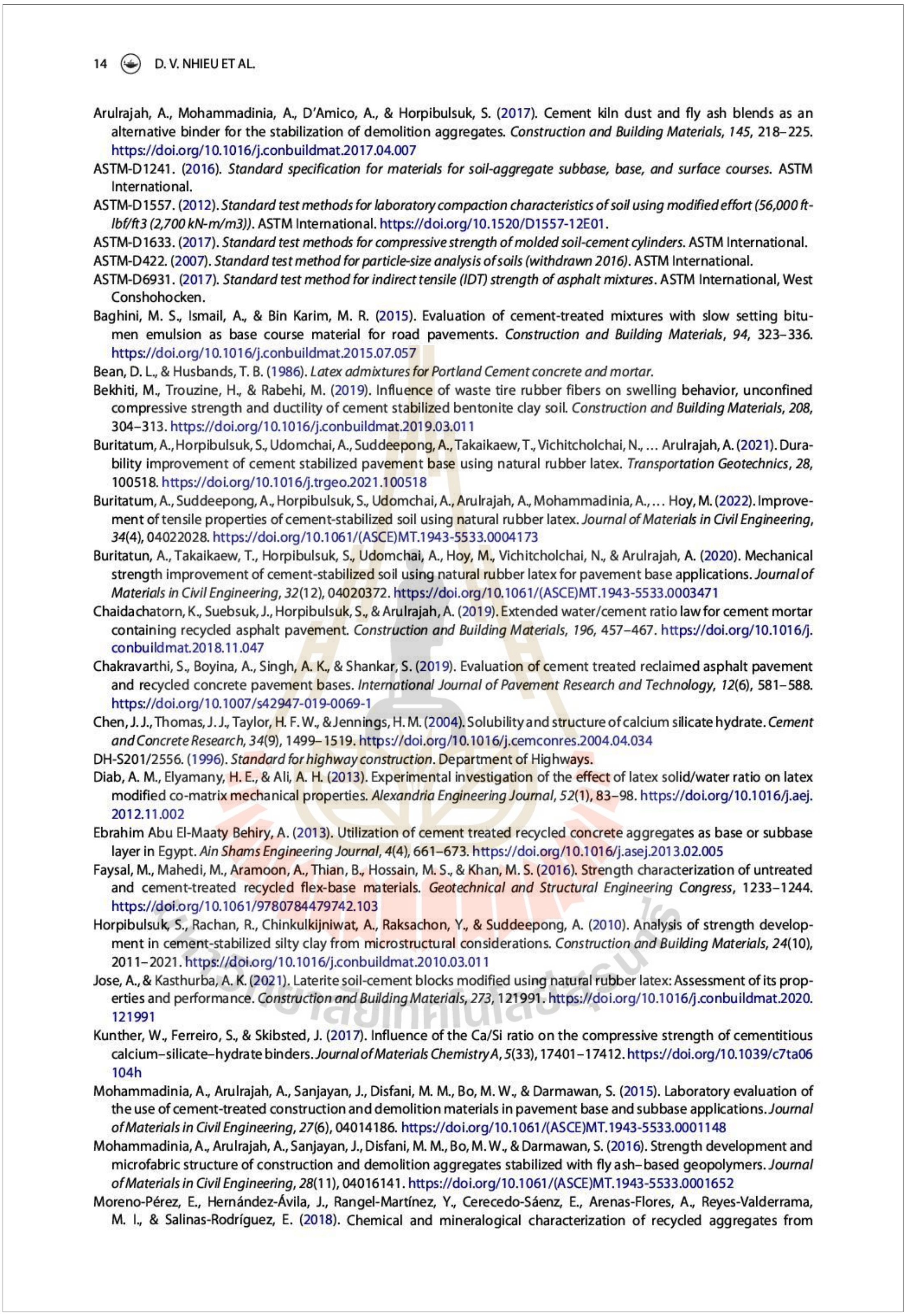

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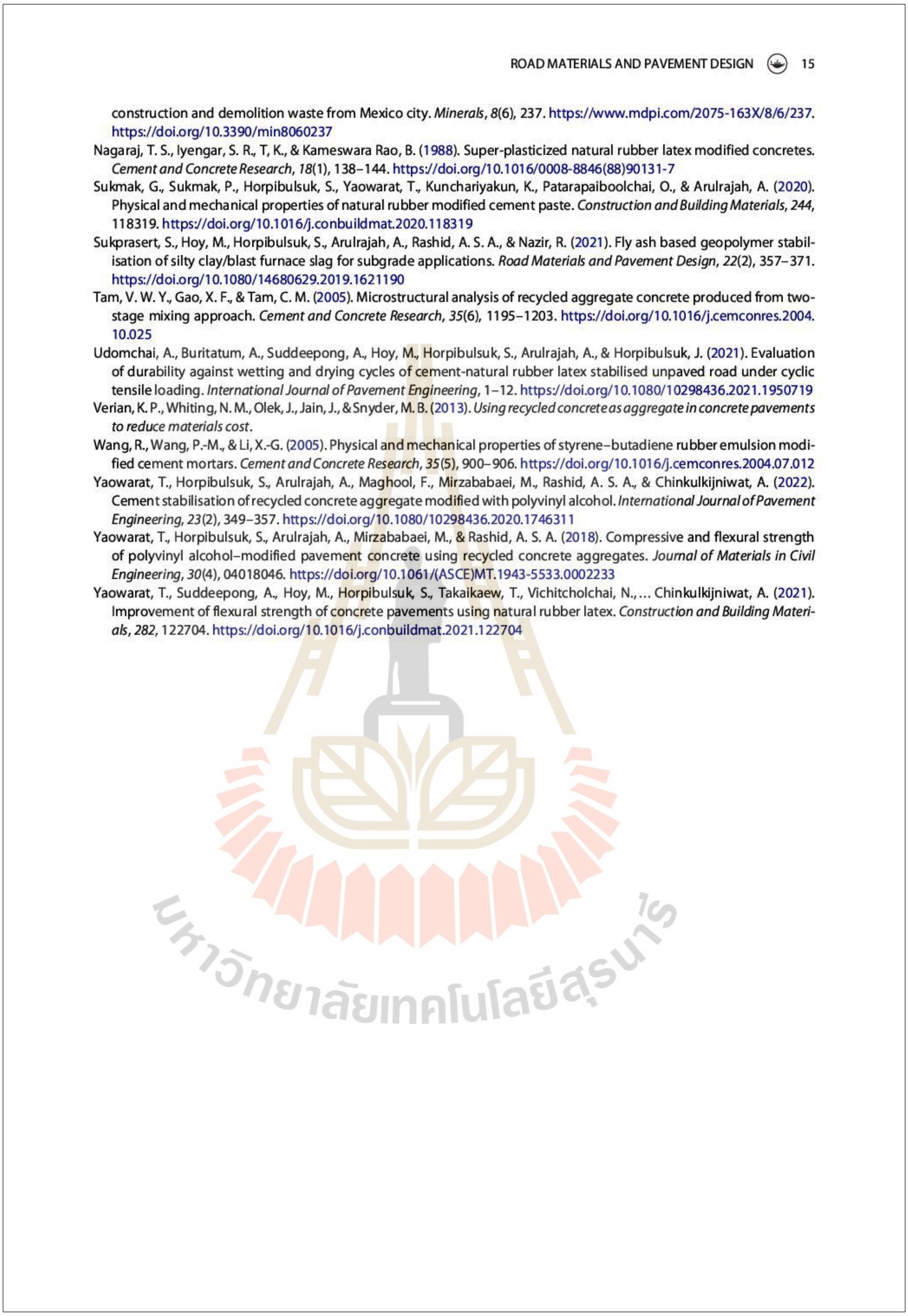

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