

NATURAL RUBBER LATEX AND FLY ASH AS ADDITIVES FOR
IMPROVING THE MECHANICAL PROPERTIES OF RIGID
PAVEMENT WITH RECYCLED CONCRETE AGGREGATE



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

Suranaree University of Technology

Academic Year 2025

การใช้น้ำยารักรักษาและถนอมเป็นสารเติมแต่งเพื่อปรับปรุงสมบัติเชิงกล
ของผิวทางคอนกรีตที่ใช้มวลรวมคอนกรีตรีไซเคิล



นายชาติ อู่ร่มพฤษ

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาปรัชญาดุษฎีบัณฑิต
สาขาวิชาวิศวกรรมโยธาและการบริหารงานก่อสร้าง
มหาวิทยาลัยเทคโนโลยีสุรนารี
ปีการศึกษา 2568

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THE MECHANICAL PROPERTIES OF RIGID PAVEMENT WITH RECYCLED
CONCRETE AGGREGATE

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

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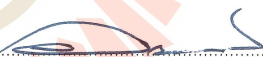
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ชาตรี อยู่ร่วมพฤษ : การใช้น้ำยางธรรมชาติและเถ้าลอยเป็นสารเติมแต่งเพื่อปรับปรุงสมบัติเชิงกลของผิวทางคอนกรีตที่ใช้มวลรวมคอนกรีตรีไซเคิล (NATURAL RUBBER LATEX AND FLY ASH AS ADDITIVES FOR IMPROVING THE MECHANICAL PROPERTIES OF RIGID PAVEMENT WITH RECYCLED CONCRETE AGGREGATE)

อาจารย์ที่ปรึกษา : ศาสตราจารย์ ดร.สุสันต์ หอพิบูลสุข, 157 หน้า

คำสำคัญ: วัสดุผสมคอนกรีตรีไซเคิล/น้ำยางธรรมชาติ/พื้นผิวทางเท้า

การนำมวลรวมคอนกรีตรีไซเคิล (Recycled Concrete Aggregate: RCA) มาใช้ในงานผิวทางคอนกรีตแข็งเป็นแนวทางที่มีศักยภาพในการพัฒนาโครงสร้างพื้นฐานอย่างยั่งยืน เนื่องจากช่วยลดการใช้มวลรวมธรรมชาติและลดปริมาณของเสียจากงานก่อสร้าง อย่างไรก็ตาม มวลรวมคอนกรีตรีไซเคิลมักมีข้อจำกัดด้านความพรุนสูง รอยแตกร้าวภายใน และสมบัติเชิงกลที่ด้อยลง งานวิจัยนี้มีวัตถุประสงค์เพื่อศึกษาการปรับปรุงสมบัติเชิงกล สมบัติความล้า และโครงสร้างจุลภาคของผิวทางคอนกรีตที่ใช้มวลรวมคอนกรีตรีไซเคิล โดยการผสมผสานน้ำยางธรรมชาติ (Natural Rubber Latex: NRL) และเถ้าลอย (Fly Ash: FA) เป็นวัสดุเติมแต่ง เพื่อพัฒนาคอนกรีตผิวทางที่มีสมรรถนะสูงและเป็นมิตรต่อสิ่งแวดล้อม

การทดลองครอบคลุมการทดสอบกำลังอัด (f_c) กำลังดัด (f_t) พฤติกรรมความล้าจากแรงดัดภายใต้การรับน้ำหนักซ้ำ และการศึกษาลักษณะโครงสร้างจุลภาคด้วยกล้องจุลทรรศน์อิเล็กตรอนแบบส่องกราด (SEM) ร่วมกับการวิเคราะห์องค์ประกอบทางเคมีด้วยเทคนิค Energy-Dispersive X-ray spectroscopy (EDX) และ X-ray diffraction (XRD) ตัวแปรหลักที่ศึกษา ได้แก่ อัตราส่วนยางแห้งต่อตัวประสานหรือปูนซีเมนต์ (r/b หรือ r/c) อัตราส่วนน้ำต่อตัวประสาน (w/c) และอัตราการแทนที่ปูนซีเมนต์ด้วยเถ้าลอยในช่วงร้อยละ 15–25 นอกจากนี้ ยังมีการประเมินการปล่อยก๊าซคาร์บอนไดออกไซด์เทียบเท่า (CO_2-e) และต้นทุนวัสดุ เพื่อพิจารณาความยั่งยืนด้านสิ่งแวดล้อมและเศรษฐศาสตร์ของส่วนผสมคอนกรีต

ผลการศึกษาพบว่า การเติมน้ำยางธรรมชาติส่งผลให้กำลังอัดลดลงในทุกระดับ r/b หรือ r/c เนื่องจากการหน่วงกระบวนการไฮเดรชันของปูนซีเมนต์ อย่างไรก็ตามเมื่อเติมน้ำยางธรรมชาติในปริมาณปานกลาง (ประมาณ 0.5–1.0%) คอนกรีตแสดงพฤติกรรมกำลังดัด ความเหนียว และอายุความล้าที่เพิ่มขึ้นอย่างมีนัยสำคัญ ส่วนผสมที่ออกแบบด้วยอัตราส่วน w/c ที่เหมาะสม เช่น $w/c = 0.3$ ที่ $r/c \leq 1.0$ และ $w/c = 0.4$ ที่ $r/c = 0.5$ สามารถผ่านเกณฑ์กำลังอัดและกำลังดัดขั้นต่ำตามข้อกำหนดผิวทางของหน่วยงานกรมทางหลวงได้ ในทางตรงกันข้ามการเติมน้ำยางธรรมชาติในปริมาณสูงเกินไปทำให้เกิดฟิล์มน้ำยางต่อเนื่องที่กีดขวางปฏิกิริยาไฮเดรชัน ส่งผลให้กำลังอัดและกำลังดัดลดลงอย่างชัดเจน การวิเคราะห์โครงสร้างจุลภาคนิยมนการเกิดฟิล์มน้ำยางที่แทรกตัวในเนื้อ

ปูนซีเมนต์และรอยต่อระหว่างมวลรวมกับเนื้อปูน ช่วยเชื่อมประสานช่องว่างและเพิ่มความสามารถในการรับแรงอัด ผลการวิเคราะห์องค์ประกอบทางเคมีและแร่ด้วยเทคนิค EDX และ XRD แสดงให้เห็นอย่างชัดเจนว่าปริมาณเฟสพอร์ตแลนด์ไดต์ ($\text{Ca}(\text{OH})_2$) มีแนวโน้มลดลงอย่างต่อเนื่องเมื่ออัตราส่วนน้ำยางธรรมชาติต่อตัวประสานหรือปูนซีเมนต์ (r/b หรือ r/c) เพิ่มขึ้น ซึ่งสะท้อนถึงการชะลอของปฏิกิริยาไฮเดรชันของปูนซีเมนต์อันเกิดจากการเคลือบผิวของอนุภาคปูนด้วยฟิล์มน้ำยาง ส่งผลให้เกิดผลิตภัณฑ์ไฮเดรชัน เช่น C-S-H เจล ลดลงในระดับมหภาค อย่างไรก็ตามในช่วงอัตราส่วนน้ำยางธรรมชาติที่เหมาะสม (r/b หรือ r/c ประมาณ 0.5–1.0%) การลดลงของพอร์ตแลนด์ไดต์ไม่ส่งผลกระทบเชิงลบต่อสมบัติเชิงกลโดยรวม เนื่องจากฟิล์มน้ำยางทำหน้าที่เป็นตัวเชื่อมประสานเชิงกายภาพช่วยลดความไม่ต่อเนื่องของโครงสร้างจุลภาค และปรับปรุงรอยต่อระหว่างมวลรวมคอนกรีตรีไซเคิลกับเนื้อปูนซีเมนต์ ส่งผลให้ความสามารถในการรับแรงอัด ความเหนียว และความต้านทานต่อการแตกร้าวเพิ่มขึ้นอย่างมีนัยสำคัญ

เมื่ออัตราส่วนน้ำยางธรรมชาติสูงเกินช่วงที่เหมาะสม ฟิล์มน้ำยางที่เกิดขึ้นมีลักษณะต่อเนื่องและหนาแน่นมากขึ้น ทำหน้าที่เป็นสิ่งกีดขวางการแพร่ของน้ำและไอออน ส่งผลให้การพัฒนาโครงสร้างไฮเดรชันถูกจำกัดอย่างชัดเจน ซึ่งสอดคล้องกับผลการลดลงของกำลังอัดและกำลังดัดในระดับมหภาค นอกจากนี้ การใช้เถ้าลอยร่วมกับน้ำยางธรรมชาติมีบทบาทสำคัญในการชดเชยผลของการหน่วงไฮเดรชัน โดยเถ้าลอยทำปฏิกิริยาปอซโซลานิกกับพอร์ตแลนด์ไดต์ที่เหลืออยู่ ส่งผลให้โครงสร้างเนื้อปูนมีความหนาแน่นมากขึ้นในระยะยาว และช่วยปรับสมดุลระหว่างสมบัติเชิงกลและความสามารถในการแปรรูปของคอนกรีต

ในมิติด้านความยั่งยืน ส่วนผสมที่แทนที่ปูนซีเมนต์ด้วยเถ้าลอยร้อยละ 25 ร่วมกับการเติมน้ำยางธรรมชาติในอัตราส่วน r/b = 0.5% ให้ค่าการปล่อยก๊าซคาร์บอนไดออกไซด์เทียบเท่า ($\text{CO}_2\text{-e}$) ต่ำที่สุด เนื่องจากการลดปริมาณปูนซีเมนต์ซึ่งเป็นแหล่งปล่อยคาร์บอนหลัก ขณะเดียวกัน ส่วนผสมที่ใช้เถ้าลอยร้อยละ 20 แสดงความคุ้มค่าด้านต้นทุนวัสดุสูงสุด โดยยังคงให้สมบัติเชิงกลและความต้านทานความล้าที่เพียงพอต่อข้อกำหนดผิวทางคอนกรีต ผลลัพธ์ดังกล่าวชี้ให้เห็นว่าการออกแบบส่วนผสมคอนกรีตโดยอาศัยหลักการสมดุลระหว่างสมรรถนะทางวิศวกรรม การลดคาร์บอน และต้นทุน สามารถนำไปสู่การพัฒนาผิวทางที่ยั่งยืนและเหมาะสมต่อการใช้งานจริง

โดยสรุป งานวิจัยนี้แสดงให้เห็นว่าการออกแบบคอนกรีตผิวทางที่ใช้มวลรวมคอนกรีตรีไซเคิลร่วมกับ เถ้าลอยและน้ำยางธรรมชาติในสัดส่วนที่เหมาะสม สามารถเพิ่มสมรรถนะทางวิศวกรรมและความต้านทานความล้า ควบคู่กับการลดผลกระทบต่อสิ่งแวดล้อมและต้นทุนวัสดุ สนับสนุนการพัฒนาผิวทางคอนกรีตคาร์บอนต่ำสำหรับโครงสร้างพื้นฐานอย่างยั่งยืนในอนาคต

สาขาวิชาวิศวกรรมโยธาและการบริหารงานก่อสร้าง
ปีการศึกษา 2568

ลายมือชื่อนักศึกษา.....

ลายมือชื่ออาจารย์ที่ปรึกษา.....

ลายมือชื่ออาจารย์ที่ปรึกษาร่วม.....

CHATREE YOUROMPHRUK : NATURAL RUBBER LATEX AND FLY ASH AS
ADDITIVES FOR IMPROVING THE MECHANICAL PROPERTIES OF RIGID PAVEMENT
WITH RECYCLED CONCRETE AGGREGATE.

THESIS ADVISOR : PROF. SUKSUN HORPIBULSUK, Ph.D., 157 PP.

Keywords: Recycled Concrete Aggregate/ Natural Rubber Latex /Surface Pavement

The use of Recycled Concrete Aggregate (RCA) in rigid pavement construction represents a promising approach for developing sustainable infrastructure by reducing the consumption of natural aggregates and minimizing construction waste. However, RCA generally exhibits inherent drawbacks, including high porosity, internal microcracking, and inferior mechanical properties. This study aims to investigate the enhancement of mechanical performance, fatigue behavior, and microstructural characteristics of rigid pavement concrete incorporating RCA through the combined use of Natural Rubber Latex (NRL) and Fly Ash (FA) as supplementary materials, with the objective of developing high-performance and environmentally friendly pavement concrete.

The experimental program comprised compressive strength (f_c), flexural strength (f_f), flexural fatigue performance under repeated loading, and microstructural characterization using Scanning Electron Microscopy (SEM), Energy-Dispersive X-ray spectroscopy (EDX), and X-ray diffraction (XRD). The primary variables investigated included the dry rubber-to-binder or cement ratio (r/b or r/c), the water-to-binder ratio (w/c), and FA replacement levels ranging from 15% to 25% by weight of cement. In addition, CO_2 -equivalent (CO_2-e) emissions and material costs were evaluated to assess the environmental and economic sustainability of the proposed concrete mixtures.

The results indicated that the incorporation of NRL led to a reduction in compressive strength at all r/b or r/c levels due to retardation of cement hydration. Nevertheless, when NRL was added at moderate dosages (approximately 0.5–1.0%), the concrete exhibited significant improvements in flexural strength, ductility, and fatigue life. Mixtures designed with appropriate w/c ratios, such as $w/c = 0.3$ at $r/c \leq 1.0$ and $w/c = 0.4$ at $r/c = 0.5$, consistently satisfied the minimum compressive and flexural strength requirements specified by the Thai Department of Highways for rigid pavement applications. In contrast, excessive NRL addition resulted in the formation of continuous

latex films that hindered hydration reactions, leading to pronounced reductions in both compressive and flexural strengths.

Microstructural analyses confirmed the presence of latex films embedded within the cement matrix and at the interfacial transition zone between RCA and cement paste, which effectively bridged microvoids and enhanced flexural performance. EDX and XRD analyses further revealed a continuous reduction in portlandite (Ca(OH)_2) content with increasing r/b or r/c ratios, reflecting hydration retardation caused by the coating of cement particles with latex films and the consequent reduction in hydration products such as C-S-H gel at the macroscopic scale. However, within the optimal NRL range (r/b or r/c $\approx$ 0.5–1.0%), the reduction in portlandite did not adversely affect overall mechanical performance, as the latex films acted as physical binders that improved microstructural continuity, enhanced the interfacial transition zone, and increased resistance to crack initiation and propagation. The incorporation of FA played a crucial role in compensating for hydration retardation by promoting pozzolanic reactions with the remaining portlandite, resulting in a denser cementitious matrix and improved long-term performance.

From a sustainability perspective, the mixture incorporating 25% FA and 0.5% r/b exhibited the lowest $\text{CO}_2\text{-e}$ emissions due to the substantial reduction in cement content, which is the primary source of carbon emissions. Meanwhile, the mixture containing 20% FA provided the most cost-effective solution while maintaining adequate mechanical properties and fatigue resistance to meet rigid pavement requirements. These findings demonstrate that optimizing concrete mixtures based on a balanced consideration of engineering performance, carbon reduction, and material cost can lead to the development of durable and sustainable rigid pavement concrete.

In conclusion, this study demonstrates that the appropriate combination of RCA, FA, and NRL can significantly enhance mechanical performance and fatigue resistance while simultaneously reducing environmental impact and material cost, thereby supporting the development of low-carbon rigid pavement materials for sustainable infrastructure applications.

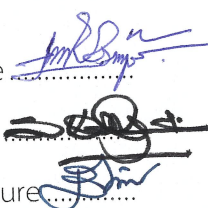
School of Civil Engineering and Construction Management

Academic Year 2025

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ACKNOWLEDGEMENTS

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

I acknowledge Dr. Teerasak Yaowarat for their discussions and encouragement. I would like to thank Suranaree University of Technology for facilities, equipment and financial support. I also would like to acknowledge Thailand Research Fund (TRF) for financial support under the Ph.D. Royal Jubilee program Grant No. 0143/2557.

Finally, I would like to appreciate my family for their love and kind support on my graduate studies.

Chatree Youromphruk

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ABBREVIATIONS AND SYMBOLS

RCA	=	Recycled Concrete Aggregate
RA	=	Recycled Aggregate
OPC	=	Ordinary Portland Cement
PMC	=	Polymer modified concretes
PVA	=	Polyvinyl alcohol
FA	=	Fly ash
NA	=	Natural aggregate
SEM	=	Scanning Electron Microscope
XRD	=	X-ray Diffraction
w/c	=	Water to cement ratio
p/c	=	Polyvinyl alcohol to cement ratio
wt%	=	Percentage by weight
TSMA	=	Two-stage mixing approach
NMA	=	Normal Mixing approach
C&D	=	Construction and demolition waste
C ₃ S	=	Tricalcium Silicate
C ₂ S	=	Dicalcium Silicate
C ₃ A	=	Tricalcium Aluminate
C ₄ AF	=	Tetracalcium Aluminoferrite
C-S-H	=	Calcium-Silicate-Hydrate
CH	=	Calcium Hydroxide
ITZ	=	The interfacial transition zone
RAC	=	Recycled Aggregate Concrete
NC	=	Natural Concrete
EDS	=	Energy-dispersive X-ray spectroscopy
GFA	=	Ground fly ash
GBA	=	Ground bagasse ash

ABBREVIATIONS AND SYMBOLS (Continued)

CON	=	Conventional concrete
POFA	=	Ground palm oil fuel ash
cNA	=	Crushed aggregates
rNA	=	River aggregates
P	=	Maximum applied load
L	=	Span length
b	=	Average width of the specimens
h	=	Average depth of the specimens
d	=	average diameter of the specimens
w/b	=	Water to binder ratio
FA/c	=	Fly Ash to cement ratio
p/b	=	Polyvinyl alcohol to binder ratio
UCS	=	Unconfined Compressive Strength
CBR	=	California bearing ratio
RLT	=	Repeated load triaxial
LA	=	Los Angeles abrasion
GP	=	General Portland
USCS	=	Unified Soil Classification System\
MDD	=	Maximum dry density
OMC	=	Optimum moisture content
γ	=	Dry unit weight (kN/m^3)
ω	=	Moisture Content (%)
M_R	=	Resilient modulus
σ_d	=	Deviator stress
ϵ_r	=	Resilient strain
σ_3	=	Confining Pressure

CHAPTER I

INTRODUCTION

1.1 Statement of the problem

In general, the structural composition of pavement concrete encompasses distinct layers, namely subgrade, sub-base course, base course, and rigid pavement. This configuration enables the pavement to efficiently sustain the load imparted by wheels and axles, thereby necessitating concrete with robust mechanical properties that ensure its durability and longevity under heavy traffic conditions. Concrete pavement offers a notable advantage in terms of cost, as its maintenance expenses are comparatively low (Pranav et al., 2020). However, several limitations accompany concrete pavement, including elevated greenhouse gas emissions and inherent deficiencies in tensile strength and flexural strength. Moreover, the susceptibility of concrete pavement to temperature variations and fluctuations is primarily attributed to its diminished tensile and flexural strength (Mohod & Kadam, 2016). Consequently, a substantial thickness of the concrete pavement layer is imperative to mitigate crack formation resulting from the applied forces by vehicles' wheels and axles (Khichad et al., 2023).

Concrete serves as the principal construction material extensively employed in civil engineering projects on a global scale. The substantial requirement for coarse aggregate derived from natural stone is vital to meet the substantial demand for concrete production. Presently, the worldwide aggregate gross output amounts to approximately 20 billion metric tons annually, with projections indicating a doubling of aggregate demand within the next 20-30 years (Kalinowska-Wichrowska et al., 2020). However, the extraction and crushing processes associated with natural aggregate entail amplified energy consumption and concurrent release of CO₂, thereby contributing to the escalating concerns of global warming and climate change. This predicament can be predominantly attributed to the heightened emission of greenhouse gases (GHGs) into the atmosphere, including but not limited

to carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), sulfur hexafluoride (SF₆), and argon. Consequently, there exists an imperative and time-sensitive necessity to curtail GHG emissions, with a particular emphasis on reducing CO₂ emissions (Infante Gomes et al., 2021).

The construction industry is currently witnessing a notable shift towards adopting alternative building materials as substitutes for natural resources, aiming to mitigate the environmental impact associated with energy consumption, pollution, and waste disposal. Concurrently, the generation of waste from construction and demolition (C&D) activities has emerged as a global concern. Consequently, the recycling and reuse of such waste materials have emerged as effective measures to diminish reliance on virgin resources and alleviate environmental repercussions (Behera et al., 2014). By recycling building materials, valuable space within limited landfills can be conserved. Notably, concrete waste constitutes a significant proportion, accounting for approximately 50% of the total waste generated. Current practices that involve landfill disposal of construction materials yield substantial volumes of waste originating from construction sites. Recycling concrete waste into recycled aggregates presents a viable approach to curbing concrete waste accumulation (Tam, 2008). Nevertheless, it is crucial to consider the energy requirements entailed in the crushing and sorting of construction and demolition waste (CDW), as well as the transportation of recycled aggregates, as these factors may impact the overall environmental balance. Extensive research has demonstrated that CDW recycling substantially enhances energy efficiency and environmental performance. However, certain quantities of concrete waste still find their way to landfills, with emissions being contingent upon various parameters, such as local conditions during raw material production processes and transportation distances (Collins, 2010). Furthermore, the utilization of recycled aggregates derived from CDW not only aids in conserving natural aggregate resources but also diminishes the demand for landfill space, thereby fostering sustainable construction practices (Martins et al., 2023).

The investigation into the application of recycled concrete aggregates (RCA) has spanned over four decades. The initial phase of this research focused on

comprehending the fundamental properties of RCA and its influence on concrete mixtures. The produced concrete incorporating RCA was deemed of lower grade, rendering it unsuitable for structural applications. The high water absorption characteristics of RCA necessitated a higher water content in the concrete mix to attain the desired workability (Frondistou-Yannas, 1997). RCA aggregates possess distinctive physical attributes, such as polygonal shape, rough surface texture, and a significantly larger specific surface area, resulting in reduced workability when higher proportions of RCA are incorporated into the concrete mix. However, this challenge can be mitigated by adequately controlling the moisture content of RCA prior to concrete mixing, thus obviating the need for excessive water addition during operations (Su & Wang, 2000; Tu et al., 2006). Furthermore, the reduction in unit weight consequent to the utilization of RCA also impacts compressive strength. Nevertheless, comparative studies with natural aggregates (Nixon, 1978; Kang & Weibin, 2018) reveal that concrete containing RCA as an admixture can still attain strength development over the curing period comparable to standard concrete. Enhancements in the mechanical properties of high-strength and high-performance concrete incorporating RCA admixtures can be achieved by incorporating supplementary admixtures like silica fume (Hendriks & Pietersen, 2000; Shayan & Xu, 2003; Tu et al., 2006).

Thailand holds the distinction of being the world's leading producer of natural rubber latex (NRL) derived from the rubber tree, *Hevea brasiliensis*. NRL, a natural polymer with inherent elastic properties, has garnered attention as a viable substitute for synthetic polymers in NRL polymer-modified concrete. Extensive research has confirmed its efficacy in enhancing the tensile and flexural strength of cement mortars, cement pastes, concrete, and stabilized cement soils (Sukmak et al., 2020; Tran et al., 2022; Yaowarat et al., 2018; Yaowarat et al., 2021). However, limited studies have explored the application of natural rubber latex (NRL) to enhance the flexural strength of recycled concrete aggregate (RCA) for pavement use. The focus of this research is to address this gap and pursue environmentally friendly solutions, which align with the primary objective of promoting sustainability.

To investigate this, the research adopts the TSMA two-step mixing method to prepare RCA concrete samples. The influence of the water-to-cement ratio (w/c) and rubber-to-cement ratio (r/c) on both compressive strength and flexural strength is examined. Advanced analytical techniques, including scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDX), and X-ray diffraction (XRD), are employed to analyze structural changes and mechanical properties. The study presents the mechanical properties of RCA concrete and highlights the improvements in compressive strength and flexural strength achieved through the incorporation of NRL in the RCA-NRL concrete samples, adhering to the stipulations set by the Department of Highways of Thailand. This research serves as evidence of the effective utilization of recycled construction and demolition waste (CDW) alongside natural rubber latex (NRL) for the development of sustainable pavement technologies.

In recent years, sustainability considerations have become an integral component of pavement material design, extending beyond conventional mechanical performance criteria. Rigid pavement concrete, while offering superior durability and structural capacity, is associated with significant environmental impacts, primarily due to the intensive use of Portland cement and natural aggregates. Cement production alone is responsible for a substantial proportion of global anthropogenic CO_2 emissions, largely attributed to both the calcination of limestone and the high energy demand of clinker production. Consequently, reducing cement content has been widely recognized as one of the most effective strategies for lowering the carbon footprint of concrete.

Fly ash (FA), a by-product of coal-fired power generation, has been extensively utilized as a supplementary cementitious material to partially replace cement in concrete. The incorporation of FA not only reduces cement consumption and associated CO_2 emissions but also contributes to improved long-term performance through pozzolanic reactions, which refine pore structure and enhance microstructural densification. From a sustainability perspective, the use of FA promotes industrial symbiosis by diverting waste from landfills and converting it into value-added construction materials. However, the interaction between FA and recycled concrete aggregate (RCA), particularly under the influence of polymeric modifiers such as

natural rubber latex (NRL), remains insufficiently understood in the context of rigid pavement concrete.

In parallel, the environmental benefits of RCA utilization are closely linked to life-cycle considerations. Although RCA production requires energy for crushing, sorting, and transportation, numerous studies have demonstrated that, when evaluated over the entire life cycle, recycled aggregates generally exhibit lower environmental impacts than virgin aggregates, especially in regions where natural aggregate resources are scarce or transportation distances are long. The combined use of RCA and FA therefore represents a promising low-carbon strategy, provided that mechanical performance requirements can be satisfied.

Beyond environmental impacts, economic feasibility is a critical factor governing the practical adoption of sustainable pavement materials. While FA and RCA are often lower-cost alternatives to cement and natural aggregates, the incorporation of NRL introduces additional material costs that must be justified by performance improvements. From a cost-performance perspective, enhancing flexural strength, ductility, and fatigue resistance may allow for reduced pavement thickness or extended service life, ultimately offsetting higher initial material costs. Consequently, sustainability assessment of pavement concrete should not be limited to material substitution alone but should consider the balance between cost, performance, and durability.

Life-cycle thinking provides a comprehensive framework for evaluating the overall sustainability of pavement materials by integrating mechanical performance, environmental impact, and economic cost throughout the material life span. Rather than focusing solely on early-age strength or material quantities, life-cycle-oriented approaches emphasize performance-based design, CO₂-equivalent emissions, and long-term durability. In this context, simplified life-cycle indicators, such as embodied CO₂ emissions per cubic meter of concrete and material cost per unit volume, offer practical tools for comparing alternative mix designs during the material selection and design stages.

Despite growing interest in low-carbon concrete technologies, limited studies have simultaneously addressed mechanical properties, fatigue performance,

microstructural behavior, CO₂ emissions, and cost efficiency of FA–NRL–RCA concrete for rigid pavement applications. The lack of integrated assessment hampers the development of clear design guidelines and limits the broader implementation of sustainable pavement materials. Therefore, a holistic evaluation framework that incorporates life-cycle thinking is essential to identify optimal concrete mixtures that satisfy structural requirements while minimizing environmental impact and cost.

In response to these challenges, the present study adopts a performance- and sustainability-oriented approach to evaluate rigid pavement concrete incorporating RCA, FA, and NRL. By quantifying mechanical performance, microstructural characteristics, CO₂-equivalent emissions, and material costs, the study aims to provide practical insights into the life-cycle implications of alternative pavement concrete mixtures. The outcomes are expected to support decision-making in the design of low-carbon, cost-effective, and durable rigid pavement systems aligned with sustainable infrastructure development goals.

1.2 Objectives of the study

1.2.1 To evaluate the feasibility of using Recycled Concrete Aggregate (RCA) as coarse aggregate in rigid pavement concrete modified with Natural Rubber Latex (NRL).

1.2.2 To investigate the combined effects of Natural Rubber Latex (NRL) and Fly Ash (FA) on the mechanical properties of RCA-based concrete, including compressive strength, flexural strength, ductility, and fatigue resistance.

1.2.3 To examine the influence of key mix design parameters, namely rubber-to-binder (or cement) ratio, water-to-binder ratio, and FA replacement level, on the performance of RCA–NRL and RCA–FA–NRL concretes.

1.2.4 To characterize the microstructural and mineralogical changes induced by the incorporation of RCA, FA, and NRL using SEM, EDX, and XRD analyses, and to relate these changes to mechanical and fatigue behaviors.

1.2.5 To assess the environmental and economic performance of the proposed concretes by evaluating CO₂-equivalent emissions and material costs based

on life-cycle-oriented indicators, and to identify optimal mixtures for sustainable rigid pavement applications.

1.3 Organization of the dissertation

This thesis comprises five chapters, each outlined as follows:

Chapter 1: Introduction. This chapter provides an overview of the background, the significance of the problem, the study objectives, the composition of the thesis, and references to relevant research.

Chapter 2: Literature Review. In this chapter, relevant literature is reviewed, including topics such as experimental materials, concrete pavement, recycled concrete coarse aggregate, and the application of natural latex to enhance concrete properties. The chapter also explores the historical utilization of recycled concrete in construction projects.

Chapter 3: This chapter presents the findings of the study on the Enhancing the Flexural Strength of Concrete Pavements with Recycled Aggregate Using Natural Rubber Latex Additive. The study procedures involved the preparation of materials, including ordinary Portland cement (OPC), fly ash, natural stone coarse aggregate (NA), recycled concrete coarse aggregate, and fine aggregate from natural sand. Concrete mixes were designed with water-to-cement ratios (w/c) of 0.3, 0.4, and 0.5. Specimens for compressive strength testing were prepared following BS 1881-108 (BS 1983) standards, sized at 150 x 150 x 150 mm. For flexural strength testing, specimens measuring 100 x 100 x 400 mm, according to ASTM C78-02 (ASTM 2002) standards, were used. The concrete samples were divided into natural aggregate concrete and recycled aggregate concrete, with the addition of natural rubber latex in varying weight ratios per cement (r/c) of 0.0, 0.5, 1.0, 1.5, and 2.0 percent, respectively. The compressive and flexural strengths were tested, and the deflection of concrete samples during the flexural strength test was recorded. A comparative analysis was conducted to evaluate the compressive and flexural properties of natural aggregate concrete and recycled concrete, aiming to identify suitable properties for practical implementation. The microstructure of concrete samples was investigated using

scanning electron microscopy (SEM), energy-dispersive chemical composition analysis (EDS), and X-ray diffraction analysis (XRD).

Chapter 4: The integration of Recycled Concrete Aggregate (RCA) and Fly Ash (FA) offers a sustainable approach to reducing natural resource use and carbon emissions in pavement concrete. This study examined the influence of Natural Rubber Latex (NRL) on the mechanical and environmental performance of FA–RCA concrete. Tests included compressive strength, flexural strength, flexural fatigue, and microstructural analysis (SEM and EDX), along with CO₂-equivalent emission calculations. Results showed that moderate NRL contents (r/b = 0.5–1.0%) improved flexural strength and fatigue life, especially at 15–25% FA, while excessive latex reduced strength due to hydration retardation. Microstructural analysis confirmed matrix densification at optimal NRL levels and film-induced hydration barriers at higher dosages. The mix with 25% FA and 0.5% r/b achieved the lowest emissions (304.63 kg CO₂-e/m³) and highest fatigue life, while 20% FA yielded the lowest material cost. All mixtures met Thai pavement strength requirements. Overall, optimized FA–NRL–RCA concrete enhances structural performance and reduces carbon footprint, supporting its use as a low-carbon pavement material.

Chapter 5: This study showed that Natural Rubber Latex (NRL) and Fly Ash (FA) can effectively improve the performance and sustainability of RCA-based pavement concrete. Optimal NRL contents enhanced flexural strength and fatigue life, while excessive latex reduced compressive strength by hindering hydration. FA replacement at 20–25% improved long-term strength and significantly lowered carbon emissions. The mix with 25% FA + 0.5% r/b provided the best environmental performance, while 20% FA offered the lowest material cost. All optimized mixtures met Thai rigid pavement strength requirements.

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CHAPTER II

LITERATURE REVIEW

2.1 Introduction

Since the early 2000s, considerable research has focused on incorporating recycled materials as substitutes in concrete production. This practice has become increasingly prominent in infrastructure development due to engineering, economic, and environmental advantages (Dosho, 2007; FHWA, 2004). Although many Asian countries possess abundant natural resources, the use of industrial by-products has steadily grown as the need to conserve raw materials, reduce waste disposal costs, and lower the carbon footprint of construction activities becomes more urgent. The extraction, crushing, transportation, and storage of natural aggregates demand substantial energy and contribute significantly to environmental degradation. Consequently, shifting toward the utilization of recycled and by-product materials presents an effective strategy for reducing reliance on virgin aggregates and promoting sustainable construction practices.

The integration of recycled materials into concrete production offers two principal benefits: it decreases the consumption of natural aggregates while alleviating waste management challenges, and it can also contribute to lowering construction costs. To support the widespread adoption of recycled alternatives, extensive studies have investigated the feasibility of using Recycled Concrete Aggregate (RCA) obtained from demolished structures as a substitute for natural aggregates, particularly for pavement applications.

2.2 Ordinary Portland Cement (OPC)

Ordinary Portland Cement (OPC) is a hydraulic cement composed mainly of calcium silicates, which harden through a chemical reaction with water to form a solid binder known as paste. When this paste is mixed with aggregates such as sand, gravel, or crushed stone, it binds the particles together to produce concrete—one of the most

widely used construction materials. Although the terms cement and concrete are often mistakenly used interchangeably, cement is only one component of concrete. Cement is a finely ground powder, whereas concrete is the resulting stone-like solid. Typically, cement accounts for approximately 7% to 15% of the total weight of concrete.

Portland cement, typically recognized as a fine gray powder, is composed of several hydraulic cement minerals, including tricalcium silicate, dicalcium silicate, tricalcium aluminate, and tetracalcium aluminoferrite. These constituents are identified by specific chemical formulas and abbreviated notations, as summarized in **Table 2.1**.

Table 2.1 the main composition of Portland cement.

Composition name	Chemical composition	initials
Tricalcium Silicate	$3\text{CaO} \cdot \text{SiO}_2$	C_3S
Dicalcium Silicate	$2\text{CaO} \cdot \text{SiO}_2$	C_2S
Tricalcium Aluminate	$3\text{CaO} \cdot \text{Al}_2\text{O}_3$	C_3A
Tetracalcium Aluminoferrite	$4\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{Fe}_2\text{O}_3$	C_4AF

The production of Portland cement begins with selecting and proportioning raw materials, which are then crushed, ground, and prepared for pyroprocessing. Its main chemical constituents include calcium, silicon, aluminum, iron, and oxygen, with minor components—such as magnesium, sulfur, sodium, and potassium—making up less than 5% by weight. SEM images of Ordinary Portland Cement (OPC) are shown in **Figure 2.1**, and its physical and chemical properties are summarized in **Tables 2.2**.

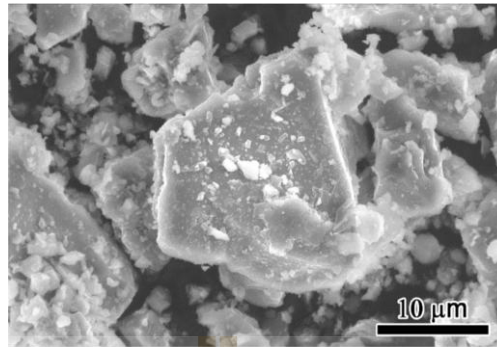


Figure 2.1 the SEM micrographs of OPC (Hongfang, 2015).

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

Chemical Composition (%)	OPC
SiO ₂	22.52
Al ₂ O ₃	5.80
Fe ₂ O ₃	3.52
SO ₃	2.54
CaO	62.08
MgO	1.55
Na ₂ O	0.05
K ₂ O	0.56
LOI	0.94
Physical property	-
Specific gravity	3.12
Retained on sieve No. 325 (%)	4.70
BET surface area (m ² /g)	2.70
Median particle size, d ₅₀ (μm)	12.00

Cement plants operate using either the wet or dry process. The wet process mixes raw materials with water to form a slurry, whereas the dry process grinds them into a powder. Modern plants in the United States exclusively use the dry process due to its lower thermal energy demand (2.7–7.3 million Btu per ton). Thermal efficiency is further improved by incorporating cyclone preheaters and calciners.

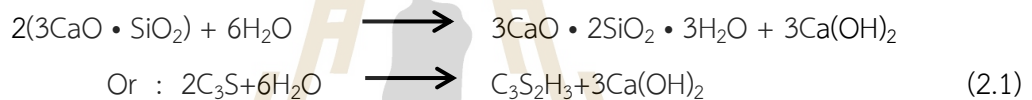
Within the rotary kiln, raw materials undergo chemical reactions to form cement clinker, which is then cooled, blended with gypsum, and ground in mills to produce Portland cement. The final product is transported in bulk or packaged bags.

2.3 The Hydration Reactions

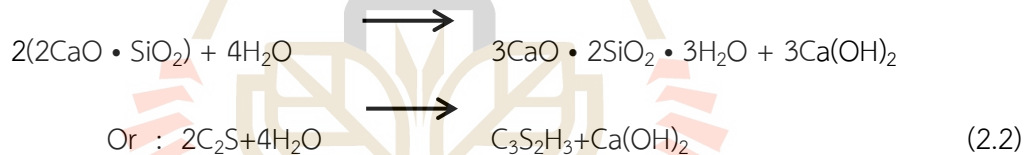
The four main cement minerals hydrate at different rates due to their distinct reactivities. Their behavior has been widely studied by hydrating each mineral in pure form under controlled conditions. Although, in actual cement hydration, all minerals dissolve into a common pore solution—meaning the resulting products cannot be linked to a single mineral—these individual studies still provide useful approximations for understanding overall hydration behavior.

2.3.1 Hydration of the calcium silicate minerals (C_3S and C_2S)

Tricalcium silicate (C_3S) is the primary and most influential mineral in Portland cement, contributing largely to its early-age strength. Its hydration reaction can be expressed as follows:



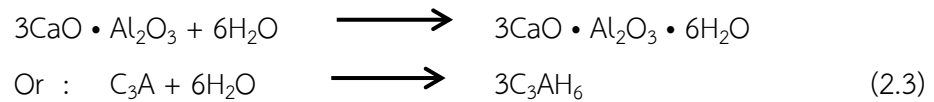
The dicalcium silicate phase (C_2S) reacts according to:



The hydration products of C_2S are similar to those of C_3S but generate less Ca(OH)_2 . Because C_2S is less soluble, it hydrates more slowly, contributing little to early strength but playing an important role in the long-term strength of hardened cement paste and concrete.

2.3.2 Hydration of the calcium aluminate/ferrite minerals (C_3A and C_4AF)

The hydration of aluminate and ferrite minerals is more complex than that of calcium silicates and is strongly affected by sulfate ions in the pore solution. C_3A is especially soluble—more so than C_3S —and when hydrated in pure water, it forms calcium aluminate hydrates through a characteristic reaction sequence:

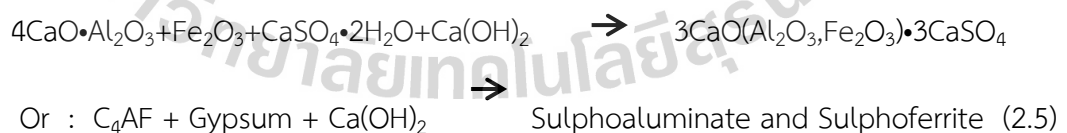


The resulting compound, C_3AH_6 , is commonly known as hydrogarnet. The initial hydration of C_3A is extremely fast, and without control it would release excessive heat and cause the paste to set within minutes—a phenomenon called flash set. To avoid this, gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) is added to cement. Because gypsum dissolves readily, it supplies calcium and sulfate ions to the pore solution, directing C_3A to follow an alternative, controlled hydration pathway. The reaction between C_3A and gypsum can be expressed as follows:



Where $3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{CaSO}_4 + 31\text{H}_2\text{O}$ is the mineral Ettringite.

The ferrite phase (C_4AF) hydrates in a manner similar to C_3A but at a slower rate. A key distinction is that some aluminum in the hydration products is replaced by iron, with the degree of substitution depending on the C_4AF composition and the conditions in the paste. Early hydration involves reactions with gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) and calcium hydroxide ($\text{Ca}(\text{OH})_2$), producing needle-like sulphotoaluminate and sulphotoferrite phases. These reactions can be represented as follows:



2.3.3 Influence of the Compound Composition on Properties of Cement

C_3S and C_2S are the primary contributors to strength development in Portland cement. C_3S governs early strength gain during the first four weeks, whereas C_2S contributes mainly beyond this period. After about one year, their contributions to ultimate strength become comparable. C_3A increases early strength within the first

three days but may lead to later strength reductions, particularly in cements high in C_3A or in total ($C_3A + C_4AF$). The role of C_4AF in strength development remains uncertain and is generally considered minimal. The compressive strength development of these compounds over time is shown in **Figure 2.2**.

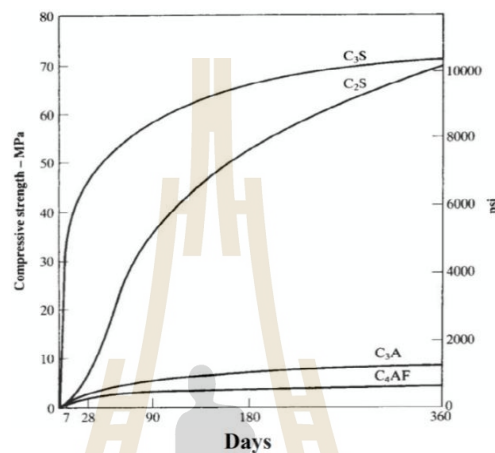


Figure 2.2 Contribution of Compressive strength of C_3S , C_2S , C_3A and C_4AF with time (Lerch, 2008)

2.3.4 Calcium-Silicate-Hydrate (C-S-H) gel

C-S-H gel is the dominant hydration product in cement paste, accounting for roughly 50% of its volume. Although not inherently strong, it forms a continuous binding phase that holds cement particles together (see Figure 2.3). Unlike other hydration products that appear as isolated crystals, C-S-H derives its binding capability from its nanoscale structure. Key characteristics of C-S-H include its internal pore system and its two primary morphologies, which are discussed in more detail in a later section.

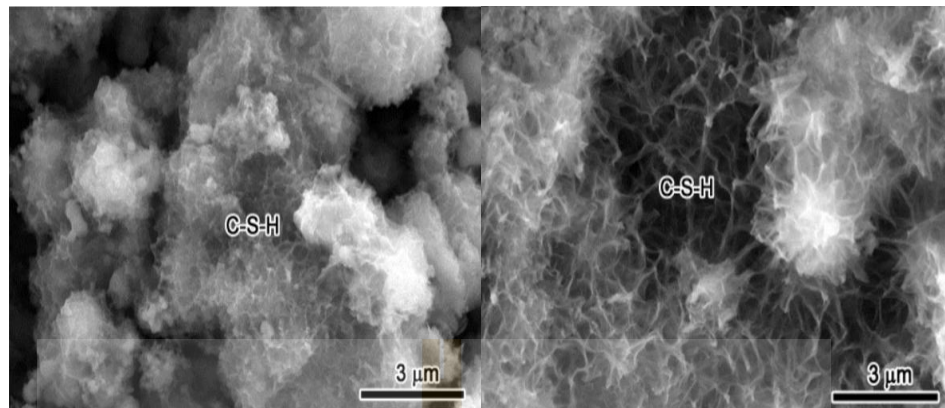


Figure 2.3 The SEM images of C-S-H structure (Li, 2015).

As C–S–H gel forms around cement grains, it creates a network of extremely fine gel pores that are much smaller than the original capillary pores. The water within these gel pores becomes physically trapped and does not participate in further hydration, resulting in variable water contents within the gel. Because C–S–H occupies more volume than the original C_3S and C_2S , its growth causes the layers to interconnect and form a continuous solid phase, leading to the setting and hardening of the paste. Since the overall paste volume changes little after mixing, this increase in solid volume reduces and disrupts the capillary pore network—particularly at low water-to-cement ratios. Consequently, the permeability of the cement paste decreases, improving its resistance to liquid water and ion penetration.

2.3.5 Calcium Hydroxide (CH)

Calcium hydroxide, or portlandite, is produced during the hydration of C_3S and C_2S and typically makes up about 15% of the volume of Portland cement paste. Its crystals vary in shape and size depending on the available space for growth. When formed in capillary pores, they often appear as irregular hexagonal plates several microns wide, which can be seen under an optical microscope. (refer to **Figure 2.4**).

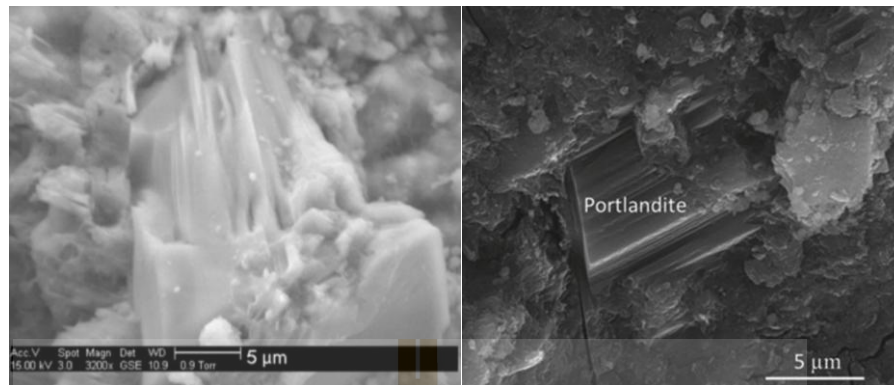


Figure 2.4 The SEM images of CH structure (Wang, 2008; Frias, 2015).

Besides forming larger plate-like crystals, calcium hydroxide (CH) can also appear as much smaller crystals that grow within and interact with low-density C–S–H. These fine CH crystals, often less than 1 μm, are restricted by the surrounding solid matrix. Studies also indicate the presence of nanometer-scale CH in cement paste, consistent with the nanoscale morphology of C–S–H formed alongside it. At this scale, distinguishing CH from C–S–H becomes difficult because C–S–H also contains many Ca–OH bonds.

2.3.6 Calcium trisulfoaluminate hydrate (Ettringite)

When cement first comes into contact with water, hydration begins quickly. Gypsum dissolves early, after which the remaining tricalcium aluminate (C_3A) reacts with the ettringite formed initially (**Figure 2.5a**) to produce calcium monosulfoaluminate ($3CaO \cdot Al_2O_3 \cdot CaSO_4 \cdot 12H_2O$), as shown in **Figure 2.5b**. Monosulfoaluminate occupies less volume than ettringite and remains stable unless additional sulfate becomes available. If extra sulfate enters the system, it can react with monosulfoaluminate to reform ettringite, causing expansion—this is the basis of sulfate attack in hardened concrete exposed to external sulfate sources.

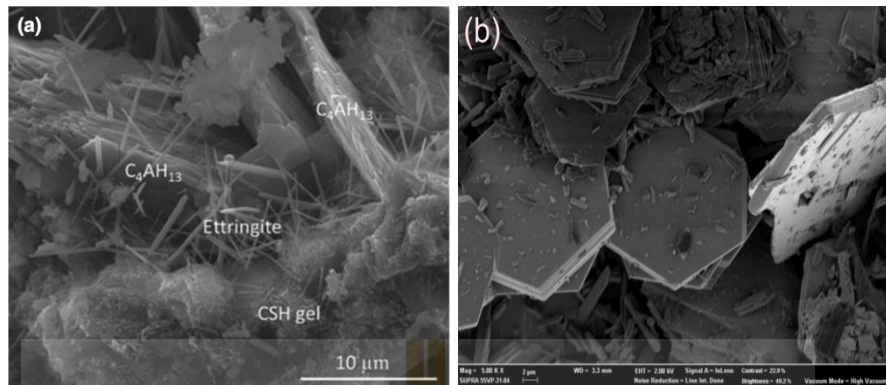


Figure 2.5 The SEM images of (a) Ettringite (Frias, 2015) (b) Monosulfate (Choi, 2012)

Locher et al. (1974) described the formation of hydration products and the development of cement paste structure after mixing. They identified three distinct stages that characterize the hydration process and the evolution of the paste structure, as illustrated in **Figure 2.6**.

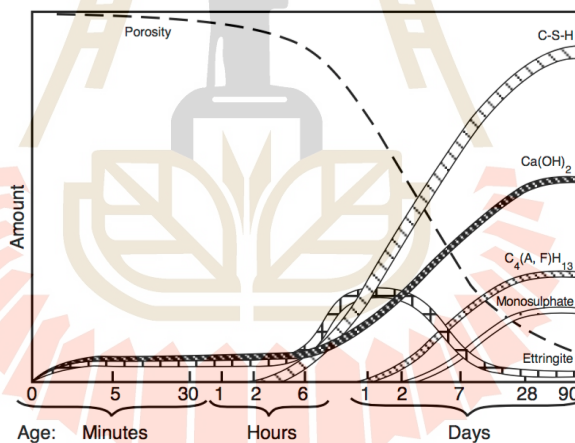


Figure 2.6 Formation of the of hydration products and the creation of cement paste structure (Locher, 1974)

2.4 General features

The hydration products in cement paste are not separate phases but are interwoven at micro- to nanoscale levels, except for high-density C–S–H that forms within the original cement grains. Thus, descriptions of cement paste microstructure focus on the distribution of solid phases and porosity rather than the structure of

individual hydrates. A useful and simplified representation divides the microstructure into three primary phases, as shown in **Figure 2.7**.

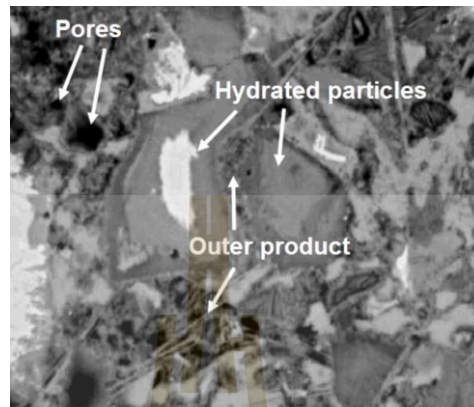


Figure 2.7 Backscattered SEM image of a mature cement paste showing the main microstructural features. (Image courtesy of Paul Stutzmann, Concrete Microscopy Library).

2.4.1 The interfacial transition zone (ITZ): In fresh concrete, the packing of cement particles near large solid inclusions, such as aggregates, is disrupted by the well-known “wall effect.” This disturbance is intensified during mixing, as aggregates impose shear forces that cause water to separate from the cement particles. As a result, a thin region forms around each aggregate with fewer cement particles and more water. This area is known as the interfacial transition zone (ITZ), as shown in **Figure 2.8**.

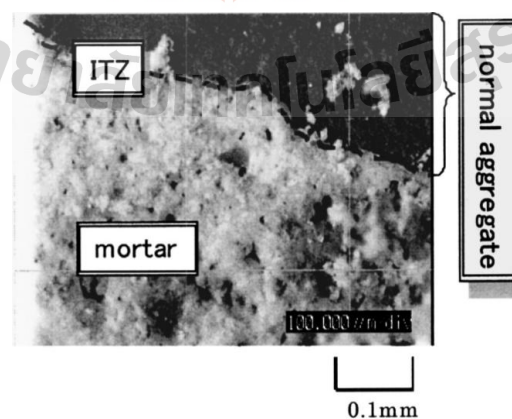


Figure 2.8 The ITZ between mortar and aggregate in concrete (Otsuki, 2003).

2.4.5 Effect of w/c Ratio

Kim et al. (2014) reported that adding more mixing water improves the workability of cement mortar but also increases porosity, leading to reduced durability and structural performance. Higher water content produces a coarser pore structure. As shown in Figure 2.13, increasing the w/c ratio from 0.45 to 0.60 raises porosity by up to 150% while lowering compressive strength to about 75.6%. Similar trends were noted by Albano et al. (2009), Ait-Aider et al. (2007), Ma et al. (2014), Alawode et al. (2011), Moghadam et al. (2012), and Singh et al. (2015). Although the cement content remains unchanged, adding 33% more water significantly alters paste performance, confirming that higher w/c ratios create larger, more connected pores. This increase in porosity directly reduces compressive strength, stiffness, elastic modulus, and durability, as shown in Figure 2.14.

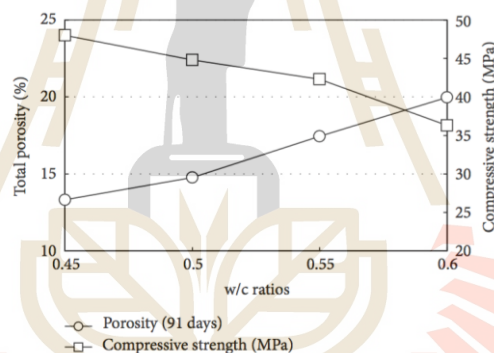


Figure 2.9 Strength and porosity with different w/c ratios (Kim, 2014)

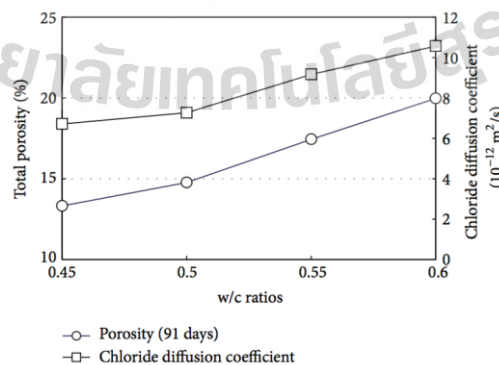


Figure 2.10 Chloride diffusion coefficient and porosity with different w/c ratios (Kim, 2014)

2.5 Recycled Concrete Aggregate (RCA)

Olorunsogo et al. (2002) evaluated the durability of concrete containing recycled aggregate (RA) using indicators such as chloride conductivity, oxygen permeability, and water sorptivity. Three mixtures with 0%, 50%, and 100% RA were tested at 3, 7, 28, and 56 days. The results showed that durability declined as the RA content increased but improved with longer curing, as illustrated in **Figure 2.11**. By 56 days, concrete with 100% RA displayed notably higher durability index values than the natural-aggregate mix—an 86.5% increase in chloride conductivity and a 28.8% increase in water sorptivity..

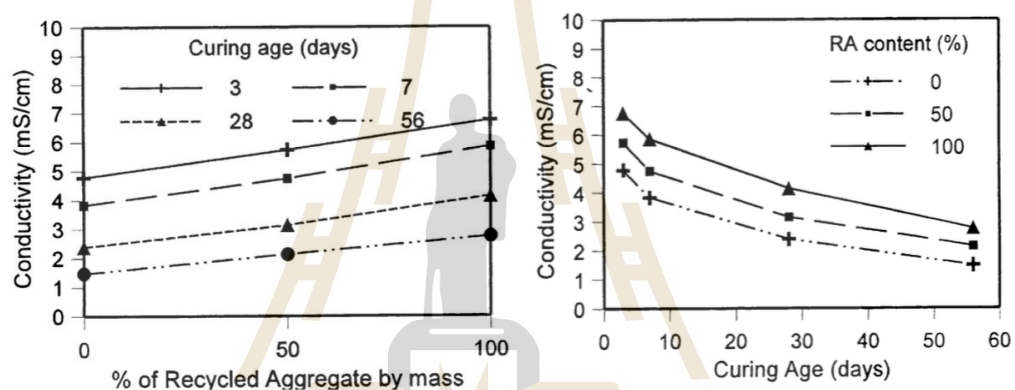


Figure 2.11 Chloride conductivity (Olorunsogo, 2002)

Behera et al. (2014) reported that recycled aggregate (RA) generally shows poor particle size distribution and inadequate grading, largely due to variations introduced by different crushing processes. RA typically contains a higher proportion of fine particles and retains an aged interfacial transition zone (ITZ) from the adhered mortar or cement paste. This ITZ is structurally weak, containing micro-pores, cracks, and fissures formed during crushing, as illustrated in **Figure 2.12**. RA also tends to have a rough, irregular surface and a partially rounded shape due to the attached mortar. Compared with natural aggregate, RA exhibits inferior mechanical properties, including lower crushing strength, reduced impact resistance, and poorer abrasion resistance.

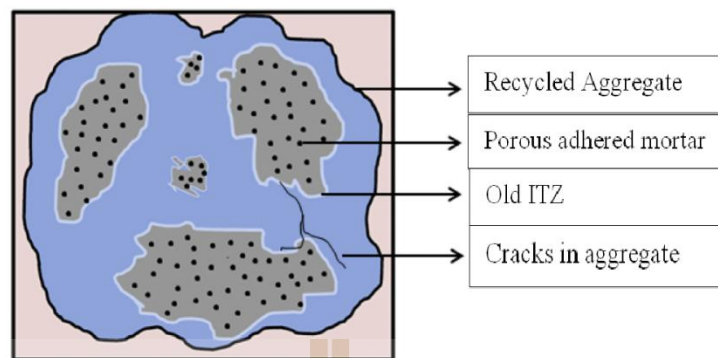


Figure 2.12 Pictorial representation of physical characteristics of recycled aggregate (Bahera, 2014)

Recycled aggregate concrete (RAC) consists of three key phases: the aggregate phase, the mortar phase, and the interfacial transition zones (ITZ)—both between the new matrix and the coarse aggregate and within the adhered mortar. **Figure 2.13a** and **b** schematically compare these phases in natural aggregate concrete and RAC, highlighting their fundamental differences. Because these phases strongly influence RAC behavior, its performance must be carefully considered when recycled aggregate is incorporated into concrete mixtures.

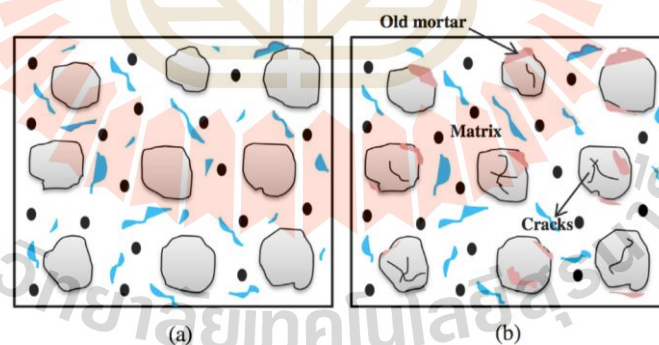


Figure 2.13 Difference between matrixes of (a) natural aggregate concrete and (b) recycle aggregate concrete (Bahera, 2014)

Thomas et al. (2013) investigated the microstructure of recycled aggregate concrete (RAC) using SEM. As shown in **Figure 2.14**, the new cement paste was found

to coat the recycled aggregates, which contain remnants of old paste and natural aggregate. The newly formed paste exhibited a denser and more tightly bonded structure than the original adhered mortar.

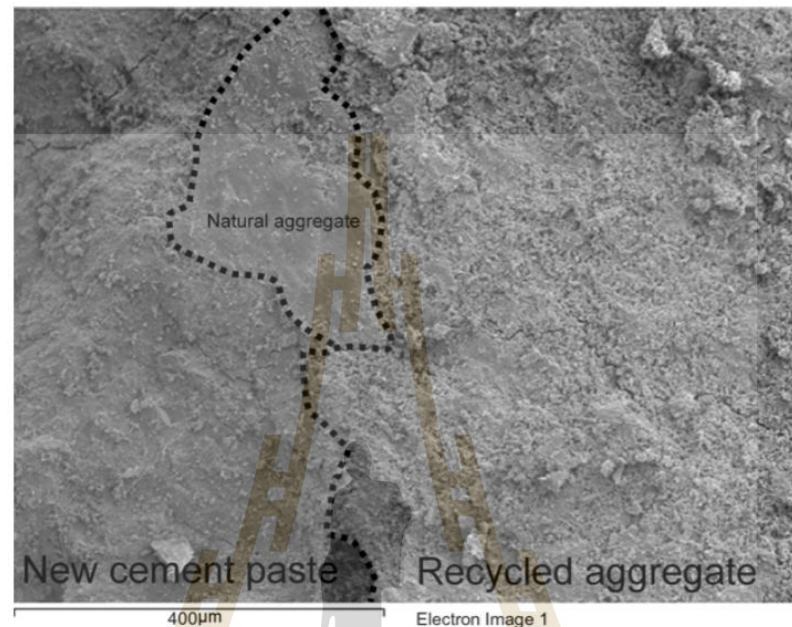


Figure 2.14 Micrograph of RAC structure (Thomas, 2013)

Lee et al. (2013) reported that recycled aggregate concrete (RAC) contains a larger extent of interfacial transition zones (ITZ) than conventional concrete. This is illustrated in **Figure 2.15**, which shows a sectional view emphasizing the ITZ characteristics in RAC.

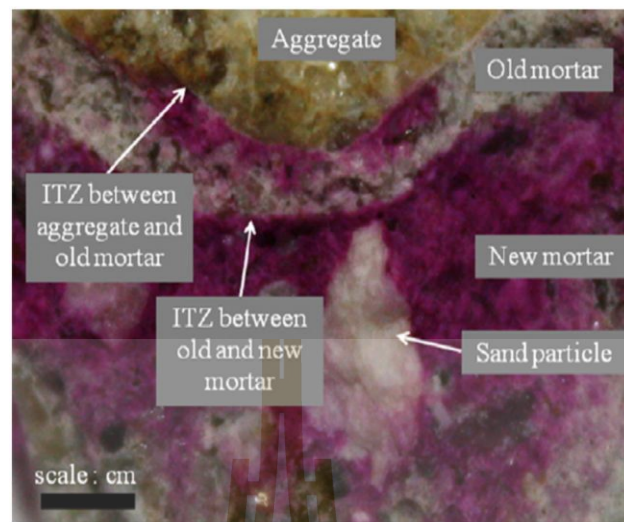


Figure 2.15 Classification of aggregate, old mortar and new mortar by discoloration of phenolphthalein solution (Lee, 2013)

Topcu and Sengel (2008) tested concrete with varying levels of recycled concrete aggregate (RCA), up to 100% replacement. They found that concrete density decreased as RCA content increased, though the change was less pronounced than the corresponding rise in water absorption. **Figure 2.16** summarizes findings from multiple studies, showing a consistent reduction in 28-day compressive strength with higher RA replacement levels.

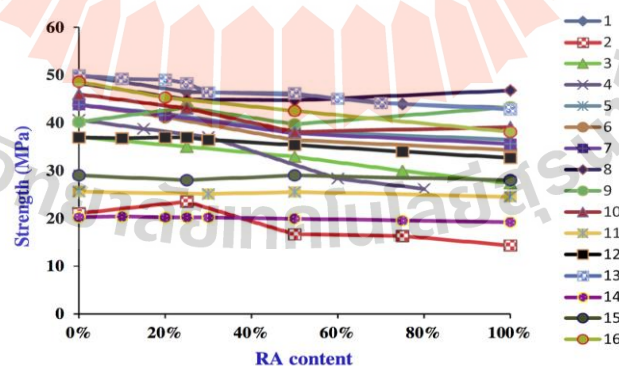


Figure 2.16 Variation in 28 days strength compressive strength w.r.t. RA replacement percentage by various researchers

Tam et al. (2004) introduced the two-stage mixing approach (TSMA) to improve the compressive strength and reduce the variability of recycled aggregate concrete (RAC). Experimental results showed significant strength gains using TSMA. The improvement is attributed to the porous nature of recycled aggregates, where the premixing step helps fill internal pores and cracks, producing a denser matrix and a better interfacial zone than conventional mixing. **Figure 2.17** illustrates the TSMA procedure, while SEM images in **Figures 2.18a** and **2.18b** show that cracks within recycled aggregates are effectively filled under TSMA but remain unfilled with normal mixing.

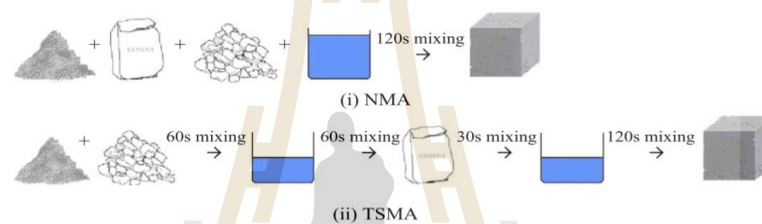


Figure 2.17 Mixing procedures of the (i) normal mixing approach and (ii) two-stage mixing approach (Tam, 2004)

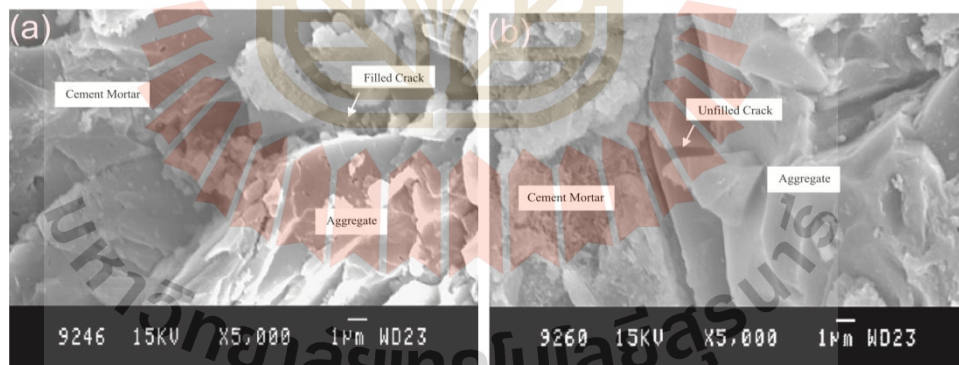


Figure 2.18 (a) Filled crack in RA using TSMA. (b) Unfilled crack in RA using NMA.

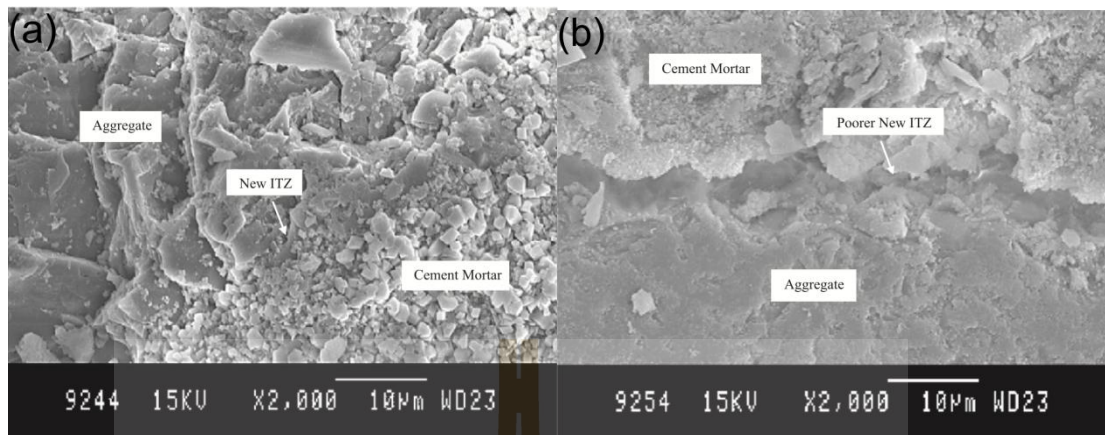


Figure 2.19 (a) New interfacial zone for TSMA. (b) Poorer new interfacial zone for NMA.

Recycled aggregate concrete (RAC) contains both old and new interfacial zones. When the two-stage mixing approach (TSMA) is used, a dense and well-formed new ITZ is observed, as shown in **Figure 2.19a**. In contrast, **Figure 2.19b** shows that normal mixing with natural aggregate (NMA) produces a comparatively weaker ITZ.

Somna et al. (2012) studied the effects of ground fly ash (GFA) and ground bagasse ash (GBA) on the durability of recycled aggregate concrete. In their work, crushed limestone was fully replaced with recycled aggregate, while GFA and GBA were used to substitute Portland cement Type I at 20%, 35%, and 50% of the binder weight. The results showed that both GFA and GBA significantly improved durability. The best performance—in terms of compressive strength, reduced water permeability, and high resistance to chloride penetration and sulfate attack—was achieved at a 20% replacement level. **Figure 2.20** presents the compressive strength of mixes containing GFA (F20, 35, 50) and GBA (B20, 35, 50), and **Figure 2.21** shows the corresponding chloride penetration depths.

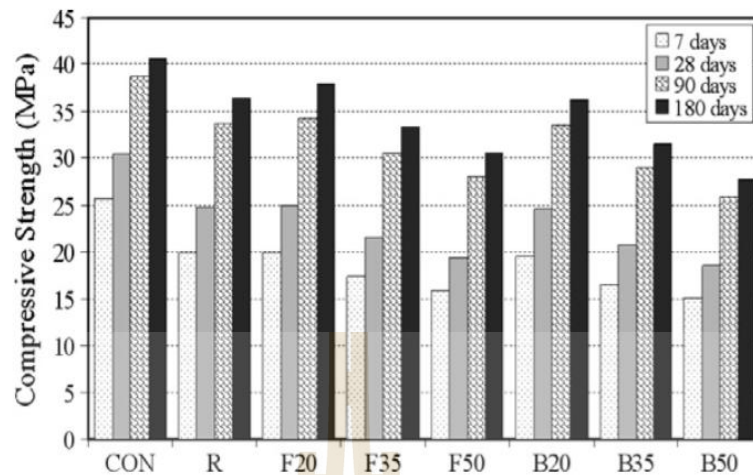


Figure 2.20 Compressive strength of concrete replacement by GFA and GBA

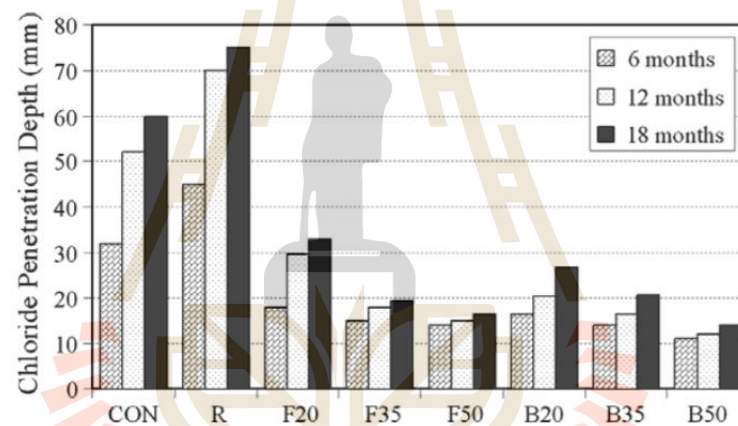


Figure 2.21 Chloride penetration depth of concrete immersed in 3% sodium chloride solution at 6, 12, and 18 months.

Tam et al. (2008) highlighted the improved performance of recycled aggregate (RA) concrete when using the Two-Stage Mixing Approach (TSMA) and a modified version incorporating silica fume and proportional cement content (TSMA_{sc}). In both methods, the premixing step helps fill weak areas within the RA, producing a stronger interfacial layer around the aggregate and increasing concrete strength. The study demonstrates that TSMA and TSMA_{sc} are effective alternatives for enhancing the quality of recycled aggregate, as shown in Figure 2.22.

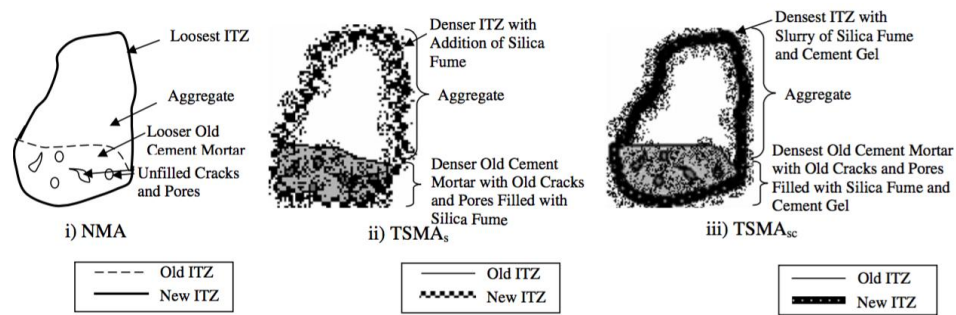


Figure 2.22 RA structure after adopting (i) NMA, (ii) TSMA_s and (iii) TSMA_{sc}.

2.6 Natural Rubber Latex (NRL) modified concrete.

Yaowarat et al. (2021) evaluated natural rubber latex (NRL) as a sustainable additive to improve the flexural performance of concrete pavements. The study examined the compressive and flexural strengths of NRL-modified concrete across different water-to-cement (w/c) ratios, dry rubber-to-cement (r/c) ratios, and curing periods. Results showed that compressive strength decreased as the r/c ratio increased for all w/c ratios and curing ages (Figure 2.23). In contrast, optimal r/c ratios of 0.58%, 1.16%, and 1.73% for w/c values of 0.3, 0.4, and 0.5, respectively, produced the highest flexural strengths (Figure 2.24). Concrete mixtures with $w/c \leq 0.4$ and $r/c \leq 2.31$, as well as those with $w/c = 0.5$ and r/c between 0.58 and 1.73, met the compressive and flexural strength requirements of the Department of Highways, Thailand, indicating their suitability for pavement applications.

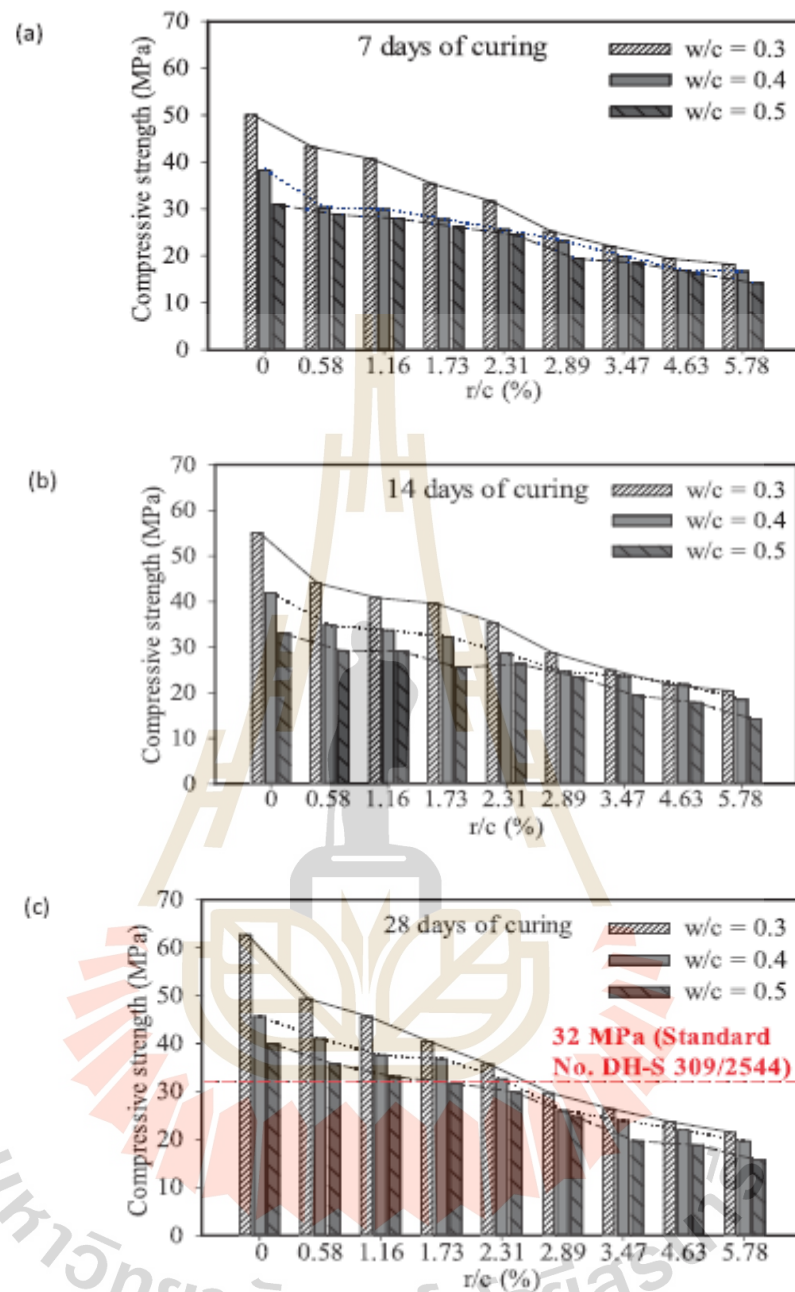


Figure 2.23 Compressive strength of NRL-concrete at (a) 7 days; (b) 14 days; (c) 28 days (Yaowarat et al., 2021)

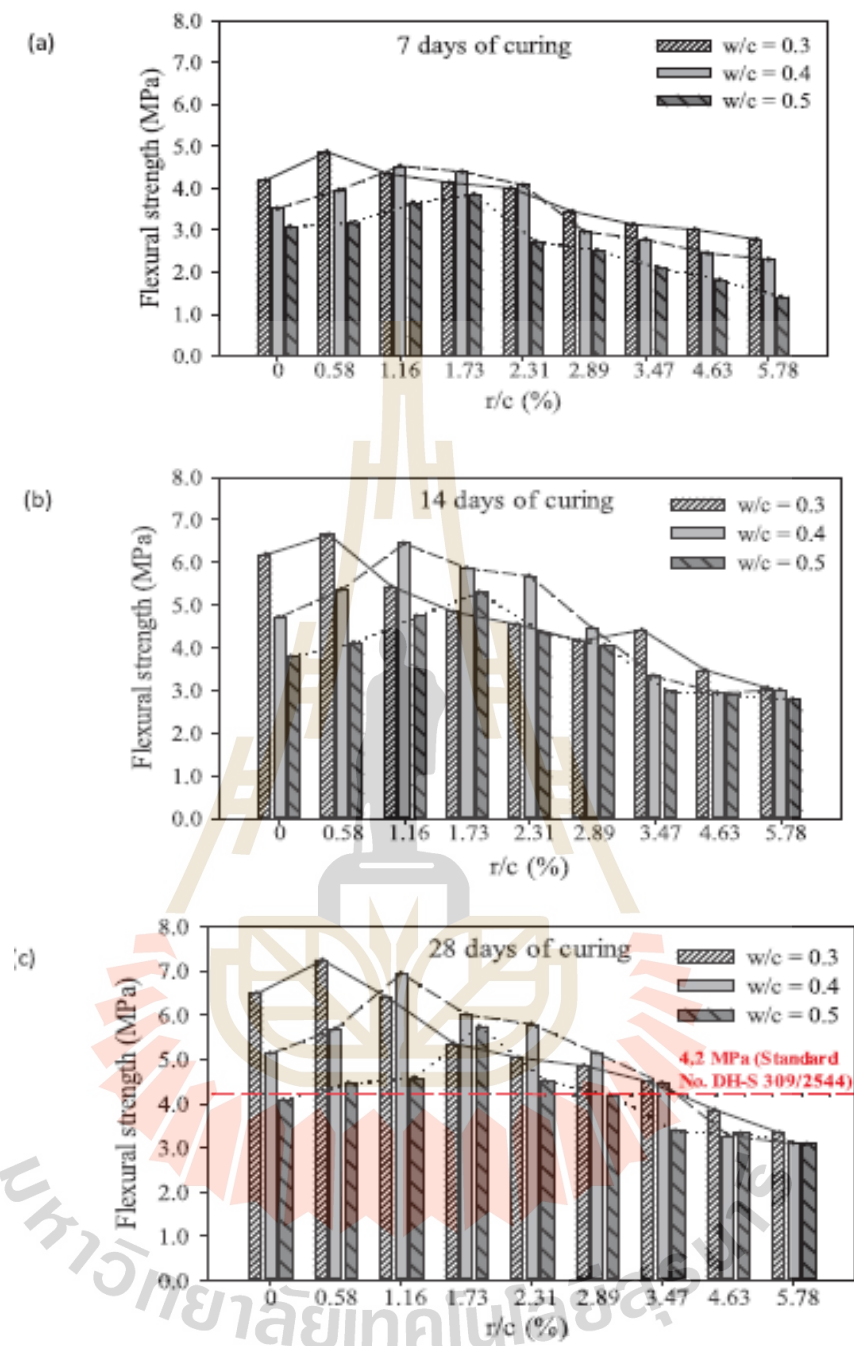


Figure 2.24 Flexural strength of NRL-concrete at (a) 7 days; (b) 14 days; (c) 28 days (Yaowarat et al., 2021)

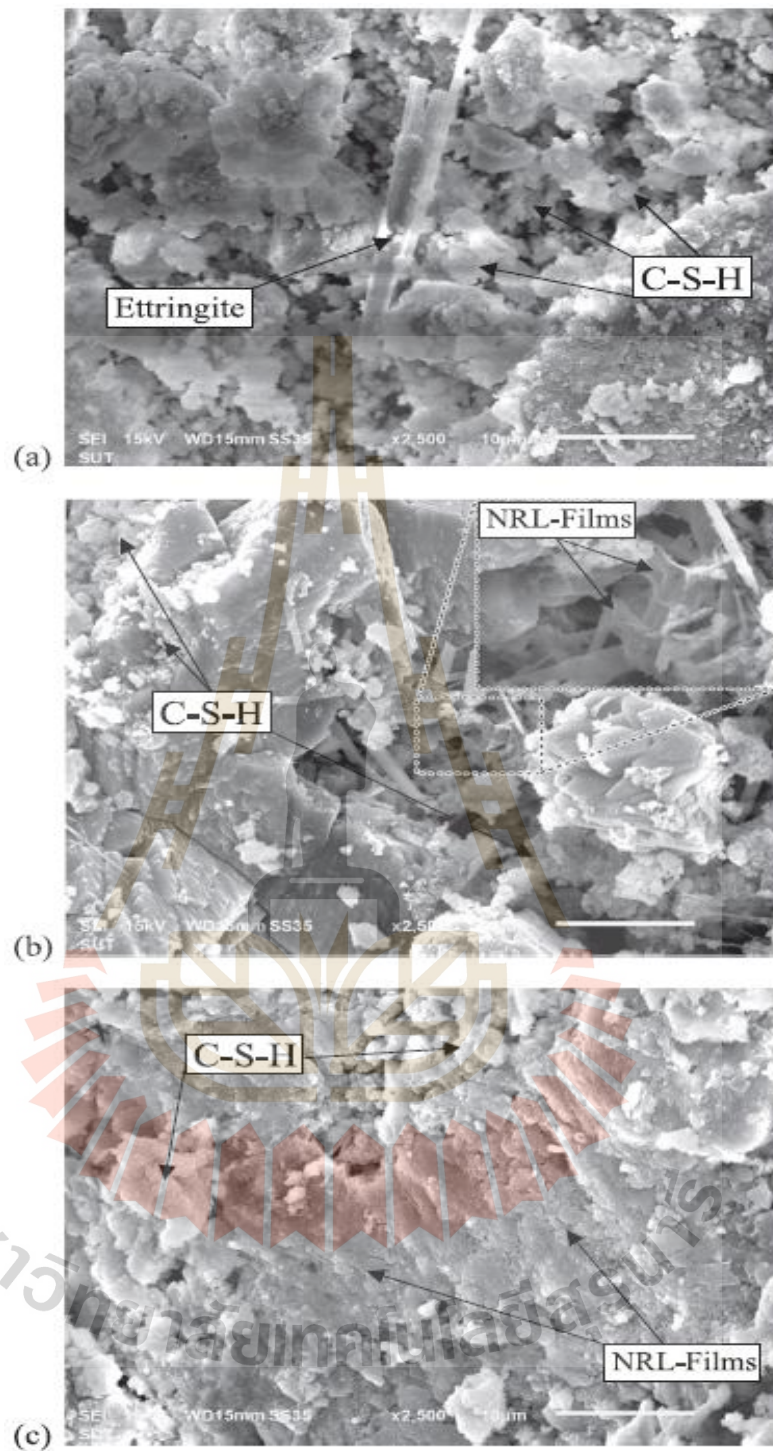
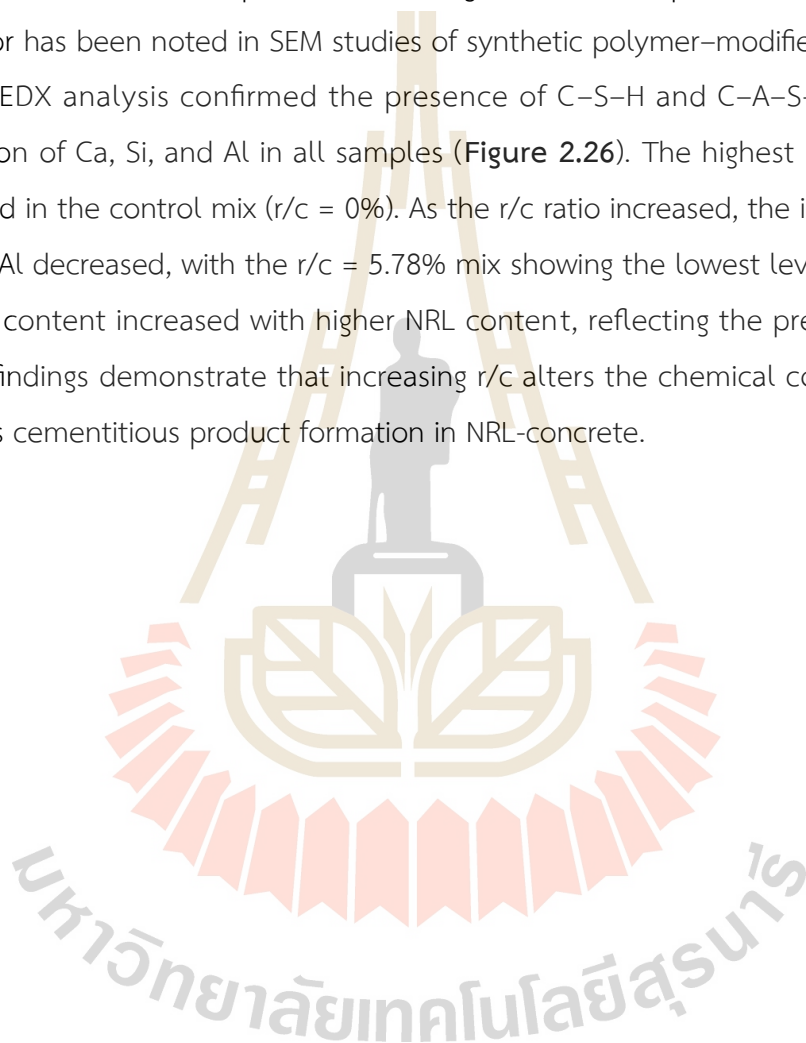


Figure 2.25 SEM images of NRL-concrete for $w/c = 0.4$ at (a) $r/c = 0$; (b) $r/c = 1.16$ (optimal); (c) $r/c = 5.78$. (Yaowarat et al., 2021)

SEM images showed clear C–S–H gel formation in the normal concrete mix without NRL (**Figure 2.25a**). In NRL-modified specimens, NRL films infiltrated the pore structure (**Figure 2.25b**). At the optimal r/c ratio of 1.16%, thin films were visible within the matrix, while at a higher r/c ratio of 5.78%, thicker films surrounded the C–S–H products (**Figure 2.25c**). These thicker films impeded hydration and reduced the amount of cementitious products, leading to lower compressive strength. Similar behavior has been noted in SEM studies of synthetic polymer-modified concrete.

EDX analysis confirmed the presence of C–S–H and C–A–S–H through the detection of Ca, Si, and Al in all samples (**Figure 2.26**). The highest peak intensities occurred in the control mix (r/c = 0%). As the r/c ratio increased, the intensities of Ca, Si, and Al decreased, with the r/c = 5.78% mix showing the lowest levels. Conversely, carbon content increased with higher NRL content, reflecting the presence of latex. These findings demonstrate that increasing r/c alters the chemical composition and reduces cementitious product formation in NRL-concrete.



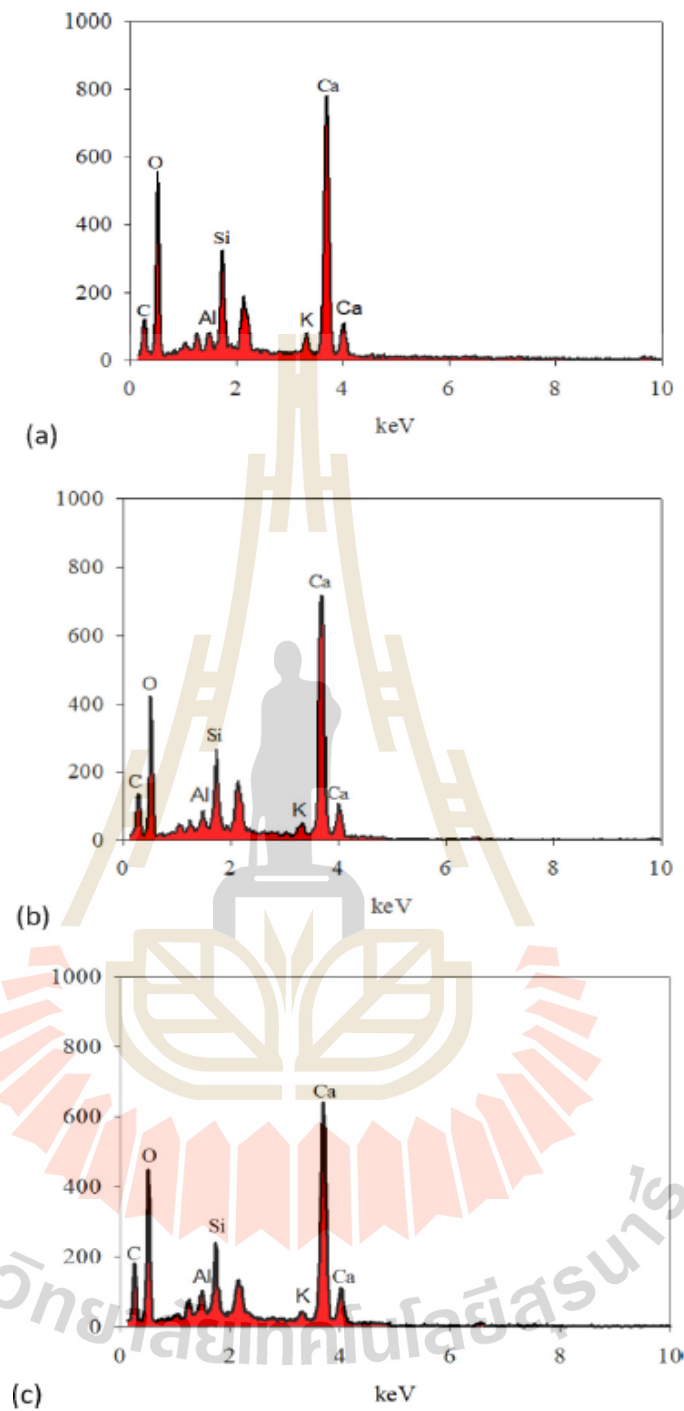


Figure 2.26 EDX results of NRL-concrete for $w/c = 0.4$ at (a) $r/c = 0$; (b) $r/c = 1.16$ (optimal); (c) $r/c = 5.78$.

Suddeepong et al. (2022) conducted a study to investigate the use of natural rubber latex (NRL) as a means to enhance the mechanical strength and flexural

fatigue resistance of conventional concrete. The study examined the influence of various factors, including the water-to-cement (w/c) ratio and dry rubber-to-cement (r/c) ratio, on the compressive strength, flexural strength, and flexural fatigue behavior of the modified concrete. The results of the study indicate that an increase in the dry rubber-to-cement (r/c) ratio leads to a larger area under the flexural stress-deformation curve, indicating an improvement in flexural toughness. **Figure 2.27** depicts the flexural toughness of NRL-concrete at different water-to-cement (w/c) ratios of 0.3, 0.4, and 0.5, with varying r/c ratios. It is observed that, at the same w/c ratio, the flexural toughness increases with an increasing r/c ratio, reaching its highest value at the optimal r/c ratio for each w/c ratio. However, beyond the optimal r/c ratio, the flexural toughness decreases as the r/c ratio continues to increase..

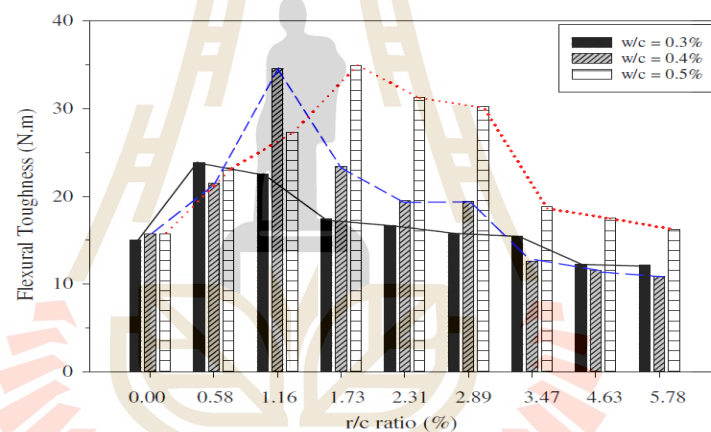


Figure 2.27 Flexural toughness of NRL concrete at different w/c and r/c ratios (Suddeepong et al., 2022)

NRL-concretes with r/c ratios at or below the optimum showed higher fatigue life (N_f) than normal concrete at the same w/c ratio. They also resisted total and plastic deformation more effectively under equivalent stress levels (**Figure 2.28**), exhibiting roughly 45% less plastic deformation than normal concrete.

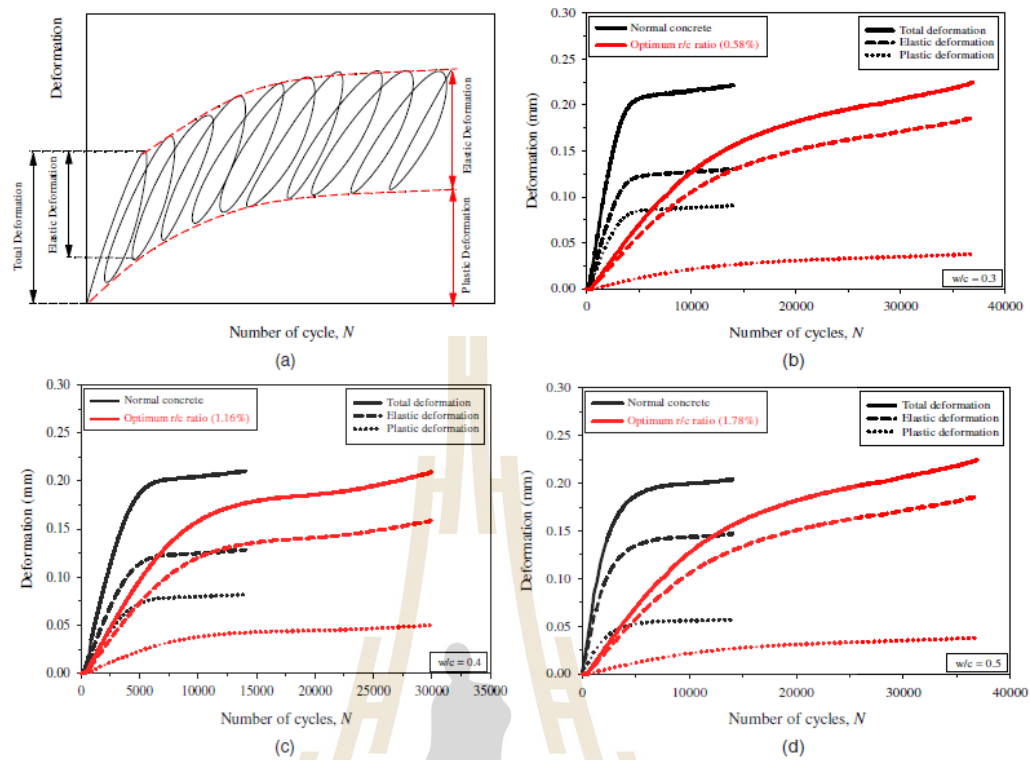


Figure 2.28 Comparison of total, elastic and plastic deformations behavior under repetitive flexural stress of NRL concrete for different r/c ratios at w/c ratio of (a) schematic plot; (b) 0.3%; (c) 0.4%; and (d) 0.5% (Suddepong et al., 2022)

The study also proposed a stress ratio hypothesis for NRL-concretes, stating that fatigue life remains unchanged as long as the stress ratio (SR) is the same, regardless of differences in w/c ratio, r/c ratio, or pavement thickness. This implies that, for a given target service life, rigid pavements using NRL-modified concrete with r/c values below the optimum can be designed with reduced thickness compared to pavements made with normal concrete (Figure 2.29).

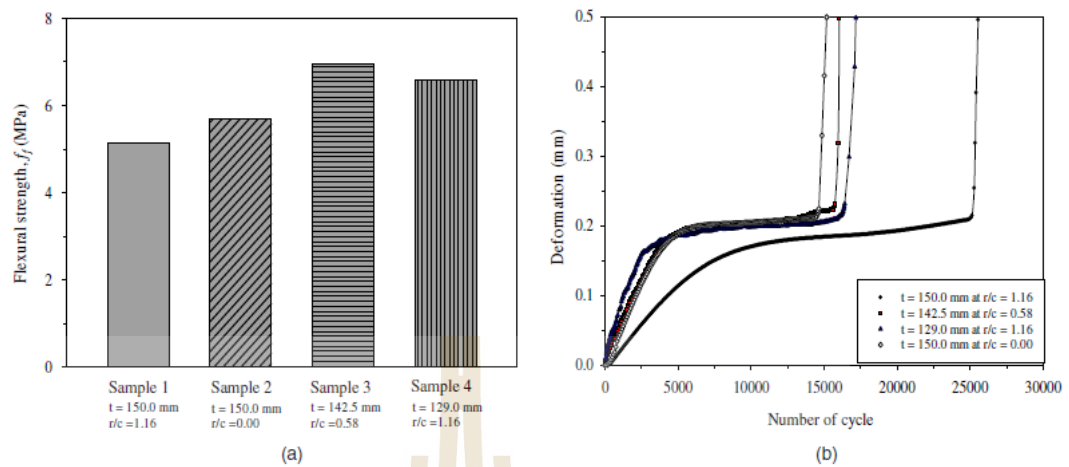


Figure 2.29 (a) Influences of flexural strength on reduction in thickness of normal and NRL concretes; and (b) relationship between deformation and number of cycles at same stress ratio for different thickness and r/c ratios (Suddeepong et al., 2022)

Figure 2.30 shows the relationship between stress ratio (SR) and fatigue life (Nf) for NRL-concretes at different w/c and r/c ratios, compared with the PCA (1984) fatigue model. The NRL-concrete data scatter around the model curve, indicating that SR is a key factor governing fatigue life. The results also show that the PCA fatigue equation can be applied to both normal and NRL-modified concrete pavements.

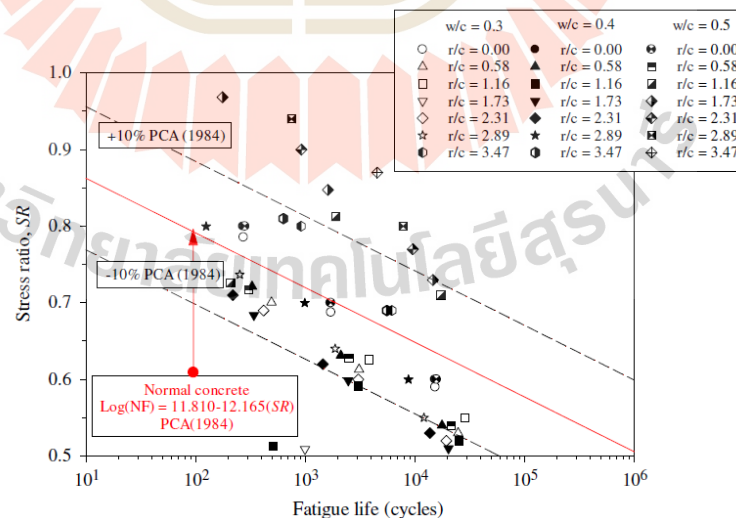


Figure 2.30 Relationship between stress ratio and fatigue life of normal and NRL-concretes at different w/c and r/c ratios (Suddeepong et al., 2022)

Muhammad and Ismail (2012) examined the microstructure of several concrete mixes—normal mix (NM), modified mixes (MM-10% and MM-20%), and latex film. The NM showed noticeable voids and gaps at the interface between cement oxides and aggregate particles, reflecting the typical porosity of conventional concrete (Figure 2.31a). In contrast, the modified mixes were more compact, with compaction increasing as latex content increased. MM-10% displayed a denser texture than NM (Figure 2.31b), while MM-20% effectively filled voids and coated the surfaces of cement oxides and aggregates, producing a structure with minimal inter-particle gaps (Figure 2.31c).

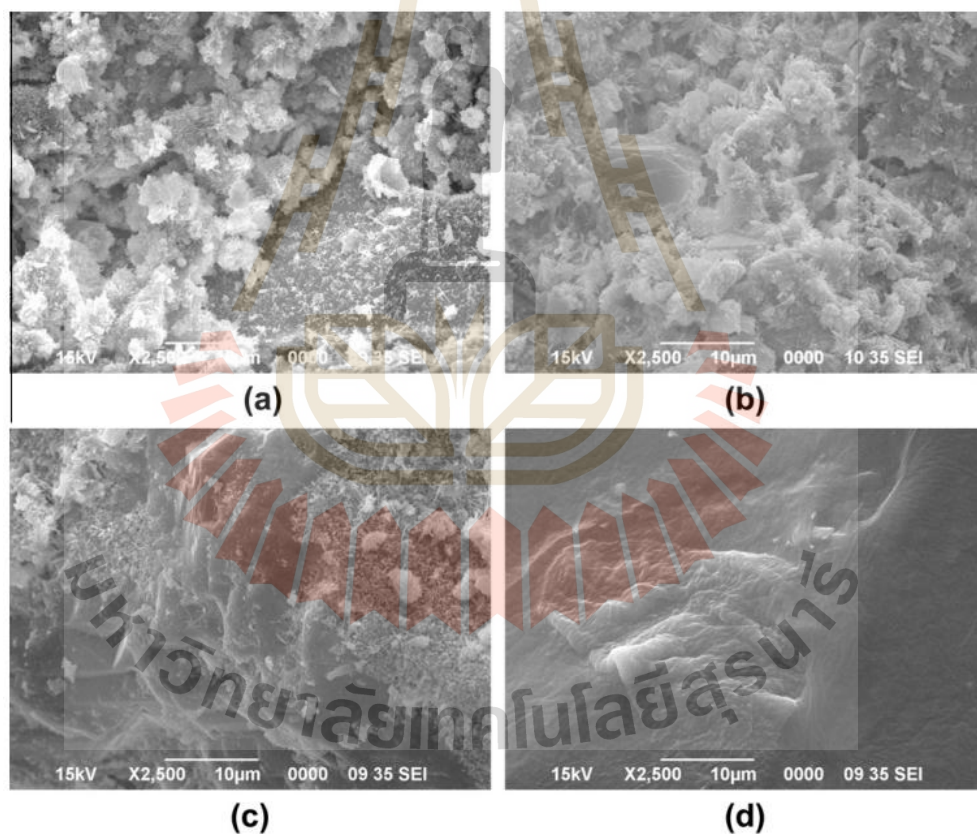


Figure 2.31 Morphologies; (a) normal cement-sand matrix, (b) cement-sand with 10% latex, (c) cement-sand with 20% latex and (d) latex-film (Muhammad and Ismail, 2012)

The latex film itself exhibited a fine, grain-textured membrane (**Figure 2.31d**). In its liquid form, natural rubber latex (NRL) contains dispersed poly-1,4-isoprene particles, but as the water phase drains, the particles draw closer and eventually coalesce into a continuous film. When NRL is added to concrete in small amounts, however, full film formation is less likely; instead, clusters of isoprene particles may accumulate within capillary pores and voids.

2.7 Fly Ash (FA) modified concrete.

Fly ash (FA) is a finely divided residue generated from the combustion of pulverized coal in thermal power plants and has been widely utilized as a supplementary cementitious material in concrete. Its incorporation into concrete has attracted significant attention due to both its technical benefits and its contribution to sustainable construction. FA typically consists of spherical particles rich in amorphous silica and alumina, which can react with calcium hydroxide produced during cement hydration to form additional calcium silicate hydrate (C-S-H) gel through pozzolanic reactions. This secondary C-S-H formation plays a crucial role in refining pore structure, enhancing microstructural densification, and improving long-term performance of concrete.

From a fresh-state perspective, FA generally improves workability due to its spherical particle shape and ball-bearing effect, which reduces internal friction among solid particles. This characteristic is particularly beneficial in mixtures containing recycled concrete aggregate (RCA), which typically exhibits rough surface texture and high water absorption. The improved workability provided by FA can reduce water demand, thereby helping to control the water-to-binder ratio and mitigate the adverse effects associated with RCA incorporation.

In terms of mechanical properties, FA-modified concrete often exhibits lower early-age strength compared to conventional Portland cement concrete due to the slower kinetics of pozzolanic reactions. However, at later ages, the continued reaction between FA and calcium hydroxide leads to progressive strength gain, which can equal or exceed that of control mixtures. This long-term strength development is particularly advantageous for rigid pavement applications, where durability and

sustained load-carrying capacity are more critical than early-age strength alone. Moreover, the refined microstructure resulting from FA incorporation enhances the interfacial transition zone (ITZ) between aggregates and cement paste, contributing to improved mechanical performance.

Durability enhancement is another major benefit of FA-modified concrete. The reduction in calcium hydroxide content and pore connectivity leads to lower permeability, which improves resistance to chloride ingress, sulfate attack, and alkali-silica reaction. These durability improvements are essential for pavement concrete exposed to aggressive environmental conditions, repeated traffic loading, and moisture fluctuations. In RCA-based concrete, FA further contributes to mitigating the negative effects of residual mortar by densifying the cementitious matrix and improving ITZ quality.

From an environmental standpoint, FA plays a pivotal role in reducing the carbon footprint of concrete. Cement production is the dominant source of CO₂ emissions in concrete, and partial replacement of cement with FA directly lowers embodied carbon. In addition, FA utilization promotes waste valorization by diverting industrial by-products from landfills and reducing the demand for energy-intensive clinker production. When evaluated through life-cycle-oriented indicators, FA-modified concrete consistently demonstrates lower CO₂-equivalent emissions compared to conventional concrete mixtures.

Economic considerations further support the adoption of FA-modified concrete. FA is generally less expensive than Portland cement, and its use can reduce overall material cost while maintaining or enhancing long-term performance. In pavement applications, improved durability and fatigue resistance associated with FA incorporation may also contribute to extended service life and reduced maintenance frequency, resulting in lower life-cycle costs.

Despite these advantages, the performance of FA-modified concrete is highly dependent on replacement level, curing conditions, and interaction with other mix constituents. Excessive FA replacement may lead to insufficient early-age strength, particularly when combined with other materials that retard hydration. Therefore, careful optimization of FA content is essential, especially in multi-component systems

incorporating recycled aggregates and polymer modifiers. When properly designed, FA-modified concrete represents a key component in the development of low-carbon, durable, and cost-effective rigid pavement materials aligned with sustainable infrastructure goals.

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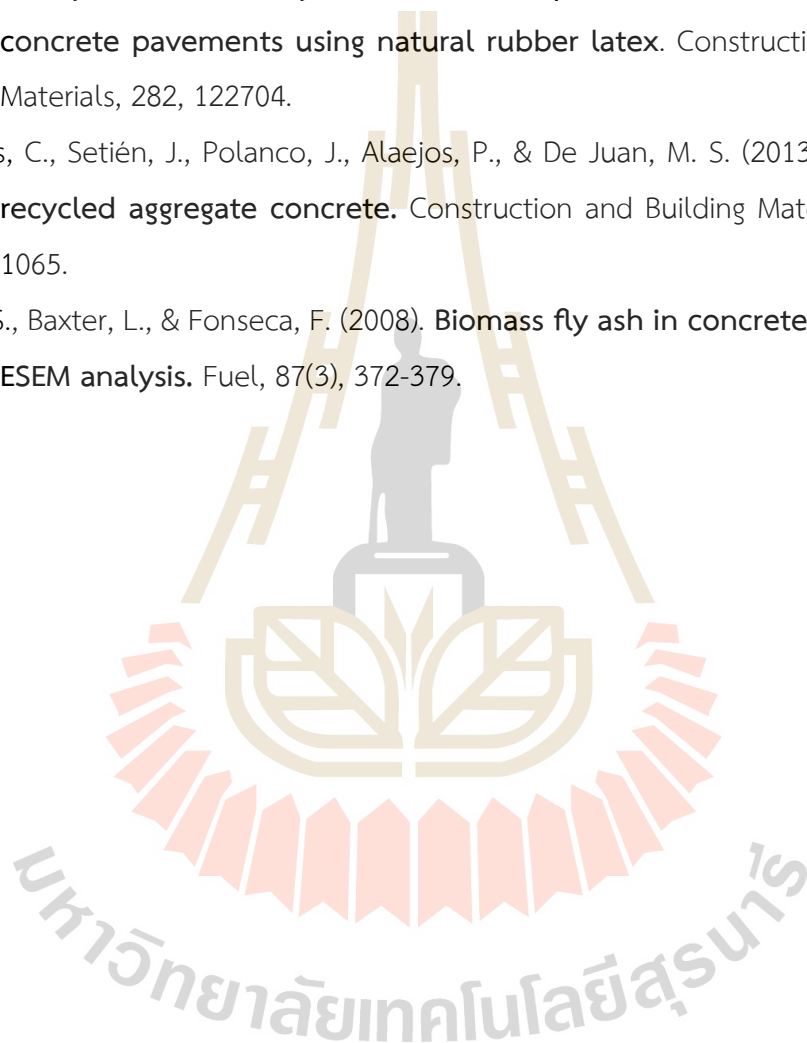
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CHAPTER III

ENHANCING THE FLEXURAL STRENGTH OF CONCRETE PAVEMENTS WITH RECYCLED AGGREGATE USING NATURAL RUBBER LATEX ADDITIVE

3.1 Introduction

The integration of waste materials as substitutes for natural resource-based materials in the construction industry has garnered considerable attention and widespread recognition, underscoring a firm commitment to waste recycling and the subsequent reduction of environmental impact. Consequently, the development of advanced techniques and management methodologies, aimed at establishing comprehensive guidelines, serves as a catalyst for achieving sustainable economic and social progress. Presently, there is a notable prevalence in the utilization of aggregate derived from construction and demolition waste (CDW) in concrete production, with particular emphasis on the substantial proportion of concrete scrap. The proportion of CDW-derived aggregate in CDW-based concrete typically ranges from 70-80% of the total volume, making the quality of the aggregate a critical factor in determining the mechanical strength of the concrete.(Omary et al. 2016).

The aggregate derived from CDW is transformed into recycled concrete coarse aggregate (RCA) to replace the conventional natural stone coarse aggregate (NA) in concrete mixtures. This practice effectively reduces the accumulation of concrete waste in landfills (Omary et al. 2016). A comprehensive investigation conducted by Silva et al. (2014) explored the factors influencing the physical, chemical, and mechanical properties, permeability, and composition of recycled aggregate. However, research on RCA has revealed limitations in terms of low compressive strength, high absorption value, and low elastic modulus. The compressive strength of RCA concrete is primarily influenced by the abrasion resistance of the recycled concrete coarse aggregate, as determined by the Los Angeles test. Additionally, the tensile strength is

influenced by the porosity of the original concrete adhering to the recycled coarse aggregate (Omary et al. 2016).

Numerous previous studies have substantiated the practicality and effectiveness of incorporating RCA as a viable substrate in pavement applications (Arulrajah et al. 2015). Additionally, the research conducted by Dilbas et al. (2014) suggested that a suitable ratio for the inclusion of RCA in concrete mixtures is approximately 30% of the aggregate content. These findings, derived from past investigations, have shed light on various properties of RCA, showcasing its potential as a reliable alternative to natural aggregate (NA). Importantly, RCA has demonstrated the ability to produce concrete that exhibits the desired properties typically associated with conventional structural concrete (Behera et al. 2014). Such insights emphasize the valuable role of RCA in contributing to sustainable construction practices and reducing the environmental impact of the construction industry.

Tam et al. (2005) have proposed the two-stage mixing approach (TSMA), representing a groundbreaking approach aimed at improving the compressive strength of RCA-based concrete. Additionally, the studies conducted by Jansen et al. (2012) and Plank et al. (2015) have delved into the effects of various superplasticizer types on the permeability of chemicals within concrete. These research endeavors contribute significant insights to the field, offering valuable knowledge on enhancing the mechanical properties and durability of RCA-based concrete. The innovative two-step TSMA mixing method demonstrates considerable potential for optimizing compressive strength, while the investigations on superplasticizer types shed light on the crucial role of chemical permeability in augmenting the long-term performance and resilience of RCA concrete structures. These findings hold substantial importance for the sustainable advancement and practical implementation of RCA in construction applications.

In the context of conventional concrete pavement design, the evaluation of flexural strength assumes utmost significance as it facilitates the determination of the minimum pavement thickness necessary to endure deflection resulting from bending (Yaowarat et al. 2021). However, the current body of research on the flexural strength of concrete incorporating RCA remains constrained, primarily owing to the inherent

variability inherent in its physical properties. Notably, RCA-based concrete exhibits inferior flexural strength and elastic modulus in comparison to natural stone aggregate (Etxeberria et al. 2007).

The flexural strength of concrete can be improved by incorporating various reinforcing materials and additives. For instance, the inclusion of polypropylene fibers in RCA-based concrete has been identified as an effective approach to enhance flexural strength (Ye et al. 2022). Additionally, research has demonstrated that the incorporation of cement mortar modified with a soluble polymer type, specifically utilizing polyvinyl alcohol (PVA) that dissolves at a 1% concentration in water, leads to improved flexural strength (Knapen and Van Gemert 2015). PVA has also been successfully utilized as an additive in RCA concrete, contributing to the development of sustainable pavement solutions aimed at enhancing flexural strength (Yaowarat et al. 2018; Yaowarat et al. 2019). Furthermore, the application of natural rubber latex (NRL), a natural polymer, as an additive in cement pastes, has shown promising results in increasing flexural strength (Sukmak et al. 2020). This aligns with previous findings indicating that NRL concrete improves the flexural strength of concrete pavement (Yaowarat et al. 2021).

A thorough review of existing literature reveals a dearth of research studies exploring the application of natural rubber latex (NRL) for enhancing the flexural properties of RCA concrete. Thus, the current study was specifically conducted with the primary objective of investigating and addressing this research gap by focusing on improving the flexural properties of RCA concrete through the utilization of NRL. RCA-based concrete samples were prepared meticulously, adhering to the TSMA mixing method, to assess the impact of water-to-cement ratio (w/c) and dry rubber content-to-cement ratio (r/c) on strength. The impact of incorporating natural rubber latex (NRL) on the compressive and flexural strength of RCA-NRL concrete was comprehensively elucidated using advanced techniques, including scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS), to elucidate the mechanical strength development of RCA concrete. The study presented compelling evidence of a noteworthy and substantial improvement in strength resulting from the inclusion of NRL, with meticulous documentation of the findings. Additionally, the

compressive and flexural strength of RCA-NRL concrete samples underwent evaluation in strict adherence to the established standards set forth by the Department of Highways of Thailand.

The present study addresses a notable research gap in the existing literature by investigating the potential application of natural rubber latex (NRL) to enhance the flexural properties of RCA concrete. Extensive research efforts were dedicated to the specific objective of improving the flexural properties of RCA concrete through the incorporation of NRL. The preparation of RCA-based concrete samples was conducted, employing the TSMA. The impact of NRL in term of dry rubber content-to-cement ratio (r/c) and water-to-cement ratio (w/c) on the compressive and flexural strength of RCA-NRL concrete was comprehensively analyzed using sophisticated analytical techniques, including scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS), facilitating an in-depth understanding of the mechanical strength development within RCA concrete. Moreover, the compressive and flexural strength of RCA-NRL concrete samples underwent rigorous evaluation, ensuring compliance with the established standards mandated by the Department of Highways of Thailand.

3.2 Material and Methods

3.2.1 Materials

Table 3.1 Chemical composition of ordinary Portland cement (OPC).

Component OPC	(%)
Silicon dioxide (SiO_2)	20.9
Aluminium oxide (Al_2O_3)	4.7
Iron oxide (Fe_2O_3)	3.4
Calcium oxide (CaO)	65.4
Magnesium oxide (MgO)	1.2
Sulfur trioxide (SO_3)	2.7
Loss on ignition (LOI)	0.9

In this study, Ordinary Portland Cement (OPC) was utilized for producing the RCA concrete specimens. The OPC had a specific gravity of 3.15. The chemical compositions of the OPC employed are detailed in **Table 3.1**.

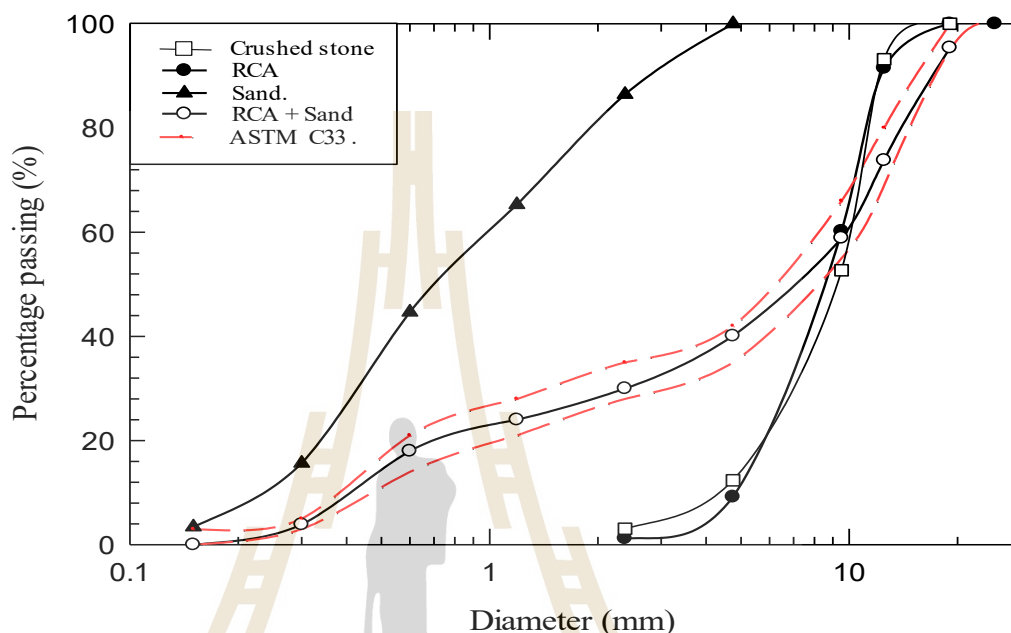


Figure 3.1 Particle size distributions of sand, Crushed Limestone, RCA and RCA + sand.

The fine aggregate utilized was natural river sand, characterized by a specific gravity of 2.65 under saturated surface dry (SSD) conditions. The sand exhibited a fineness modulus of 2.46, a void percentage of 43.6, and a water absorption rate of 1.10%. The coarse aggregate employed was recycled concrete aggregate (RCA) with a size range of 4.75-19 mm. The RCA possessed a fineness modulus of 6.3 and a specific gravity of 2.67. It displayed a water absorption rate of 5.5%, a voids percentage of 54%, and an abrasion resistance value of 34% based on the Los Angeles abrasion test. The characteristics of the coarse RCA and river sand are graphically represented in **Figure 3.1**

Natural rubber latex (NRL) is employed as an admixture to enhance the flexural properties of RCA concrete. The NRL utilized in this study was obtained from the Rubber Authority of Thailand, ensuring improved properties and production

standards. The chemical composition of the natural rubber latex (NRL) utilized is presented in **Table 3.2**.

Table 3.2 Chemical Analysis of Natural Rubber Latex.

Property	Value
Total solid content (TSC)	55.11%
Dry rubber content (DRC)	52.04%
Non rubber contents (NRC)	3.07%
Volatile fatty acid (VFA)	0.07%
Alkalinity (NH ₃)	0.69%
pH	10.42%
Mechanical stability time (MST)	7440 s

A Mid-Range water reducing concrete admixture, specifically Sika® Plastocrete®-907, is incorporated to regulate the workability of the concrete and mitigate the issue of low slump value. The selection of Sika® Plastocrete®-907 aligns with ASTM C494 Type D & G specifications.

3.2.2 Samples preparation

The RCA-NRL concrete samples were designed with varying w/c ratios of 0.3, 0.4, and 0.5. The dry rubber content (DRC) to cement ratio (r/c) was adjusted accordingly based on the specified w/c value. The mixing ratio of r/c increased incrementally from 0, 0.5, 1.0, 1.5, to 2%. According to **Table 3.3**, NRL had a chemical composition where approximately 52% of its content consisted of dry rubber content, and the remaining 48% was water. Consequently, to maintain the specified w/c value, it was necessary to adjust the amount of water used in the concrete mixing process to align with the water content present in the NRL mix. This adjustment ensured the desired w/c ratio while incorporating NRL into the concrete samples.

The mix ratio of the RCA-NRL concrete was meticulously designed according to the American Concrete Institute (ACI) method, as specified in **Table 3.3**. The design incorporated RCA recycled coarse aggregate as a viable substitute for natural aggregate (NA). The fine aggregate and RCA coarse aggregate were carefully

proportioned, constituting 35% and 65% of the mixture, respectively, in adherence to the recommended upper and lower limits stipulated by C33 (2004). To ensure the desired slump value of the concrete within the designated control limits, a superplasticizer was employed. The target slump values were set at 40-60 mm, 60-100 mm, and 100-150 mm for w/c ratios of 0.3, 0.4, and 0.5, respectively.

Table 3.3 Mixing Proportions of RCA-NRL Concrete (kg/m³)

Mix	Mixing Proportions of RCA-NRL Concrete (kg/m ³)						Slump	
	Cement	Sand	RCA	Water	NRL	SP	w/c	(mm)
WC3-NRL0.0	617	603	1018	185.00	0.00	3.70	0.3	50
WC3-NRL0.5	617	603	1018	182.15	5.93	3.70	0.3	60
WC3-NRL1.0	617	603	1018	179.30	11.86	3.70	0.3	60
WC3-NRL1.5	617	603	1018	176.46	17.80	3.70	0.3	50
WC3-NRL2.0	617	603	1018	173.61	23.73	3.70	0.3	40
WC4-NRL0.0	462.5	734	1018	185.00	0.00	2.78	0.4	80
WC4-NRL0.5	462.5	734	1018	182.87	4.45	2.78	0.4	90
WC4-NRL1.0	462.5	734	1018	180.73	8.89	2.78	0.4	90
WC4-NRL1.5	462.5	734	1018	178.60	13.34	2.78	0.4	70
WC4-NRL2.0	462.5	734	1018	176.46	17.79	2.78	0.4	60
WC5-NRL0.0	370	814	1018	185.00	0.00	2.22	0.5	130
WC5-NRL0.5	370	814	1018	183.29	3.56	2.22	0.5	150
WC5-NRL1.0	370	814	1018	181.58	7.12	2.22	0.5	150
WC5-NRL1.5	370	814	1018	179.88	10.67	2.22	0.5	130
WC5-NRL2.0	370	814	1018	178.17	14.23	2.22	0.5	120

Addressing the inherent shortcomings of RCA aggregate stemming from porosity and cracking during the crushing process, the RCA-NRL concrete samples were meticulously prepared employing the Two-Step Mixing Approach (TSMA), as originally proposed by Tam et al. (2005). This methodology aimed to enhance the overall quality and performance of the RCA aggregate, thereby improving the resulting concrete properties.

3.2.3 Initial and final setting time

The investigation of initial and final setting times was conducted on all specimens to examine the impact of NRL content on the hydration process of RCA-NRL concrete. The evaluation followed Method A, utilizing a manual Vicat needle apparatus, in accordance with ASTM C191 (2004) standards for cement pastes. The study compared the effects of various r/c mixing ratios (0, 0.5, 1, 1.5, and 2.0%) at w/c ratios of 0.3, 0.4, and 0.5. To ensure precision, each sample underwent two tests. The initial setting period was determined by submerging a 1 mm diameter Vicat needle into a 25 mm cement paste for a duration of 30 seconds. Conversely, the final setting period was defined as the point at which the Vicat needle could no longer penetrate the cement paste.

3.2.4 Compressive and flexural strengths

The concrete mixture employed in this research was designed according to the ACI method, aiming to achieve a specific target compressive strength of 350 ksc (34.32 MPa) at varying w/c of 0.3, 0.4, and 0.5, as outlined in **Table 3.3**. A thorough mixing process was carried out using a Pan mixer to ensure homogeneity of all ingredients. The workability of the concrete mixture was assessed by performing the slump test following the procedures stipulated in ASTM C143 (2015). To evaluate the compressive strength, cubic concrete samples with dimensions of 150 x 150 x 150 mm were cast in accordance with the guidelines specified in the BS 1881 Part 3 (1983) standard. In order to measure the flexural strength, elongated beam-shaped concrete samples with a square cross-section of 100 x 100 x 400 mm were prepared (**Figure 3.2**). The samples were formed by pouring the concrete into formwork in three layers and compacting each layer using a 4-pound steel ram with 35 strokes per layer, following the methodology described in ASTM C192 (2016). The cured concrete samples were carefully preserved in a moist water environment at a controlled temperature ranging between 27° and 29°. Subsequently, after aging for 7 and 28 days, the samples were subjected to compressive strength testing in accordance with either the BS 1881 Part 4 (1983) or ASTM C39 (2001) standards. To assess the flexural strength, the beam samples were subjected to a bending test using two loads positioned to divide the beam span into three equal parts. This experimental

procedure adhered to the guidelines outlined in ASTM C78 (2015). The flexural strength of the concrete samples was then calculated using the appropriate equation.

$$\text{Flexural strength (R)} = \frac{PL}{bd^2} \quad (3.1)$$

where P = maximum applied load; L = span length; and b and d = average width and depth of the specimens, respectively.

The compressive strength and flexural strength results were derived from the average values obtained from three test specimens. These values underwent a thorough assessment to verify their compliance with the predetermined standard deviation (SD) boundaries, using the criterion $SD/\bar{x} < 10\%$. Here, $\bar{x}$ represents the mean strength value of either the compressive strength or flexural strength. This meticulous scrutiny of the results was conducted to ensure the reliability and consistency of the test outcomes.



(a)

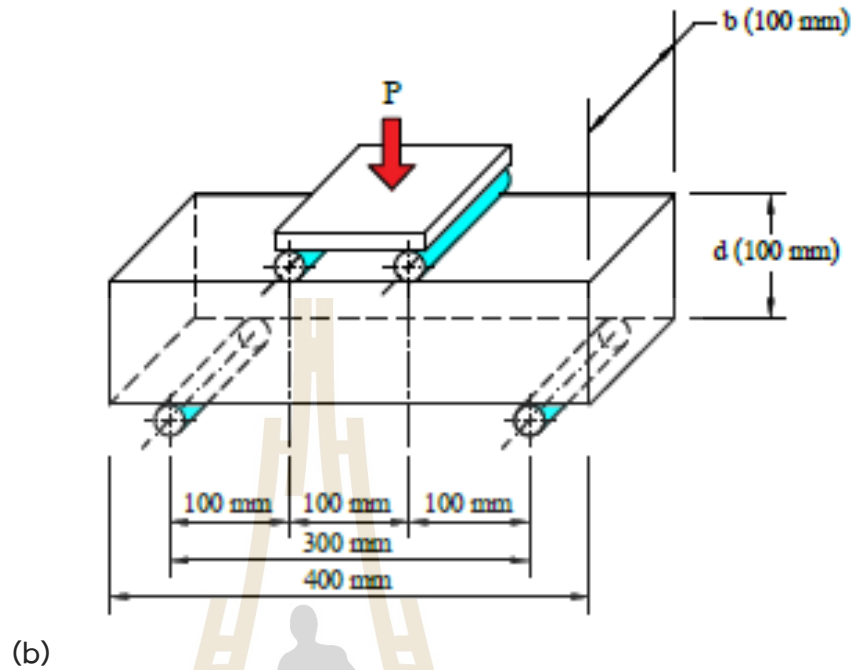


Figure 3.2 (a) Specimen; (b) schematic of the dimensions for flexural test

3.2.5 Scanning electron microscopy (SEM), Energy-Dispersive X-ray spectroscopy (EDX) and x-ray diffraction (XRD)

The influence of w/c and r/c ratios on the compressive and flexural strengths was examined through scanning electron microscopy (SEM), Energy-Dispersive X-ray spectroscopy (EDX) and X-ray diffraction (XRD) analyses. For SEM and EDX analysis, a small specimen was frozen at -195°C using liquid nitrogen and subsequently coated with a layer of gold. This preparation ensured optimal specimen quality for SEM imaging (Yaowarat et al. 2018). Additionally, the specimen was finely ground into powder form to facilitate XRD tests, enabling the acquisition of microstructural information concerning amorphous and crystalline phases. The XRD scans were conducted within a $0-90^{\circ} 2\theta$ range using a Bruker D8 ADVANCE device located in the United States.

3.3 Results

3.3.1 Initial and final setting times

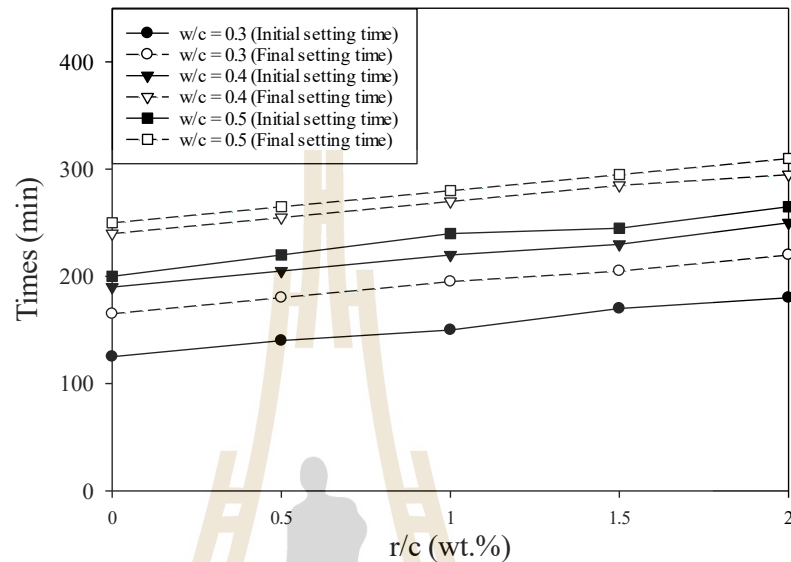


Figure 3.3 Initial and final setting times of NRL- cement paste

The results of the initial and final setting times for both the control cement paste and NRL-mixed paste, at various w/c and r/c ratios, are presented in **Figure 3.3**. The average setting time of the paste was determined using the Vicat apparatus, with two samples per batch tested at 15-minute intervals following sample preparation. The NRL-mixed cement paste exhibited a significant extension in both the initial and final setting times compared to the control paste, with higher r/c ratios contributing to longer setting times at the same w/c ratio. For instance, at a w/c ratio of 0.4, the initial setting times were 190, 205, 220, 230, and 250 minutes for r/c ratios of 0, 0.5, 1.0, 1.5, and 2.0, respectively. Similarly, the final setting times were 240, 255, 270, 285, and 295 minutes for the corresponding r/c ratios. Specifically, at an r/c ratio of 2% and w/c ratios of 0.3, 0.4, and 0.5, the initial setting time was prolonged by approximately 55, 60, and 65 minutes, respectively, while the final setting time was delayed by approximately 55, 55, and 60 minutes, respectively, in comparison to the control cement paste. These findings align with previous research

focused on utilizing NRL to enhance the flexural strength of concrete pavements (Yaowarat et al. 2021).

3.3.2 Compressive strength of RCA-NRL concrete

The compressive strength test results of the RCA-NRL concrete, with varying water-to-cement (w/c) and dry rubber content-to-cement (r/c) ratios, are presented in **Figure 3.4**. It was observed that the compressive strength of the normal RCA concrete ($r/c = 0$) exhibited higher values with increasing curing time, while it decreased as the w/c ratio increased. For instance, at a 7-day curing period (**Figure 3.4(a)**), the compressive strengths were 45.8, 42.8, and 36.8 MPa for w/c ratios of 0.3, 0.4, and 0.5, respectively. The 28-day compressive strengths of the normal RCA concrete at the same w/c ratios were 52.4, 48.1, and 43.7 MPa, respectively.

The test results also indicated that an increased r/c ratio resulted in a reduction in the compressive strength of the RCA-NRL concrete across all mix ratios. For example, at a 28-day curing period (**Figure 3.4(b)**), the compressive strength of the normal RCA concrete with an r/c ratio of 0 and w/c ratios of 0.3, 0.4, and 0.5 was 52.4, 48.1, and 43.7 MPa, respectively. However, with an r/c ratio of 2% at the same w/c ratios, the compressive strength decreased to 42.7, 31.0, and 23.7 MPa, respectively. These findings indicate that the addition of NRL to the RCA-concrete mix not only reduces the compressive strength of the specimens at a particular curing time but also affects the strength development over time. This observation is consistent with the test results for the setting times, where the initial and final setting times were prolonged with an increasing r/c ratio. This trend aligns with the findings reported in previous studies, corroborating the observed reduction in compressive strength with the incorporation of NRL in the concrete mix (Yaowarat et al. 2021).

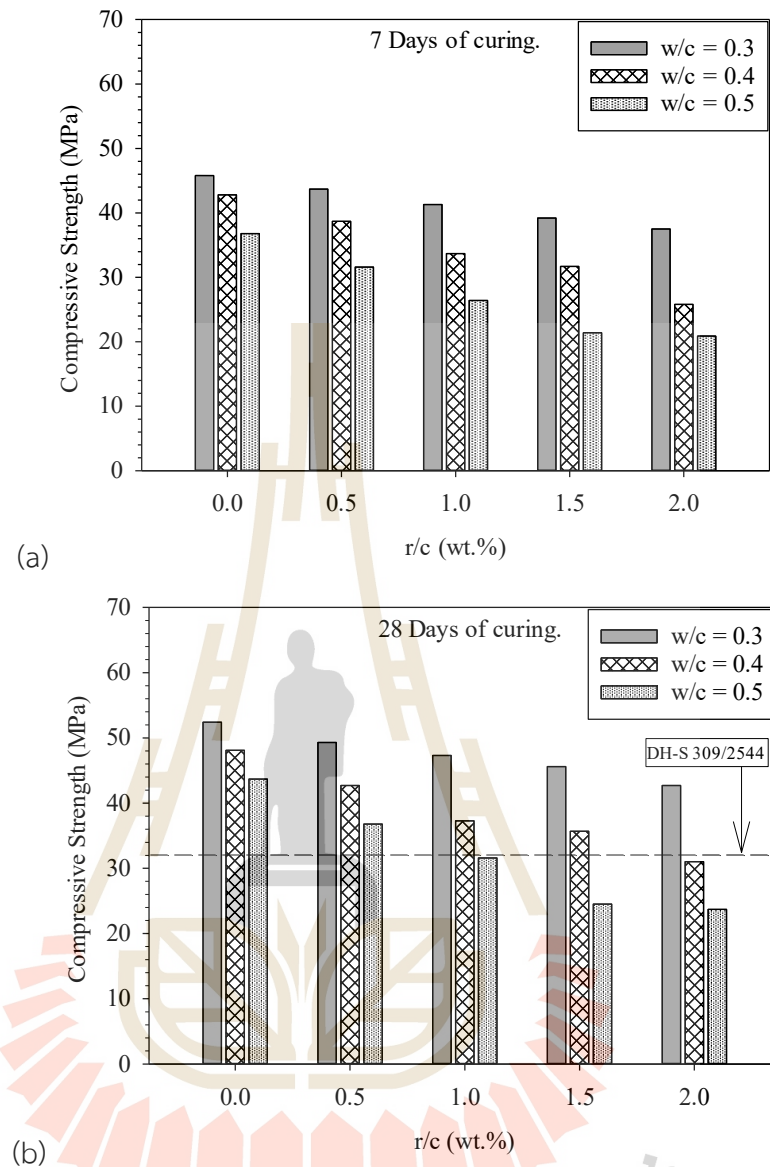


Figure 3.4 Compressive strength of RCA-NRL concrete at (a) 7 days; (b) 28 days

In comparison, the dashed line illustrated in **Figure 3.4(b)** represents the strength requirement specified by the Department of Highways in Thailand for rigid pavement (DH-S309/2544). According to this specification, which mandates a 28-day compressive strength exceeding 32 MPa, the RCA concrete (without NRL) satisfies the requirement for all tested w/c ratios. However, with the addition of NRL, the RCA-NRL concretes meet the requirement when the w/c ratio is ≤ 0.5 and the r/c ratio is ≤ 0.5 , as well as when the w/c ratio is ≤ 0.4 and the r/c ratio is ≤ 1.5 .

3.3.3 Flexural strength of RCA-NRL concrete

Figure 3.5 shows the flexural strength of the specimens at various w/c ratios, r/c ratios, and curing times. The variations in the highest strengths for each w/c ratio at different curing times are depicted by the dashed lines. The flexural strength development of RCA concrete follows a similar pattern to that of the compressive strength. With longer curing time, the flexural strength increases for the same w/c ratio, while it decreases as the w/c ratio increases. For RCA-NRL concrete, the flexural strength exhibits an increase as the r/c ratio increases until reaching an optimal r/c ratio. Beyond this optimal ratio, further increases in the r/c ratio lead to a decrease in flexural strength. For instance, at 7 and 28 days of curing time, the highest flexural strength for w/c ratios of 0.3 and 0.4 was achieved at the optimal r/c ratios of 1.0 and 0.5, respectively. At 7 days, the maximum flexural strength for w/c = 0.3 with r/c = 1.0 was 4.33 MPa, while for w/c = 0.4 with r/c = 0.5, it was 3.94 MPa. Similarly, at 28 days, the maximum flexural strength for w/c = 0.3 with r/c = 1.0 was 5.61 MPa, and for w/c = 0.4 with r/c = 0.5, it was 4.57 MPa. The increase in flexural strength compared to normal RCA concrete (r/c = 0) at the same w/c ratio was 9.14% for w/c = 0.3 with r/c = 1.0 and 7.78% for w/c = 0.4 with r/c = 0.5.

In terms of meeting requirements, normal RCA concrete (r/c = 0) at w/c ratios of 0.3 and 0.4 exhibited flexural strengths that complied with the specifications set by the Department of Highways of Thailand. The flexural strength surpassed the minimum requirement of 4.2 MPa (the red dashed lines). On the other hand, when comparing the flexural strength requirements, it was observed that RCA-NRL concrete did not meet the criterion for w/c = 0.5 in all mix ratios of r/c, while it did meet the specification for w/c = 0.3 at r/c ≤ 1.0, as well as for w/c = 0.4 at r/c = 0.5.

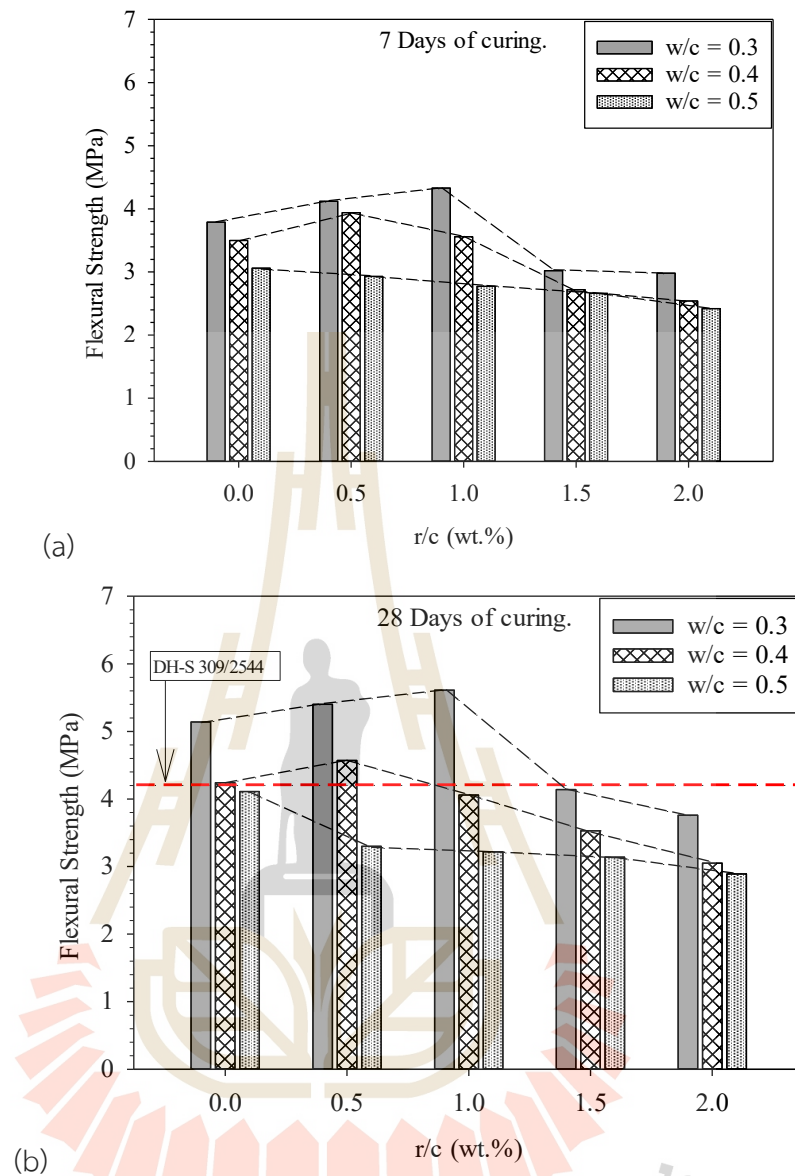


Figure 3.5 Flexural strength of RCA-NRL concrete at
(a) 7 days; (b) 28 days

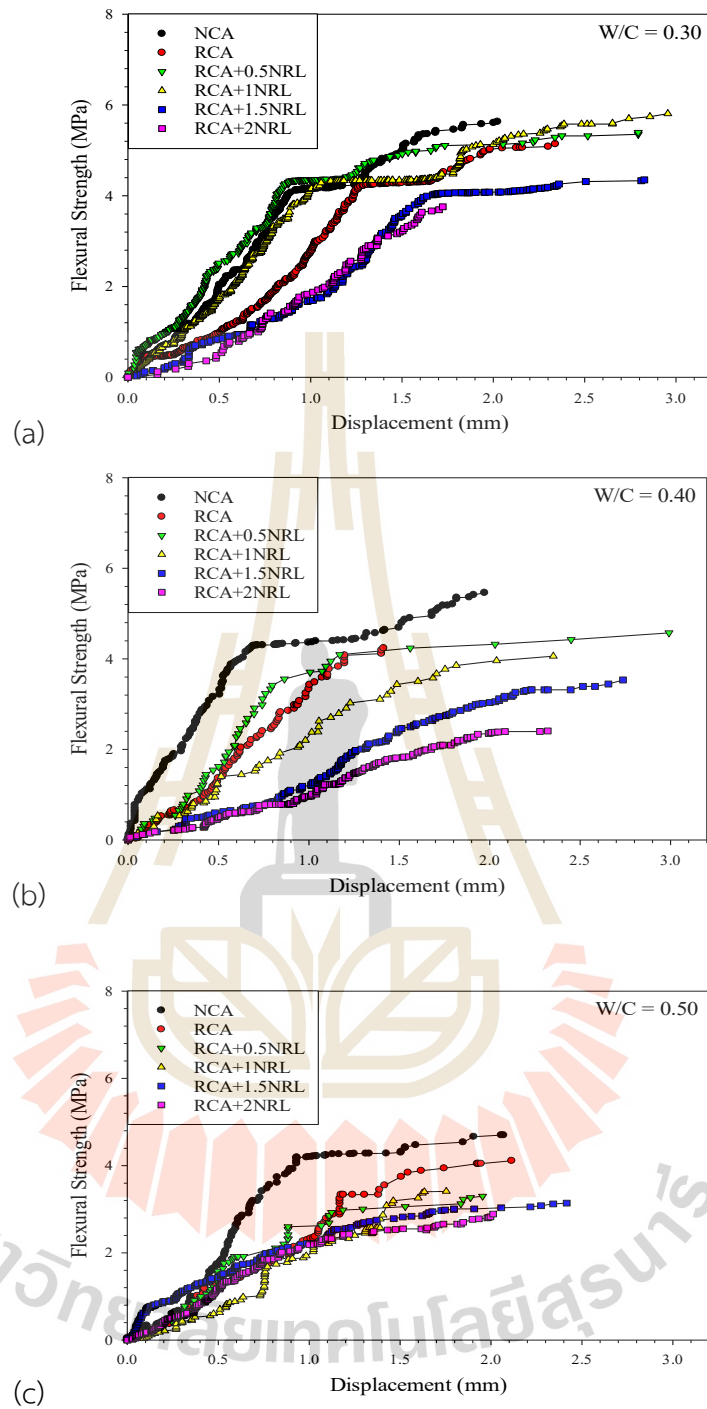


Figure 3.6 Flexural strength and mid-span displacement of specimen cured at 28 days at w/c of (a) 0.3, (b) 0.4 and (c) 0.5

The incorporation of NRL in RCA-NRL concrete resulted in notable enhancements in both ductility and stiffness during 28-day durations, as evidenced

by the observed correlation between flexural strength and deflection in the flexural beam tests performed on specimens with varying w/c ratios (**Figure 3.6**). The stiffness of the specimens, quantified by the slope of the relationship, displayed a progressive increase with higher r/c ratios until reaching the optimal r/c ratio. However, beyond the optimal r/c ratio, a decrease in stiffness was observed. Moreover, at the optimal r/c ratio, there was an increase in the displacement at mid-span, indicating a more ductile behavior of the concrete. For instance, at a w/c of 0.3, the test results revealed deflections of 2.35 mm and 2.95 mm for r/c ratios of 0 and 1.0, respectively. Similarly, at a w/c ratio of 0.4, the deflection measured 1.4 mm and 3.00 mm for r/c ratios of 0 and 0.5, respectively. Comparatively, when compared to the RCA-concrete (r/c=0) at w/c ratios of 0.3 and 0.4, the deflection increased by approximately 25.5% and 114%, respectively. These findings unequivocally demonstrate the effectiveness of NRL in enhancing the stiffness and ductility of RCA-concrete.

Figure 3.7 illustrates the relationships between flexural strength (f_f) and compressive strength (f_c) at 7 and 28 days of curing for various w/c and r/c ratios. As anticipated, the f_f of the RCA-concrete increased with higher f_c due to the improved cementation bond strength resulting from a reduction in w/c ratio, as indicated by the dashed line. In contrast, the relationship between f_f and f_c for the NRL-RCA-concrete at w/c of 0.3 and 0.4 revealed two distinct zones: the dry side and the wet side of the optimal r/c ratio. On the dry side, an increase in f_f was observed as the f_c decreased. Conversely, on the wet side, a decrease in f_f was observed with decreasing f_c , following a trend similar to that of normal concrete. This observation suggests that the flexural strength of the NRL-RCA-concrete is influenced by both the cementation bonds and the NRL films. With a specific w/c ratio, an increase in the r/c ratio results in a higher content of NRL films, which reinforce the NRL-RCA-concrete matrix and enhance its flexural strength. However, this increase in r/c ratio also leads to a reduction in the cementation bonds. On the dry side, the contribution from NRL films compensates for the decrease in cementation bond strength. The wet side of the relationship was observed consistently for a w/c ratio of 0.5 across all r/c ratios, suggesting that the incorporation of NRL into a w/c ratio of 0.5 did not yield

improvements in flexural strength and, instead, led to a reduction in compressive strength.

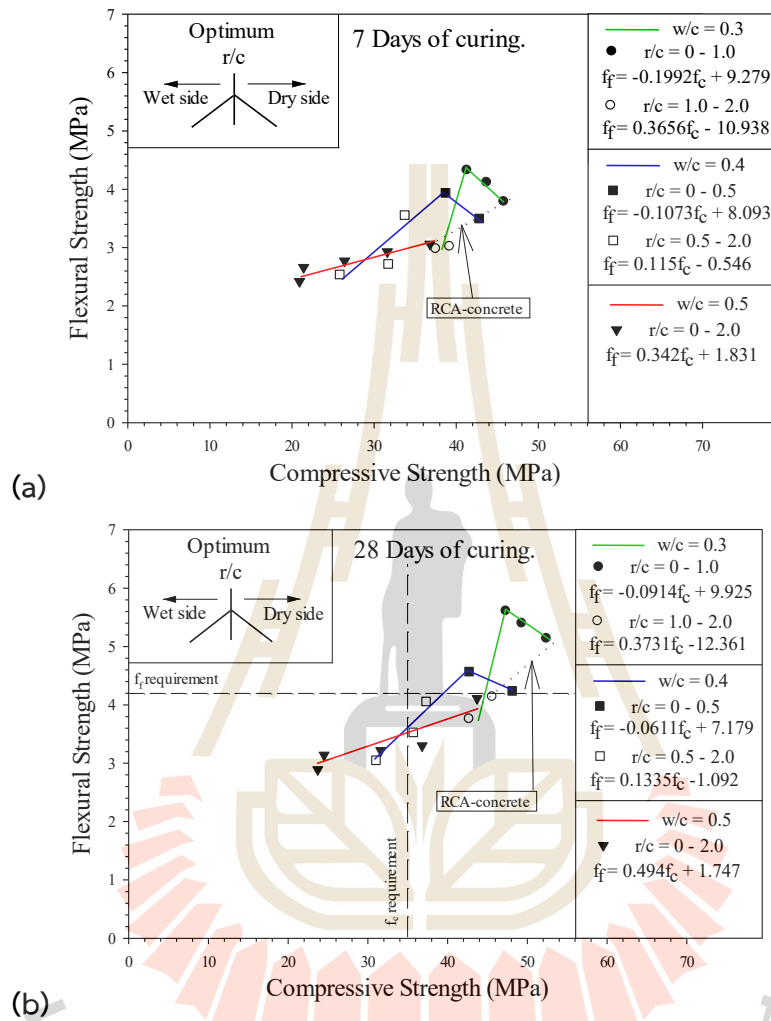


Figure 3.7 Flexural strength versus compressive strength at various r/c ratio at (a) 7 days; (b) 28 days.

In summary, the f_f of the NRL-RCA concrete increases with an increasing r/c ratio up to the optimal value for w/c ratios of 0.3 and 0.4, while the f_c decreases. However, beyond the optimal r/c ratio, both f_f and f_c show a decline. On the wet side of the optimal r/c ratio, NRL-RCA concrete specimens with a w/c ratio of 0.3 exhibit a steeper slope in the relationship compared to specimens with a w/c ratio of 0.4, indicating a higher development of flexural strength. This suggests that an excessive

increase in the r/c ratio significantly reduces both compressive and flexural strengths in NRL-concrete specimens with a w/c ratio of 0.4 when compared to specimens with a w/c ratio of 0.3.

3.4 Microstructural analysis

To investigate the microstructure of NRL-RCA-concrete, morphological analyses were conducted using a Scanning Electron Microscope (SEM) equipped with selenium detectors, operating at 15 KV. The objective was to characterize the microstructural development of the concrete mixes. **Figure 3.8** presents SEM images of NRL-RCA-concrete specimens, magnified at 2500 times, after 28-day curing with a w/c of 0.3 and varying r/c ratios of 0, 1, and 2%. The SEM images clearly revealed the prominent presence of calcium silicate hydrate (C-S-H) gel in the RCA-concrete mix (without NRL), as illustrated in **Figure 3.8 (a)**. It is worth noting that the strength development of cement-based materials primarily occurs through the formation of the primary cementitious product, the C-S-H gel.

The SEM images also showed the presence of thin NRL films in the NRL-RCA-concrete specimens at $r/c = 1\%$ **Figure 3.8 (b)**, particularly in areas where cracks were bridged. These thin NRL films acted as reinforcement and contributed to improved crack resistance and enhanced overall flexibility of the concrete. This observation suggests that the NRL films play a significant role in enhancing the performance of NRL-RCA-concrete by effectively bridging cracks and improving the structural integrity of the material. The SEM images of NRL-RCA-concrete specimens clearly demonstrate the presence of thick NRL films covering the cement matrix, as depicted in **Figure 3.8 (c)**. These films play a vital role in the microstructure of NRL-RCA-concrete, infiltrating and forming a dense layer within the cement matrix. As a result, they impede the hardening process of the cementitious products. Similarly, SEM images of synthetic polymer-concrete also confirmed the presence of synthetic polymer films incorporated within the concrete matrix. The presence of these films, whether NRL or synthetic polymer, hinders the formation of cementitious products within the matrix, subsequently leading to a reduction in compressive strength.

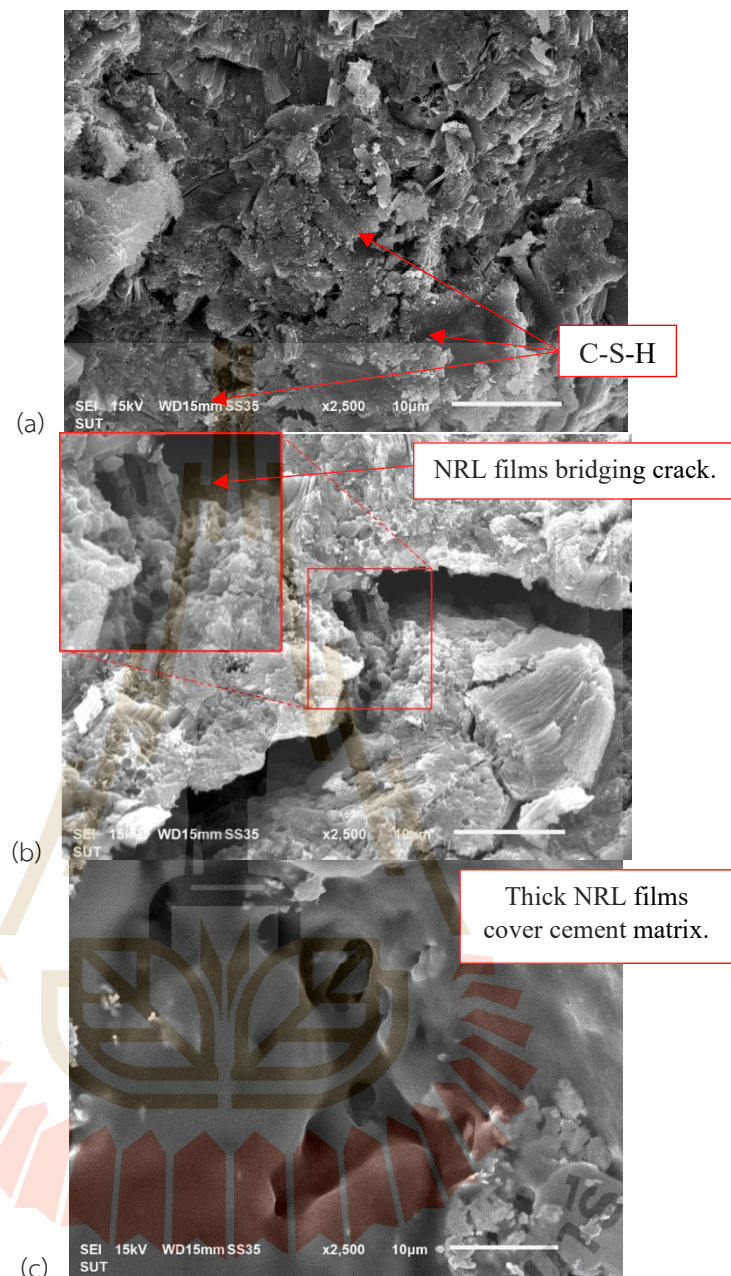


Figure 3.8 SEM images of NRL-RCA-concrete for $w/c = 0.3$ at
(a) $r/c = 0$; (b) $r/c = 1$ (optimal); (c) $r/c = 2$.

The presence of C-S-H gel retardant in NRL-RCA-concrete with varying r/c ratios (0, 1, and 2%) at a w/c ratio of 0.3 was confirmed through EDX analysis. The EDX data corresponding to SEM images are presented in **Figure 3.9**. The analysis revealed the detection of dominant elements, including Ca, Si, and Al, in all specimens, indicating the presence of C-S-H and C-A-S-H products (calcium

aluminosilicate hydrate) (Buritatun et al. 2020; Richardson and Groves 1997). Notably, the peak intensities of Ca, Si, and Al were highest in the RCA-concrete specimen ($r/c = 0\%$) (Figure 3.9a). On the other hand, Figure 3.9b and c demonstrated a decrease in the intensities of major components, including Ca, Si, and Al, with an increase in the r/c ratio from 1 to 2% compared to the RCA-concrete. The specimen with an r/c ratio of 2% exhibited the lowest intensities of these major components. Conversely, the amount of C, the main element of NRL, was observed to increase with an increasing r/c ratio.

In addition to the EDX analysis, XRD patterns were examined to further validate the retardation of cementitious products in RCA-NRL concrete at different r/c ratios. The XRD patterns of specimens cured for 28 days at a w/c ratio of 0.3 and r/c ratios of 0, 1, and 2% are presented in **Figure 3.10**. The XRD patterns exhibited the presence of an amorphous phase and a broad hump (peak) between 17 and $35^\circ 2\theta$, which is consistent with previous research findings (Abo-El-Enein et al. 2015; Hoy et al. 2016; Kontoleon et al. 2013; Lothenbach et al. 2011). The XRD results indicated a decrease in the portlandite phase with increasing r/c ratio, signifying a reduction in hydration products. In the XRD patterns of the RCA-concrete specimens (without NRL), the broad hump at approximately $29.5^\circ 2\theta$ corresponded to the presence of a significant amount of C-S-H (Alizadeh 2009; Qi et al. 2017; Xin et al. 2017), overlapping with calcite (**Figure 3.10 a**). Comparatively, the XRD pattern of the NRL-RCA-concrete specimen with a w/c ratio of 0.3 and an r/c ratio of 1 (**Figure 3.10 b**) exhibited a reduced intensity of the broad hump at approximately $29.5^\circ 2\theta$, indicating a lower amount of C-S-H products. This can be attributed to the presence of thin NRL films that cover and interweave within the cement matrix. The XRD pattern of the NRL-RCA-concrete specimen with an r/c ratio of 2.0 (**Figure 3.10 c**) demonstrated the lowest amount of cementitious products.

The microstructural analysis confirmed that NRL films were formed, which effectively interconnected and reinforced the cement matrix. This phenomenon contributed to the enhanced flexural strength of the NRL-concrete, particularly when the r/c ratio was below the optimal value. However, at excessively high r/c ratios, there was a noticeable decrease in the formation of cementitious products. Although

the NRL films provided increased cohesion, they were unable to compensate for the loss of cementation bond strength, resulting in a reduction in flexural strength.

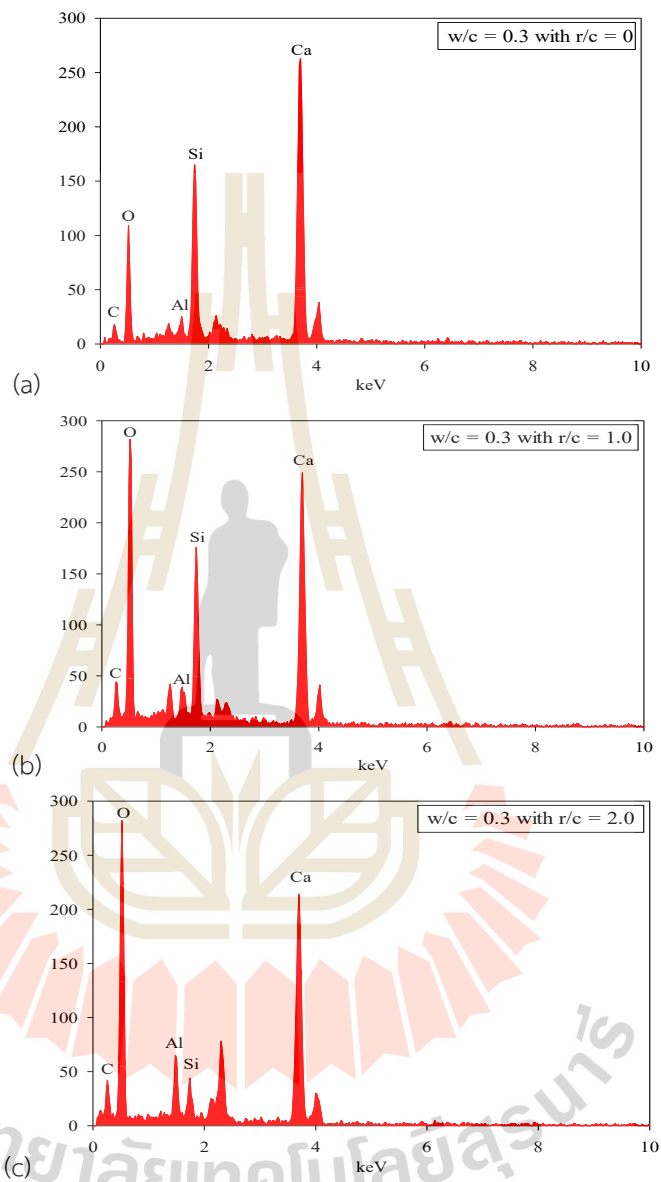


Figure 3.9 EDX results of NRL-concrete for $w/c = 0.3$ at
(a) $r/c = 0$; (b) $r/c = 1.0$ (optimal); (c) $r/c = 2.0$.

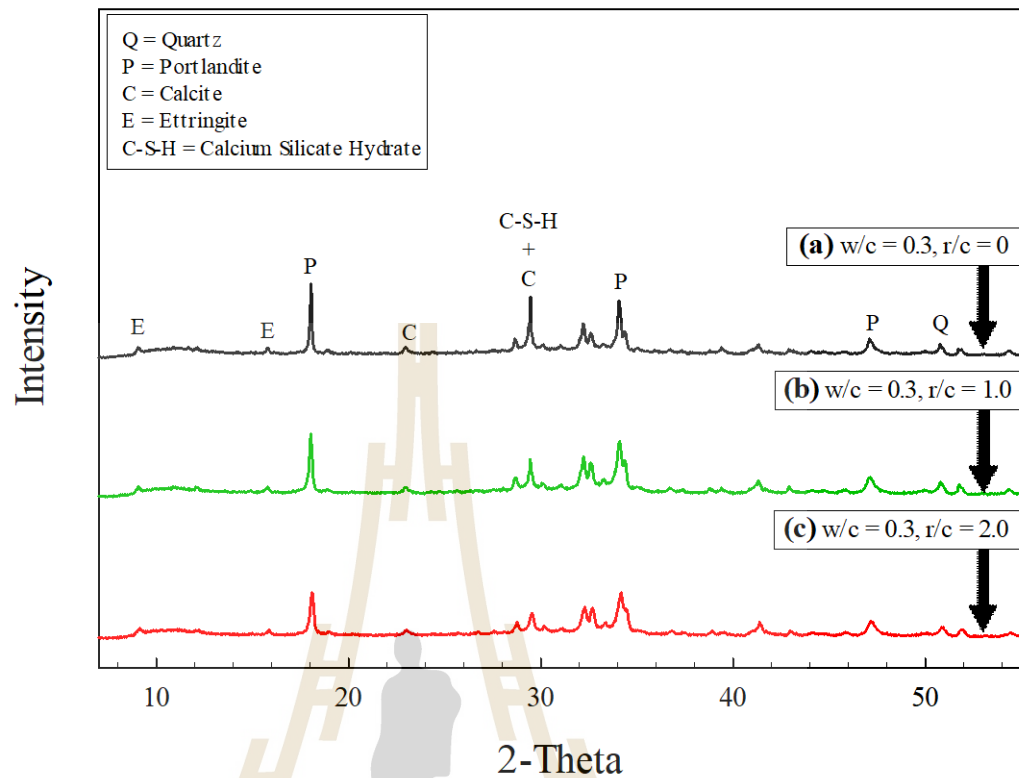


Figure 3.10 X-ray diffraction pattern of NRL-RCA-concrete at $w/c = 0.3$ with r/c ratio of (a) 0%; (b) 1%; (c) 2% at 28 days

3.5 Conclusions

The incorporation of NRL in RCA concrete resulted in notable effects on the microstructure and mechanical properties of the concrete. The NRL films were observed to cover the cement matrix, playing a significant role in the microstructure of the NRL-RCA-concrete specimens. These films hindered the hardening process of cementitious products, leading to a reduction in compressive strength. However, the NRL films also acted as reinforcement and bridged cracks, improving the flexural strength and overall flexibility of the concrete. The relationship between flexural strength and deflection demonstrated that an optimal r/c (dry side) resulted in higher flexural strength, while an excessive r/c (wet side) led to a decrease in both compressive and flexural strengths. The EDX and XRD patterns confirmed the retardation of cementitious products in NRL-RCA concrete, with a decrease in the portlandite phase and a presence of C-S-H (calcium silicate hydrate) products.

Overall, the addition of NRL in RCA-concrete showed a potential for enhancing the mechanical properties and crack resistance of the concrete, provided that the optimal r/c ratio is maintained. These findings contribute to our understanding of NRL-modified RCA-concrete and can guide future research and applications in sustainable construction practices.

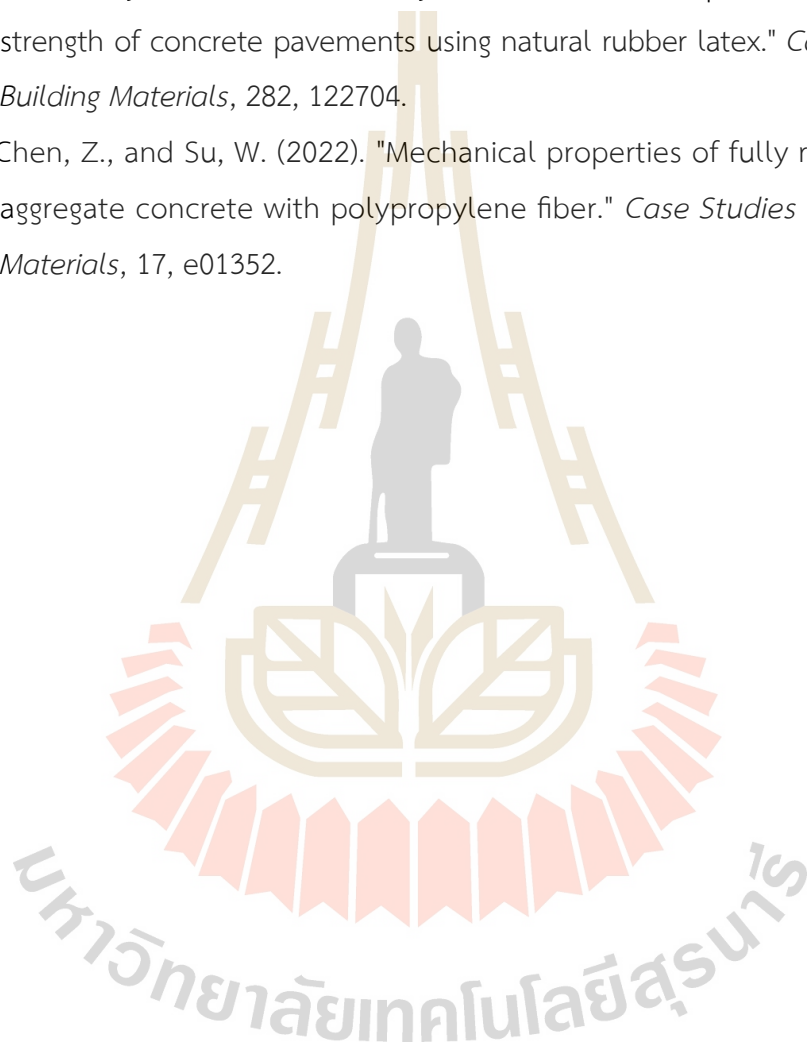
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CHAPTER IV

FLY ASH AND NATURAL RUBBER LATEX MODIFIED RECYCLED AGGREGATE CONCRETE AS SUSTAINABLE RIGID PAVEMENT SURFACE

4.1 Introduction

The construction industry has increasingly embraced sustainable approaches to mitigate the environmental impact of infrastructure development (Hasan et al., 2024; Paul et al., 2024; Toy et al., 2025). The utilization of recycled materials has gained significant attention as an alternative to conventional raw materials, aligning with global efforts to promote circular economy practices. Among the various waste-derived materials, recycled concrete aggregate (RCA) has emerged as a viable substitute for natural aggregate (NA), e.g., fiber or nano-materials in concrete applications (Accornero et al., 2024; Reddy et al., 2024). The incorporation of RCA contributes to waste reduction by diverting construction and demolition waste from landfills while conserving natural resources. However, despite its advantages, RCA-based concrete often exhibits inferior mechanical properties compared to conventional concrete due to the porous nature of RCA and the presence of adhered cementitious mortar (Silva et al. 2014). Although RCA can be directly used to replace natural coarse aggregate, even at 100% replacement levels, numerous studies have reported reductions in strength, stiffness, and durability compared with natural aggregate concrete due to the attached mortar and higher porosity of RCA. Therefore, the incorporation of supplementary materials or modification techniques-such as fly ash, slag, or polymer latex-is often recommended to enhance the mechanical performance and long-term durability of RCA-based concrete, particularly for structural and pavement applications. These considerations highlight the need for optimizing RCA concrete through material modification to achieve a balance between sustainability and mechanical performance.

Natural rubber latex (NRL), an organic polymer obtained from *Hevea brasiliensis*, has demonstrated potential in improving the mechanical properties of RCA-based concrete. Due to its elastomeric nature, NRL contributes to enhanced flexibility, adhesion, and durability when incorporated into cementitious systems (Hoy et al. 2023). Previous research has highlighted its ability to modify the interfacial transition zone (ITZ) between aggregate and cement paste, thereby affecting compressive strength (f_c) and flexural strength (f_f) (Sukmak et al. 2020). Nevertheless, some studies have reported reductions in strength when higher dosages of NRL are used, as excessive latex content can disrupt cement hydration and lead to a porous matrix (Yaowarat et al. 2021). To address these limitations, the present study investigates the incorporation of fly ash (FA) as a pozzolanic material to refine the microstructure and enhance the long-term performance of NRL–RCA concrete.

FA, a byproduct of coal combustion in thermal power plants, has been extensively used in cement-based materials due to its ability to improve workability, strength, and durability (Knapen and Van Gemert 2015). As a supplementary cementitious material, FA undergoes a pozzolanic reaction with calcium hydroxide (Ca(OH)_2) released during cement hydration, forming additional calcium silicate hydrate (C-S-H) gel (Plank et al. 2015). This secondary hydration process enhances the density of the cement matrix, refines pore structure, and contributes to improved mechanical performance over time (Etxeberria et al. 2007). Several studies have demonstrated that FA incorporation enhances the compressive strength of RCA-based concrete by mitigating the adverse effects associated with RCA's porous nature and weak ITZ (Omary et al. 2016). Furthermore, the long-term benefits of FA, including reduced permeability and enhanced resistance to sulfate attack, make it a promising solution for addressing the durability concerns of RCA concrete (Arulrajah et al. 2015).

The application of FA in RCA-based concrete has been widely studied, yet limited research has explored its synergistic role with NRL in enhancing pavement concrete performance. In pavement applications, concrete is subjected to significant tensile and bending stresses, making flexural strength a critical parameter (Yaowarat et al. 2021). Previous studies have indicated that pozzolanic reactions associated with FA contribute to microstructural refinement, thereby improving bonding within the

cementitious system (Nhieu et al. 2023). Moreover, the gradual strength development provided by FA can help offset the early-age reduction in strength often observed in NRL-modified concretes, potentially resulting in a more durable and resilient pavement material (Tran et al. 2022).

Another key aspect of FA incorporation is its impact on hydration kinetics and the overall microstructure of concrete. RCA, due to its previous exposure to hydration cycles, contains residual cementitious compounds that influence the hydration behavior of new cementitious matrix (Dilbas et al. 2014). The interaction between FA and RCA may lead to variations in reaction kinetics, affecting setting time, strength gain, and overall durability. Advanced analytical techniques, such as scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDS), and X-ray diffraction (XRD), have been employed to evaluate the microstructural characteristics of RCA-based concrete (Behera et al. 2014). These methods provide insights into phase composition, elemental distribution, and the formation of hydration products, facilitating a deeper understanding of the mechanisms governing strength development in FA-modified NRL-RCA concrete (Buritatum et al. 2021; Buritatum et al. 2020).

In addition to mechanical performance, the environmental and economic implications of FA utilization warrant consideration. The increasing generation of FA as an industrial byproduct necessitates sustainable disposal solutions (Jansen et al. 2012). By integrating FA into concrete formulations, the construction sector can contribute to waste valorization while reducing the demand for Portland cement, which is associated with high carbon emissions (Plank et al. 2015). From an economic perspective, FA is often more cost-effective than ordinary Portland cement, making it a viable option for large-scale infrastructure projects (Ye et al. 2022). The combination of RCA, NRL, and FA thus presents an innovative approach to sustainable concrete production, aligning with global efforts to promote eco-friendly construction practices (Yaowarat et al. 2018; Yaowarat et al. 2019).

Despite the potential benefits, challenges associated with FA incorporation must be acknowledged. The variability in FA composition, influenced by factors such as coal source and combustion conditions, can impact its reactivity and performance

in concrete (Omary et al. 2016). Furthermore, the optimal dosage of FA must be carefully determined to balance workability, early-age strength, and long-term durability. Excessive FA content may lead to delayed strength gain, which could pose limitations in applications requiring rapid construction cycles (Silva et al. 2014).

Another critical aspect in evaluating pavement materials is their behavior under cyclic or repeated loading. Unlike static tests, cyclic tests simulate the real service conditions of pavements, which are continuously subjected to traffic-induced stresses and fatigue over their service life. Parameters such as resilient modulus, permanent deformation, and flexural fatigue life provide essential insights into the long-term performance and durability of concrete materials under repeated loads (Werkmeister et al. 2004). However, limited research has investigated the cyclic performance of FA-modified NRL-RCA concrete. Addressing this gap is crucial for assessing the feasibility of such mixtures in pavement applications, where resistance to fatigue and deformation directly governs service life.

A comprehensive review of existing literature highlights the gap in research concerning the combined effect of FA and NRL in RCA-based concrete. While previous studies have investigated FA in RCA concrete and the benefits of NRL separately, limited research has explored their combined influence on f_c and f_t . Given the importance of these properties in pavement applications, this study aims to bridge the knowledge gap by systematically assessing the performance of FA-modified NRL-RCA concrete, thereby contributing to the development of sustainable and durable pavement materials.

By building upon the limitations of earlier studies, the present work advances the understanding of sustainable pavement concrete through a unified investigation of mechanical, fatigue, microstructural, and environmental behaviors. Whereas previous research has often examined fly ash or natural rubber latex separately, this study explores their combined effect within an RCA-based system specifically designed for rigid pavement applications. The research emphasizes the optimization of material proportions that satisfy Thai pavement strength standards while simultaneously minimizing CO₂ emissions and material costs. The findings are expected to offer practical guidelines for producing high-performance, low-carbon

pavement concrete and to support the broader adoption of recycled aggregate technology in sustainable infrastructure development.

4.2 MATERIAL AND METHODS

4.2.1 Materials

Ordinary Portland cement (OPC) was utilized as the primary cementing material, possessing a specific gravity of 3.15. The detailed chemical composition of the Portland cement is presented in **Table 4.1**.

FA used in this research was sourced from a cement manufacturing plant in Nakhon Ratchasima Province, located in northeastern Thailand. According to its chemical composition (**Table 4.1**), FA contained 39.18% silicon dioxide (SiO_2), 22.64% aluminum oxide (Al_2O_3), and 15.45% iron oxide (Fe_2O_3), which are key contributors to its pozzolanic activity. With a high calcium oxide (CaO) content of 11.3%, the FA was classified as Class C in accordance with ASTM C618 (2019) standards. The specific gravity of FA was measured at 2.39, and the particle size distribution is illustrated in **Figure 4.1**.

Table 4.1 Chemical compositions of OPC and Fly Ash

Materials	Composition (%)						
	SiO_2	SO_3	Fe_2O_3	Al_2O_3	CaO	MgO	LOI
Cement	20.9	2.7	3.32	4.7	65.4	2.54	0.9
FA	39.18	4.29	15.45	22.64	11.3	1.69	1.61

River sand was selected as the fine aggregate in this study. Under a saturated surface dry (SSD) condition, it exhibited a specific gravity of 2.65. Additional properties of the sand included a water absorption capacity of 1.10%, a fineness modulus of 2.46, and a void content of 43.6%. The coarse aggregate used was recycled concrete aggregate (RCA), ranging in size from 4.75 to 19 mm. The RCA had a fineness modulus of 6.3 and a specific gravity of 2.67. It exhibited a water absorption rate of 5.5%, a porosity of 54%, and a Los Angeles abrasion value of 34%. A visual representation of the particle characteristics of both RCA and river sand is illustrated in **Figure 4.1**.

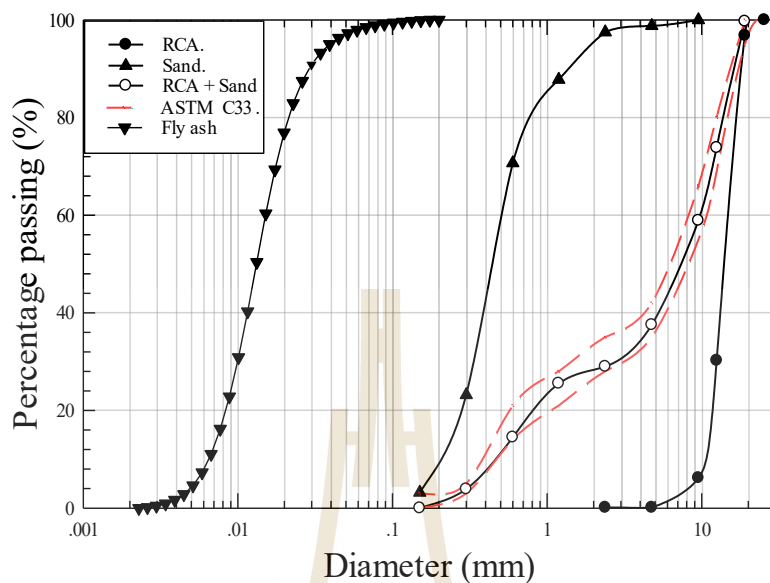


Figure 4.1 Particle size distributions of Sand, RCA, RCA+Sand and FA.

Natural rubber latex (NRL) was introduced as an additive to enhance the flexural performance of RCA-based concrete mixtures. The NRL utilized in this study was certified by the Rubber Authority of Thailand, ensuring compliance with industry production standards. The chemical composition of NRL is outlined in **Table 4.2**.

To maintain adequate workability and address low slump values, a water-reducing admixture, specifically Sika® Plastocrete®-907, was incorporated into the concrete mix. This admixture meets the ASTM C494 Type D & G specifications and aids in improving the overall flowability of the concrete.

Table 4.2 Chemical Analysis of Natural Rubber Latex.

Property	Value
Total solid content (TSC)	55.11%
Dry rubber content (DRC)	52.04%
Non rubber contents (NRC)	3.07%
Volatile fatty acid (VFA)	0.07%
Alkalinity (NH ₃)	0.69%
pH	10.42%
Mechanical stability time (MST)	7440 s

4.2.2 Specimens Preparation

FA-NRL-RCA concrete specimens were prepared with a fixed water-to-binder ratio (w/b) of 0.4, while varying the dried rubber content-to-binder ratio (r/b). The NRL additive was incorporated at five different percentages relative to the binder (cement + FA) weight e.g. 0%, 0.5%, 1%, 1.5%, and 2.0% to evaluate its influence on workability and water retention in concrete, as referenced by Kim and Robertson (1998), Kim et al. (1999), and Ohama (1998). FA was introduced as a partial cement replacement at three levels: 15%, 20%, and 25% (FA/c). According to **Table 4.2**, the chemical composition of NRL consisted of approximately 52% dry rubber and 48% water. To maintain the designated w/c ratio, adjustments were made to the total mixing water to account for the water content present in the NRL mix.

In this research, NRL was used in liquid form and mixed with distilled water to prepare the concrete specimens. The method followed ensures accurate incorporation of NRL into the mix while maintaining the specified w/b and r/b ratios. Specifically, the distilled water was partially replaced by NRL to achieve the target w/b ratio, as suggested by previous studies (Yaowarat et al., 2021). Considering the NRL contains 52% dry rubber, each kilogram of liquid NRL consists of 520 g of dry rubber and 480 g of water. The required NRL dosage for each r/b ratio was determined using the formula $((r/b)/100)B \cdot (1/0.52)$, where B represents the total binder content (OPC + FA) in kilograms. To maintain the targeted w/b ratio, the mixing water for the concrete was adjusted using the equation $[(w/b)B - 0.48((r/b)/100)B]$, ensuring that the water introduced through NRL was properly accounted for in the overall mix design.

The mix proportions of the FA-NRL-RCA concretes were meticulously designed following the American Concrete Institute (ACI) methodology, as detailed in **Table 4.3**. RCA was fully utilized as a substitute for natural aggregate, with the fine and coarse aggregate proportions set at 44% and 56%, respectively, adhering to the upper and lower limits prescribed by ASTM C33 (2004). A superplasticizer was incorporated to ensure that the slump values remained within the target range of 40–60 mm for the w/c ratio of 0.4. To mitigate the inherent deficiencies of RCA, such as increased porosity and microcracking caused by the crushing process, the FA-NRL-RCA concrete mixtures were produced using the Two-Stage Mixing Approach (TSMA) as recommended by Tam

et al. (2005). This method is specifically employed to enhance RCA quality, ultimately improving the overall mechanical and durability properties of the concrete.

Table 4.3 The mix proportions of the FA-NRL-RCA concretes.

Mix	r/b (wt.)%	OPC (kg/m ³)	FA (kg/m ³)	Sand (kg/m ³)	RCA Coarse Agg. (kg/m ³)	Water (kg/m ³)	NRL (kg/m ³)	SP (kg/m ³)	volume (m ³)
0%FA	0.0	462.5	0	734	1018	185	0	2.78	0.99008
15%FA	0.0	393.125	69.375	734	1018	185.00	0.00	2.36	0.99708
15%FA+0.5%NRL	0.5	393.125	69.375	734	1018	182.87	4.45	2.36	0.99708
15%FA+1.0%NRL	1.0	393.125	69.375	734	1018	180.73	8.89	2.36	0.99495
15%FA+1.5%NRL	1.5	393.125	69.375	734	1018	178.60	13.34	2.36	0.99281
15%FA+2.0%NRL	2.0	393.125	69.375	734	1018	176.46	17.79	2.36	0.99068
20%FA	0.0	370	92.5	734	1018	185.00	0.00	2.22	0.98855
20%FA+0.5%NRL	0.5	370	92.5	734	1018	182.87	4.45	2.22	0.99942
20%FA+1.0%NRL	1.0	370	92.5	734	1018	180.73	8.89	2.22	0.99942
20%FA+1.5%NRL	1.5	370	92.5	734	1018	178.60	13.34	2.22	0.99728
20%FA+2.0%NRL	2.0	370	92.5	734	1018	176.46	17.79	2.22	0.99515
25%FA	0.0	346.875	115.625	734	1018	185.00	0.00	2.08	0.99301
25%FA+0.5%NRL	0.5	346.875	115.625	734	1018	182.87	4.45	2.08	0.99088
25%FA+1.0%NRL	1.0	346.875	115.625	734	1018	180.73	8.89	2.08	1.00175
25%FA+1.5%NRL	1.5	346.875	115.625	734	1018	178.60	13.34	2.08	1.00175
25%FA+2.0%NRL	2.0	346.875	115.625	734	1018	176.46	17.79	2.08	0.99962

The cement was partially replaced by fly ash (FA) on a mass basis to maintain consistency with the reference RCA-NRL concrete used for comparison. Although mass-based replacement can introduce slight volumetric variation due to the lower specific gravity of FA, the mix proportions were carefully adjusted to ensure a total volume of approximately 1.00 m³ for all mixtures, as shown in **Table 4.3**. This approach allows a direct evaluation of FA's influence on hydration behavior, microstructural refinement, and long-term performance while maintaining comparable batch volumes. A total binder content of approximately 450 kg/m³ was adopted for the mix design to meet the requirements of rigid pavement applications in accordance with the Department of Highways, Thailand specification (DH-S309/2544), which specifies minimum strengths of $f_c \geq 32$ MPa and $f_f \geq 4.2$ MPa at 28 days. This relatively

high binder content was selected to ensure adequate fatigue resistance and workability for pavement-grade concrete while compensating for the higher porosity and water absorption of RCA.

4.2.3 Engineering and Microstructural Investigation

4.2.3.1 Compressive strength (f_c) and flexural strength (f_f)

The FA-RCA-NRL concrete specimens were prepared following the ACI method, aiming to achieve a f_c of 350 ksc (34.3 MPa) at $w/c = 0.4$, as presented in **Table 4.3**. A rotary drum mixer was employed to ensure uniform distribution of all components throughout the mixing process. The workability of the fresh concrete mixture was assessed using the slump test, conducted in accordance with ASTM C143 (2015). To evaluate the f_c , cubic concrete specimens measuring $150 \times 150 \times 150 \text{ mm}^3$ were cast following the standards outlined in BS 1881 Part 3 (1983). Similarly, for f_f , testing beam-shaped specimens of $100 \times 100 \times 400 \text{ mm}^3$ were prepared. The fresh FA-RCA-NRL concrete was poured into molds in three layers, with each layer compacted using a 4-pound steel ram, applying 35 strokes per layer, as specified in ASTM C192 (2019). The specimens were cured in a moist environment at a controlled temperature of $27^\circ - 29^\circ$ to ensure proper hydration and strength development. After 7, 28 and 56 days, f_c testing was performed following either BS 1881 Part 4 (1983) or ASTM C39 (2021) standards. For f_f evaluation, the beam specimens underwent a third-point loading test, where two loads were applied to divide the beam span into three equal sections, adhering to ASTM C78 (2021). The f_f values of the FA-RCA-NRL concretes were subsequently calculated using the relevant equation based on these experimental procedures.

$$\text{Flexural strength } (f_f) = \frac{PL}{bd^2} \quad (4.1)$$

where P is the maximum load, L is the span length, and b and d are the average width and depth of the specimen.

The average values of f_c and f_f were determined based on data obtained from three test specimens. To ensure the reliability and consistency of the results, these values were rigorously evaluated within the standard deviation (SD) threshold,

following the criterion $SD/\bar{\mu} < 10\%$, where $\bar{\mu}$ represents the mean value of either f_f or f_c .

4.2.3.2 Flexural Fatigue

The three-point flexural fatigue test was conducted on FA-RCA-NRL concrete specimens, maintaining the same mix proportions and dimensions as those used in flexural strength testing. A 500 kN electro-hydraulic servo testing machine equipped with an autonomous data recorder was utilized to evaluate fatigue performance. The impact of NRL and FA incorporation on the fatigue resistance of concrete beams was evaluated across all r/b and FA replacement ratios by applying cyclic vertical loads at stress ratio (SR) levels of 60%, 70%, and 80%, referenced to their flexural strength (f_f). To ensure a consistent loading condition throughout the test, a stress-controlled approach was implemented to maintain a constant load at the target SR.

The stress ratio (SR), which accounts for both applied flexural stress and concrete strength, was determined using the equation proposed by Smith and Roesler (2004)

$$SR = \frac{\sigma}{f_f} \quad (4.2)$$

where σ represents the applied flexural stress, and f_f denotes the flexural strength of the FA-RCA-NRL concrete.

To simulate the vehicular traffic loading conditions expected in pavement applications, a haversine loading pulse with a frequency of 10 Hz was applied to the FA-RCA-NRL concrete specimens.

To improve the reliability and transparency of the experimental findings, all bar charts illustrating compressive strength, flexural strength, and fatigue life were updated to include error bars representing one standard deviation (SD), derived from three specimens per mix condition. This addition highlights the reproducibility of the results and provides a clearer visualization of data variability across the tested mixtures.

4.2.3.3 Scanning electron microscopy (SEM) and Energy-Dispersive X-ray spectroscopy (EDX)

The development of f_c and f_f in relation to varying r/b and FA replacement ratios was analyzed using scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDX). To facilitate SEM and EDX examinations, a thin section of the specimen was first frozen at -195°C in liquid nitrogen and subsequently coated with a protective gold layer, ensuring optimal image quality for SEM analysis (Yaowarat et al. 2018).

4.2.3.4 Calculation of carbon emissions

Life cycle assessment is a cradle-to-grave or cradle-to-cradle analysis technique to assess environmental impacts associated with all the stages of a product's life, which is from raw material extraction through materials processing, manufacture, distribution, and use. The carbon is a dominant category to assess the environment impacts compared to other impact categories (Lazarevic and Martin 2016; Reijnders 2012). The carbon footprint is a key greenhouse gas that drives global climate change and global warming effect (Hertwich and Peters 2009). In practice, the evaluation of carbon footprint of a product is the key process for the life cycle assessment. Carbon emissions was calculated using the following equation:

$$\sum \text{CO}_2 = V \times EF \quad (4.3)$$

where V is the amount of tested materials (kg), and EF is the emission factors of tested materials ($\text{kg CO}_2\text{-e/kg}$).

4.3 RESULTS

4.3.1 Compressive strength of FA-RCA-NRL concrete

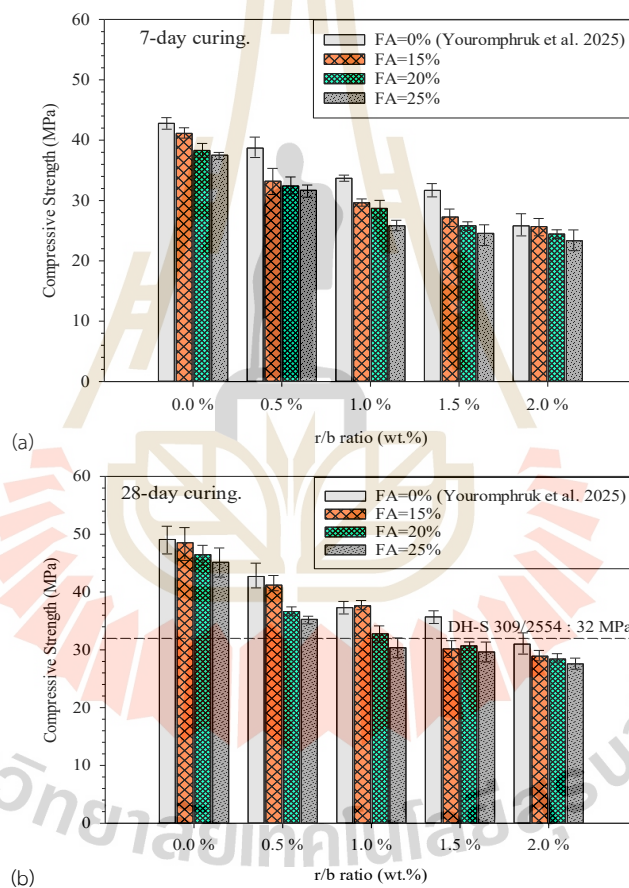
Figure 4.2 illustrates the compressive strength (f_c) development of FA-RCA-NRL concrete specimens cured for 7, 28, and 56 days, with FA replacement levels of 0% (Youromphruk et al. 2025), 15%, 20%, and 25%, and various r/b ranging from 0.0% to 2.0%, under a constant w/b ratio of 0.4. At all curing periods, the specimens without NRL ($r/b = 0\%$) exhibited the highest f_c . As expected, the f_c of all mixtures

increased with longer curing durations, while it decreased with an increasing r/b ratio. For instance, at 7 days (**Figure 4.2(a)**), the f_c of the control mix ($r/b = 0\%$) reached 42.80 MPa for FA = 0% (Youromphruk et al. 2025), which was higher than the corresponding values of 41.14 MPa, 38.32 MPa, and 37.52 MPa for FA replacement levels of 15%, 20%, and 25%, respectively. However, when the r/b ratio was increased to 2.0%, the f_c values dropped markedly to 25.80 MPa for FA = 0% and to 25.68 MPa, 24.44 MPa, and 23.32 MPa for FA = 15%, 20%, and 25%, respectively. A similar trend was observed at 28 days (**Figure 4.2(b)**), where the control mixes continued to outperform the NRL-modified ones. The f_c values at $r/b = 0\%$ were 49.10 MPa for FA = 0% (Youromphruk et al. 2025), followed by 48.52 MPa, 46.47 MPa, and 45.15 MPa for FA levels of 15%, 20%, and 25%, respectively. In contrast, at the highest NRL content ($r/b = 2.0\%$), the f_c values decreased to 31.00 MPa for FA = 0% and to 28.92 MPa, 28.43 MPa, and 27.57 MPa for FA = 15%, 20%, and 25%, respectively.

Interestingly, the 56-day strength results (**Figure 4.2(c)**) reveal a noteworthy gain in f_c , particularly for higher FA replacement levels. For example, the control mix ($r/b = 0\%$) demonstrated increasing strength with increasing FA content, reaching 53.35 MPa, 55.78 MPa, and 59.63 MPa for 15%, 20%, and 25% FA, respectively. This long-term strength gain is attributed to the pozzolanic reaction of FA, which becomes more pronounced over time. Despite the strength reductions observed at early ages with higher r/b ratios, the 56-day strength results for NRL-modified mixes showed measurable improvement. At $r/b = 2.0\%$, f_c improved to 33.10 MPa, 33.76 MPa, and 32.76 MPa for FA contents of 15%, 20%, and 25%, respectively indicating that the delayed strength development associated with NRL and FA can be partially recovered over time.

The horizontal dotted line in **Figure 4.2(b)** indicates the minimum f_c requirement for rigid pavement, as specified by the Department of Highways, Thailand ($f_c > 32$ MPa at 28-day) [DH-S309/2544]. It was observed that the control mixtures without NRL ($r/b = 0\%$) met the requirement for all levels of FA replacement. In particular, the FA = 0% mix achieved the highest compressive strength at 28 days (49.1 MPa), clearly surpassing the minimum requirement and outperforming the FA-blended concretes. For mixes incorporating NRL, the requirement was still satisfied at $r/b \leq 1.0\%$

for FA = 15% and FA = 20%, with f_c of 41.21 MPa and 36.63 MPa at $r/b = 0.5\%$, and 37.63 MPa and 32.78 MPa at $r/b = 1.0\%$, respectively. However, for FA = 25%, only the mixes with $r/b = 0.5\%$ (35.28 MPa) met the standard. Mixes with $r/b \geq 1.5\%$ for all FA replacement levels fell below the required 32 MPa threshold, highlighting that higher NRL content adversely affected strength development at 28 days. This suggests that, for applications requiring compliance with the Department's rigid pavement criteria, the allowable r/b ratio should be limited according to the FA content: up to 1.0% for FA levels below 20%, and restricted to 0.5% when FA content reaches 25%.



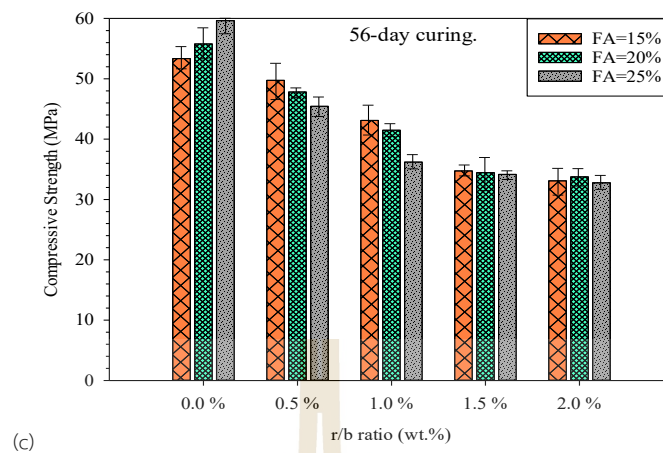


Figure 4.2 Compressive strength of FA-RCA-NRL concrete at
(a) 7 days; (b) 28 days; (c) 56 days.

4.3.2 Flexural strength of FA-RCA-NRL concrete

Figure 4.3 presents the f_f development of FA-RCA-NRL concrete specimens at 7, 28, and 56 days with different FA replacement levels (0%, 15%, 20%, and 25%) and r/b ratios of 0.0%, 0.5%, 1.0%, 1.5%, and 2.0%, under a constant w/b ratio of 0.4. The results indicated that at a given r/b ratio and FA content, f_f increased over time, with the highest values observed at 56 days, similar to the compressive strength trend. At 7 days (**Figure 4.3(a)**), the control mix (r/b = 0%) exhibited the highest f_f , reaching 4.15 MPa for FA = 0% (Youromphruk et al. 2025), which was slightly higher than the values of 4.00 MPa, 3.80 MPa, and 3.66 MPa for FA levels of 15%, 20%, and 25%, respectively. With the incorporation of NRL, the f_f decreased across all FA contents, particularly at r/b ≥ 1.5 , where the f_f values dropped to 3.55 MPa for FA = 0% (Youromphruk et al. 2025) and to 3.26 MPa, 3.22 MPa, and 2.75 MPa for FA = 15%, 20%, and 25%, respectively.

At 28 days (**Figure 4.3(b)**), an increase in f_f was observed across all mixes. The control concrete (r/b = 0%) achieved 4.65 MPa for FA = 0% (Youromphruk et al. 2025), compared with 4.55 MPa, 4.50 MPa, and 3.92 MPa for FA replacement levels of 15%, 20%, and 25%, respectively. The highest f_f was recorded at r/b = 0.5, where f_f exceeded that of the control mix, reaching 4.82 MPa for FA = 0% (Youromphruk et al. 2025) and 4.57 MPa, 4.62 MPa, and 4.38 MPa for FA = 15%, 20%, and 25%, respectively.

At $r/b = 1.0$, a slight reduction was noted, with corresponding values of 4.62 MPa for FA = 0% (Youromphruk et al. 2025) and at 4.68 MPa, 4.57 MPa and 3.76 MPa for FA = 15%, 20% and 25%, respectively. Beyond this level, a consistent decline in f_f was evident, with $r/b = 2.0$ producing the lowest values: 3.72 MPa for FA = 0% (Youromphruk et al. 2025) and to 3.69 MPa, 3.16 MPa, and 2.89 MPa for FA = 15%, 20%, and 25%, respectively. These results suggest that a low-to-moderate NRL dosage ($r/b = 0.5$ -1.0%) enhances flexural performance, whereas higher dosages ($r/b \geq 1.5\%$) negatively affect strength development, likely due to changes in the cementitious matrix and bond structure.

At 56 days (**Figure 4.3(c)**), the highest f_f was recorded, with f_f exceeding 5.0 MPa for some mixes. The control mix ($r/b = 0\%$) exhibited 4.82 MPa, 4.92 MPa, and 5.47 MPa for FA replacement levels of 15%, 20%, and 25%, respectively. The highest recorded f_f was 5.62 MPa at $r/b = 0.5\%$ and FA = 25%, suggesting that a moderate addition of NRL contributed positively to long-term strength development. However, a decline was noted for $r/b \geq 1.5$, where f_f values dropped to 4.13 MPa, 4.54 MPa, and 3.56 MPa at FA levels of 15%, 20%, and 25%, respectively.

The f_f of FA-RCA-NRL concrete exhibited ages-dependent trends rather than a single distinct pattern. At 7 days, f_f generally decreased with increasing r/b ratio for all FA levels, which is attributed to the insufficiently developed cementitious matrix at early age; consequently, NRL is not yet effective and higher latex contents can even disrupt hydration. At 28 days, an optimum emerged: mixes with $r/b \approx 0.5$ –1.0% achieved equal or higher f_f than the $r/b = 0\%$ control for FA = 15–20% (with the peak at $r/b = 1.0\%$), while the FA = 25% series benefited only at $r/b = 0.5\%$ and declined beyond this dosage. By 56 days, the optimum shifted toward $r/b \approx 0.5\%$ for all FA levels, after which f_f decreased markedly at higher r/b ratios of $\geq 1.5\%$. This evolution reflects the combined effects of latex-film coalescence and the delayed pozzolanic reaction of FA, which enhance matrix integrity at moderate NRL dosages.

The horizontal dotted line in **Figure 4.3(b)** represents the minimum f_f requirement for rigid pavements, as per the Department of Highways, Thailand ($f_f > 4.2$ MPa at 28-day) [DH-S309/2544]. The control concrete ($r/b = 0\%$) met this requirement for FA = 0%, 15% and 20% at 28 days but failed for FA = 25%. Among the NRL-modified

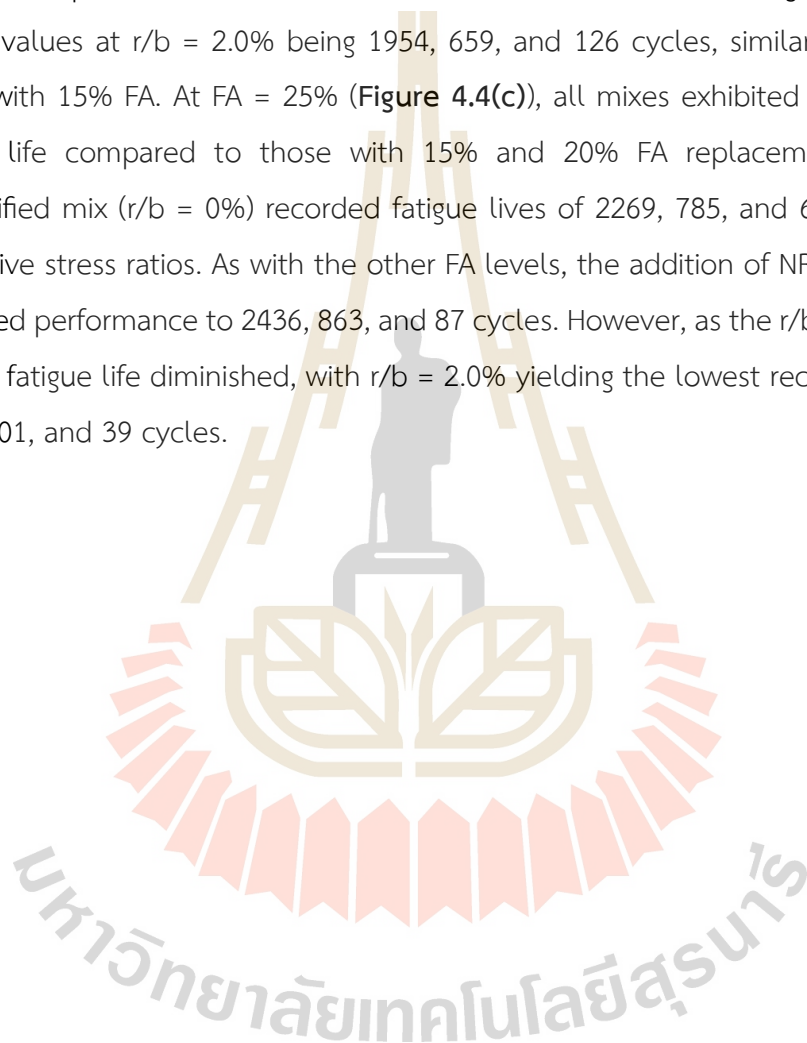
concretes, the requirement was satisfied for $r/b \leq 1.0\%$ at $FA = 0\%, 15\%$ and 20% , achieving f_f above 4.2 MPa. For $FA = 25\%$, only the mix with $r/b = 0.5\%$ met the standard, recording 4.38 MPa at 28 days, while $r/b \geq 1.5\%$ failed to meet the requirement across all FA levels. When evaluating both f_c and f_f requirements, the control concrete ($r/b = 0\%$) met the requirement when $FA < 20\%$, while FA-RCA-NRL-concrete met the requirement when $r/b \leq 1.0\%$ for $FA < 20\%$, and when $r/b = 0.5\%$ for $FA < 25\%$. These findings suggest that while NRL improves workability and water retention, its proportion must be optimized to ensure compliance with structural performance standards. Moreover, the inclusion of FA contributes long-term benefits through its pozzolanic reaction, which improves the microstructure, enhances durability, and supports continued strength development beyond 28 days, thereby improving the overall service life of RCA-based pavement concrete.

4.3.3 Fatigue performance

Figure 4.4 illustrates the fatigue performance of FA-RCA-NRL concrete at 28 days of curing, incorporating various levels of FA replacement ($15\%, 20\%$, and 25%) and r/b , under three applied stress ratios ($60\%, 70\%$, and 80%). It should be noted that the fatigue behavior of the $FA = 0\%$ mixtures was not further investigated in this study, since the research objective focused on reducing cement consumption to lower material costs and mitigate greenhouse gas emissions. In addition, the results of compressive and flexural strength tests confirmed that concretes with FA replacement levels of $15\text{--}25\%$ still satisfied the minimum requirements of the Department of Highways, Thailand with superior long-term performance, ensuring their suitability for pavement applications.

In general, fatigue life decreased as the stress ratio increased, regardless of FA content or r/b ratio. For example, at $FA = 15\%$ (**Figure 4.4(a)**), the fatigue life of unmodified concrete ($r/b = 0\%$) was 2022, 750, and 122 cycles at stress ratios of $60\%, 70\%$, and 80% , respectively. The inclusion of NRL at $r/b = 0.5\%$ significantly enhanced the fatigue life to 2564, 895, and 263 cycles under the same stress levels. However, increasing the r/b ratio beyond 1.0% resulted in a gradual reduction in fatigue life, reaching the lowest values of 1507, 562, and 55 cycles at $r/b = 2.0\%$, likely due to excessive NRL content retarding hydration and limiting pozzolanic reaction.

A similar trend was observed at FA = 20% (**Figure 4.4(b)**), where the fatigue life of the unmodified mix ($r/b = 0\%$) was 2546, 988, and 253 cycles at 60%, 70%, and 80% stress ratios, respectively. The optimum fatigue performance was again recorded at $r/b = 0.5\%$, where fatigue life increased to 2868, 1263, and 364 cycles, demonstrating that moderate NRL content improves resistance to cyclic loading. Beyond this point, further increases in r/b caused a decline in fatigue life, with the lowest values at $r/b = 2.0\%$ being 1954, 659, and 126 cycles, similar to the pattern found with 15% FA. At FA = 25% (**Figure 4.4(c)**), all mixes exhibited generally lower fatigue life compared to those with 15% and 20% FA replacement ratios. The unmodified mix ($r/b = 0\%$) recorded fatigue lives of 2269, 785, and 62 cycles at the respective stress ratios. As with the other FA levels, the addition of NRL at $r/b = 0.5\%$ improved performance to 2436, 863, and 87 cycles. However, as the r/b ratio increased further, fatigue life diminished, with $r/b = 2.0\%$ yielding the lowest recorded values of 1544, 201, and 39 cycles.



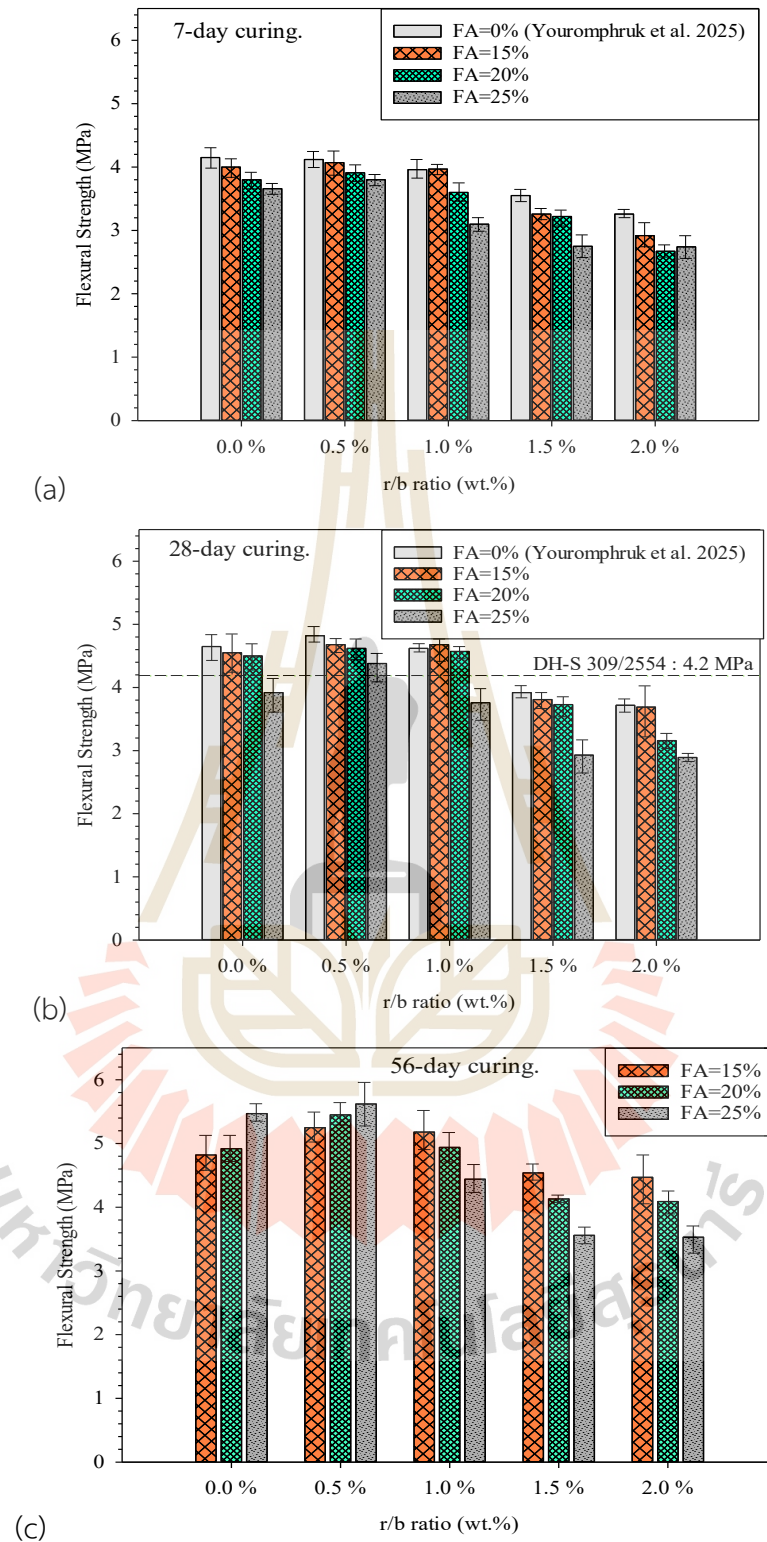


Figure 4.3 Flexural strength of FA-RCA-NRL concrete at
(a) 7 days; (b) 28 days; (c) 56 days.

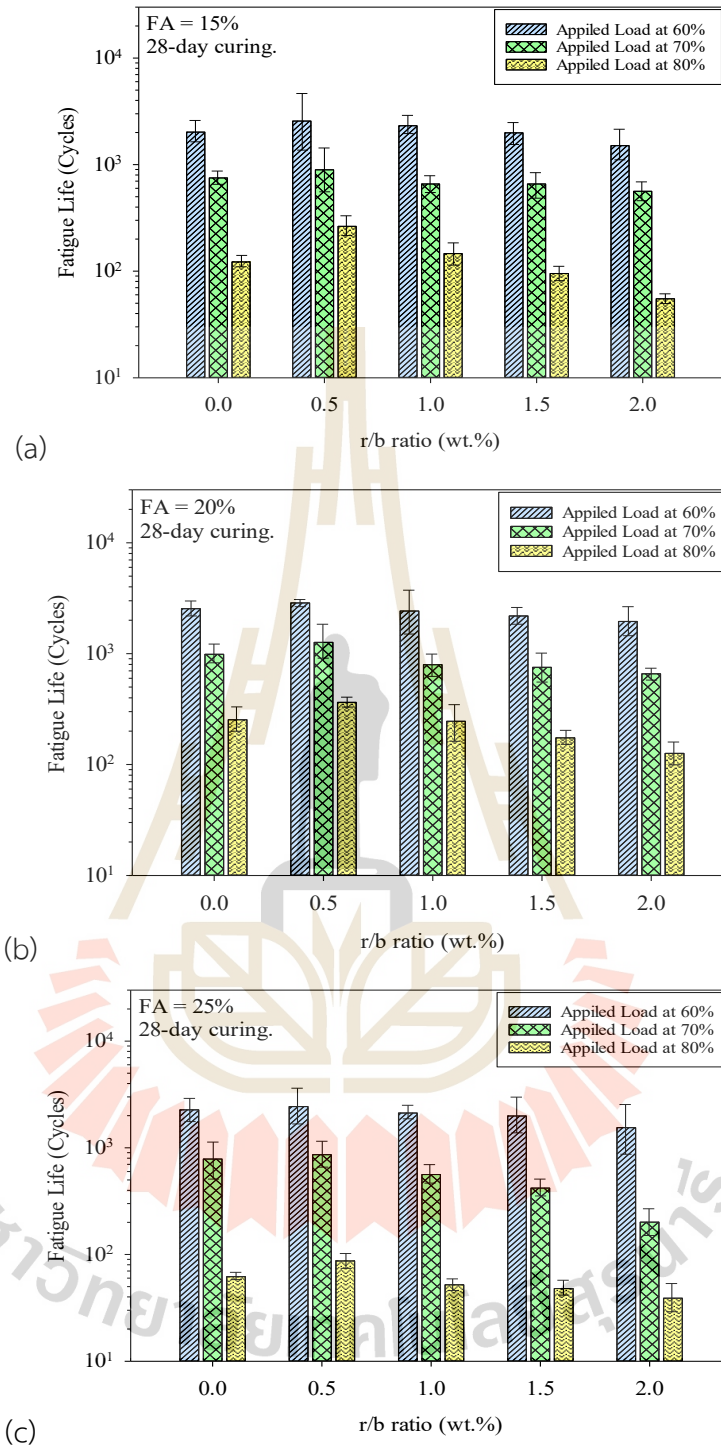


Figure 4.4 Fatigue life of FA-RCA-NRL concrete at 28 days for FA replacement levels of (a) 15%, (b) 20%, and (c) 25%.

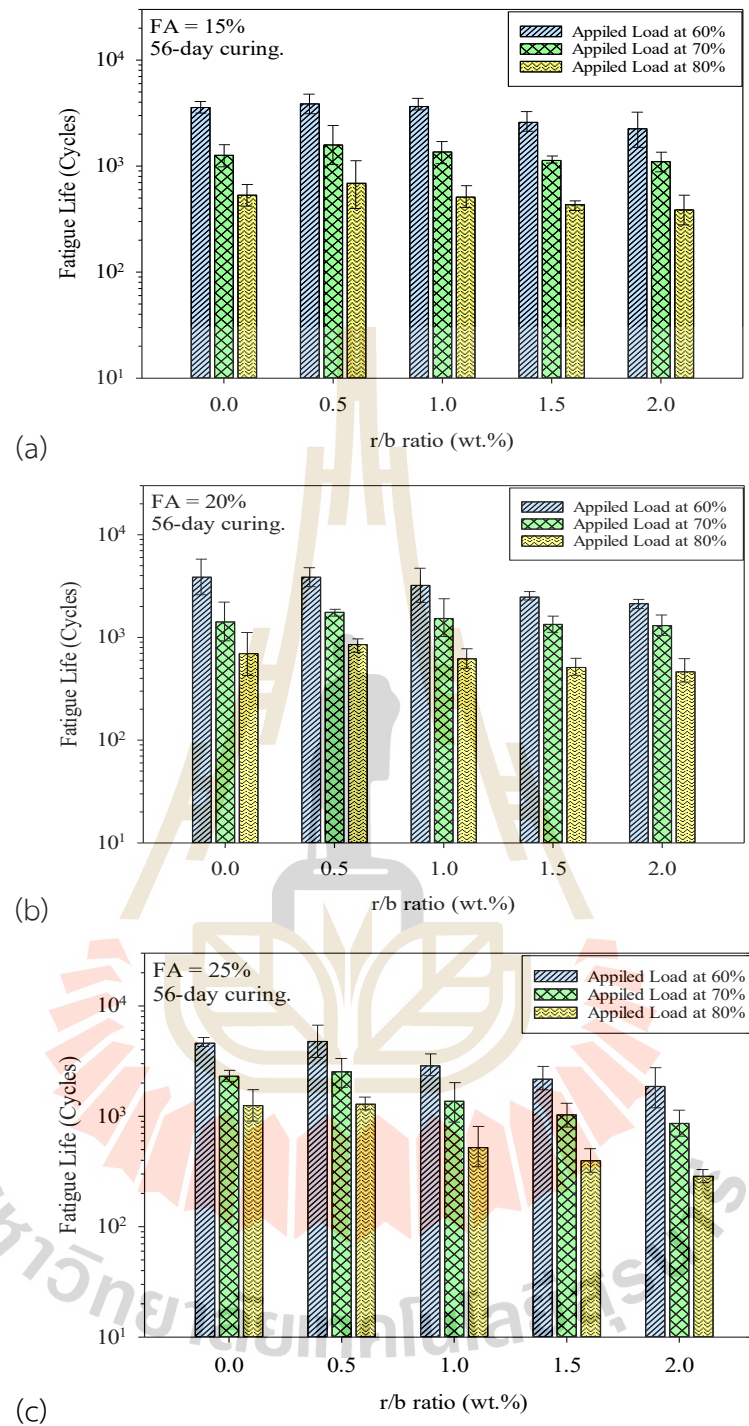


Figure 4.5 Fatigue life of FA-RCA-NRL concrete at 56 days for FA replacement levels of (a) 15%, (b) 20%, and (c) 25%.

Figure 4.5 illustrates the fatigue performance of FA-RCA-NRL concrete at 56 days of curing, incorporating various levels of FA replacement (15%, 20%, and 25%) and different r/b ratios, under three applied stress ratios (60%, 70%, and 80%). At 15% FA replacement ratio (**Figure 4.5(a)**), the unmodified concrete ($r/b = 0\%$) exhibited moderate fatigue resistance, recording 3567, 1265, and 532 cycles at stress ratios of 60%, 70%, and 80%, respectively. These values reflect limited long-term performance, particularly under high-stress conditions, likely due to the relatively low pozzolanic reactivity at this replacement level. Importantly, the incorporation of NRL at an optimum dosage ($r/b = 0.5$) extended the fatigue life to 3856, 1584 and 689 cycles at stress ratios of 60%, 70%, and 80%, respectively, confirming the beneficial interaction of latex film formation and FA-induced microstructural refinement at later ages. However, when the r/b ratio increased to 2.0, the fatigue life significantly decreased to 2247, 1101, and 386 cycles, suggesting that excessive NRL content impaired hydration and weakened bonding within the cementitious matrix.

At 20% FA replacement (**Figure 4.5(b)**), the unmodified concrete ($r/b = 0\%$) showed a marked improvement, achieving 3862, 1416, and 696 cycles at the respective stress levels. In this case, the addition of NRL at $r/b = 0.5$ further enhanced fatigue performance to 3896, 1756 and 852 cycles at stress ratios of 60%, 70%, and 80%, respectively, particularly under low-to-moderate stress ratios, highlighting the synergistic effect of FA's pozzolanic activity and latex bridging in prolonging fatigue life. Although a reduction in fatigue life was observed at $r/b = 2.0\%$, with values of 2136, 1306, and 463 cycles, the overall performance remained acceptable—especially under lower and moderate stress ratios. This indicates that the higher pozzolanic activity at 20% FA helped mitigate the negative effects of elevated NRL dosage.

The trend continued at 25% FA (**Figure 4.5(c)**), where the unmodified concrete ($r/b = 0\%$) achieved the highest fatigue life among all tested groups: 4596, 2305, and 1253 cycles at 60%, 70%, and 80% stress ratios, respectively. At this FA level, the presence of NRL at $r/b = 0.5$ sustained high fatigue resistance even beyond the control mix, with values of 4768, 2534, and 1288 cycles, underscoring the strong synergy between high-volume FA and moderate latex addition. Notably, even at $r/b = 2.0$, the fatigue performance remained relatively robust, with 1863, 862, and 286 cycles.

Although this represented a reduction compared to the unmodified mix, the decline was more gradual, suggesting that high-volume FA contributes to improved matrix resilience and can partially offset the detrimental impact of excessive latex content. Overall, these findings emphasize the critical role of FA replacement level in moderating the influence of NRL on fatigue life, especially over extended curing periods. In addition to fatigue life, **Figure 4.6** illustrates the displacement response of FA-RCA-NRL concrete under flexural fatigue loading at a stress ratio of 60%, incorporating 25% FA replacement and a constant w/c ratio of 0.4 across various r/b ratios. The number of cycles to failure (N_f) is plotted along the x-axis, while the y-axis represents the total displacement at the center of the beam during cyclic loading. The unmodified concrete ($r/b = 0\%$) exhibited moderate fatigue life, with a notable increase in displacement toward the final stages of loading, indicating failure after about 80% of its fatigue life. In contrast, the mix with $r/b = 0.5\%$ showed the highest fatigue life and noticeably lower displacement accumulation than the mixes with $r/b = 1.5\%$, and 2.0% , identifying it as the optimum r/b ratio for this mix. This trend is consistent with the findings of Suddeepong et al. (2022), which demonstrated that low dosages of NRL can enhance ductility, energy absorption, and fatigue resistance by improving the microstructural bond and limiting microcrack propagation. However, further increases in r/b ratio to 1.0, 1.5, and 2.0 led to a noticeable decline in fatigue performance, as seen in the lower fatigue life and greater displacement accumulation. This behavior is attributed to the adverse effects of excessive latex, which can retard hydration, disrupt matrix formation, and increase plastic deformation. The shape of the displacement curves also reflects the typical three-phase fatigue behavior observed in cementitious materials: an initial phase of crack initiation, a stable crack propagation phase, and a final phase characterized by rapid displacement growth leading to failure. The $r/b = 0.5$ mix maintained a prolonged stable phase with low deformation progression, suggesting superior crack control and energy dissipation under repeated loading.

Figure 4.7 presents the flexural fatigue performance of FA-RCA-NRL concrete at 56 days of curing under stress ratios of 60%, 70%, and 80%, with varying r/b ratios and FA replacement levels of 15%, 20%, and 25%, compared with the PCA (1984) fatigue model. The results show that the NRL-modified RCA concretes scatter closely

around the PCA model line, confirming that SR predominantly governs fatigue life. The results clearly showed that fatigue life was strongly influenced by both the r/b ratio and the applied stress ratio. At FA = 15%, the unmodified mix (r/b = 0%) recorded fatigue lives of 3567, 1265, and 532 cycles at stress ratios of 60%, 70%, and 80%, respectively. A similar trend was observed at FA = 20%, where the unmodified mix achieved 3862, 1416, and 696 cycles. The peak performance was again at r/b = 0.5% (3996, 1756, and 852 cycles), suggesting an optimum NRL dosage. Beyond this point, fatigue life progressively declined, particularly at r/b = 2.0%, where the fatigue life dropped to 2136, 1306, and 463 cycles. These findings align with (Suddeepong et al. 2022), who demonstrated that NRL-modified concrete at optimum r/b ratios exhibits superior flexural fatigue resistance compared with conventional concrete, due to reduced plastic deformation and improved ductility.

Figure 4.7 presents the regression analysis between the logarithmic fatigue life ($\log N_f$) and the applied stress ratio (SR) for the FA-NRL-RCA concrete. This behavior demonstrates the beneficial effect of optimal NRL incorporation in improving the fatigue resistance of FA-RCA concrete. The strong correlation between the measured and predicted fatigue lives further confirms that the proposed regression model reliably represents the fatigue behavior of the developed mixtures.

From a mechanistic design perspective, the Department of Highways (DH-S309/2544) specifies fatigue life as a controlling factor in rigid pavement performance. For normal concretes, fatigue life is strongly governed by the stress ratio (SR) in accordance with the PCA model. However, recent studies indicate that in NRL-concretes, this relationship is modified: at equivalent SR, the presence of latex films improves crack resistance and extend fatigue life beyond conventional predictions. This suggests that mix design for NRL-concrete pavement should not only satisfy compressive ($f_c > 32$ MPa) and flexural strength ($f_f > 4.2$ MPa) requirements but also optimize the r/b ratio at ~0.5 to achieve superior fatigue performance. By adopting this approach, pavement thickness can potentially be reduced without compromising service life, offering both economic and sustainability benefits, consistent with design recommendations by (Suddeepong et al. 2022 and Yaowarat et al. 2021).

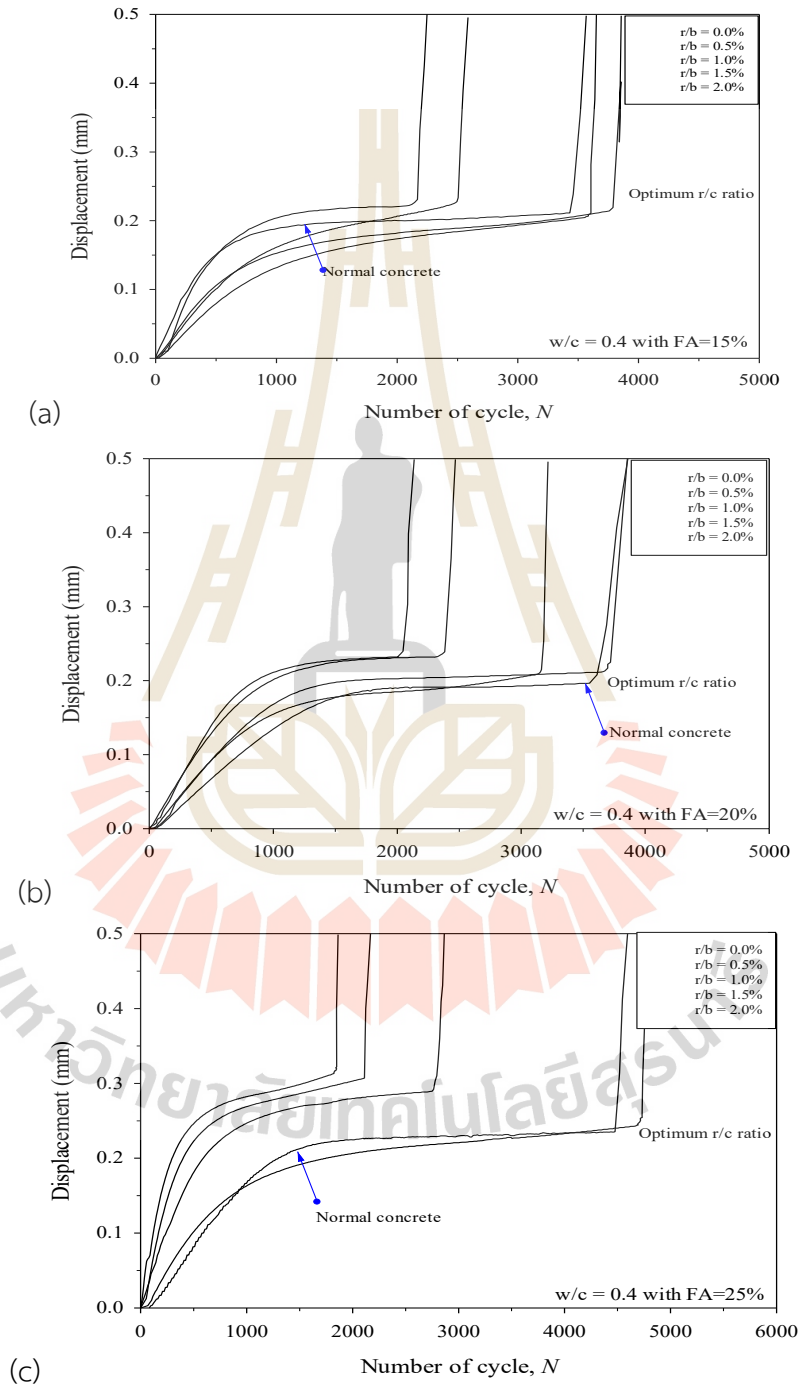


Figure 4.6 Flexural fatigue response of FA-RCA-NRL concrete under a stress ratio of 60% after 56 days for FA replacement levels of (a) 15%, (b) 20%, and (c) 25%.

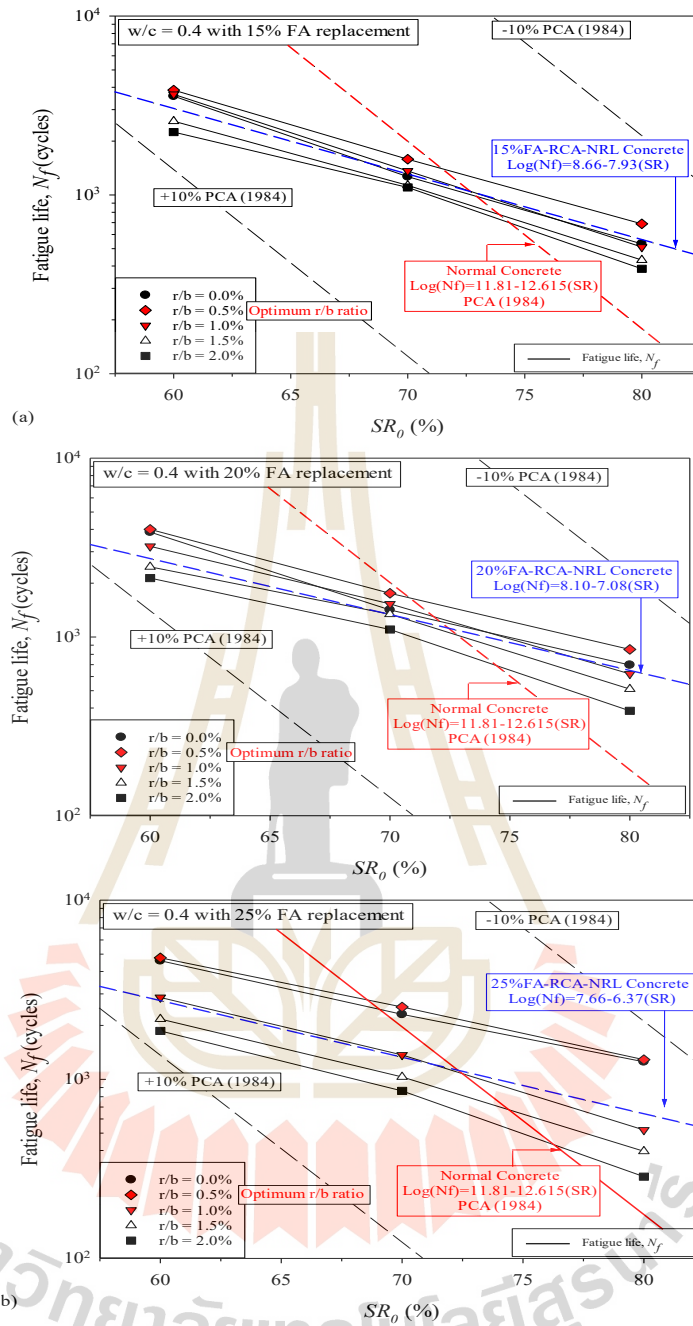


Figure 4.7 Effect of r/b ratio on fatigue life versus SR_0 relationship of FA-RCA-NRL concrete at 56 days for varying fly ash replacement levels: (a) 15%, (b) 20%, and (c) 25%.

4.4 MICROSTRUCTURAL ANALYSIS

To understand the microstructural characteristics of FA-RCA-NRL concrete, scanning electron microscope (SEM) analysis was performed at 28 days of curing. The SEM was operated at 15 kV with secondary electron imaging to characterize the morphology of the concrete surface. **Figure 4.8** illustrates the microstructure of FA-RCA-NRL concrete incorporating 25% FA as a partial cement replacement and varying r/b ratios of 0%, 0.5%, and 2%. In **Figure 4.8(a)** (r/b = 0%), the microstructure displays a relatively dense matrix with well-formed C-S-H gel and needle-like ettringite crystals, reflecting active early-age hydration (Park et al. 2016; Yaowarat et al. 2019). Smooth and spherical FA particles are embedded in the matrix, indicating partial pozzolanic reaction (Arulrajah et al. 2019; Elyasigorji et al. 2023; Golewski 2022). In the absence of NRL, no polymer films are observed, allowing for uninterrupted hydration and gel formation. In **Figure 4.8(b)**, corresponding to the optimal r/b ratio of 0.5%, the microstructure appears more homogeneous and compact compared to the r/b = 0% mix (**Figure 4.8(a)**). Thin and continuous NRL films were evident, interwoven with the hydration products and bridging microvoids within the matrix. These films likely fill capillary pores and reinforce interfacial zones, resulting in enhanced flexural strength and fatigue life due to the improved ductility and crack-bridging capability of the latex (Hoy et al. 2023; Li et al. 2021; Stirewalt 2021). The smoother surface texture and denser C-S-H gel formation suggest a favorable interaction between pozzolanic FA reaction and moderate latex addition. The microstructure at this dosage reflects a balanced synergy: sufficient hydration, strong inter-particle bonding, and enhanced toughness from the polymer network (Yaowarat et al. 2018; Yaowarat et al. 2021).

In contrast, **Figure 4.8(c)**, representing a higher r/b ratio of 2%, shows a more porous and disrupted morphology. Thicker NRL films are visible, particularly around unreacted or partially hydrated FA particles and hydration products. These films appear to cluster or isolate phases, forming physical barriers that retard water transport and ion exchange, which are essential for continued hydration (Han et al. 2024; Kang et al. 2015; Knapen and Van Gemert 2015; Wang et al. 2023). The resulting structure is less cohesive, with poorly developed C-S-H gel and visible voids. This morphology correlates with a reduction in compressive strength, as the excessive latex interferes

with the formation of continuous cementitious bonds. Moreover, the plastic nature of the excess NRL may have introduced internal weaknesses that compromise the material's load-bearing capacity under compression (Awoyera et al. 2024).

In **Figure 4.9(a)** ($r/b = 0\%$), the matrix revealed a dense and well-developed microstructure, featuring numerous etched spherical FA particles and needle-like ettringite crystals embedded within a continuous C-S-H gel network. The pronounced surface dissolution of the FA indicates active and advanced pozzolanic reaction, contributing to the formation of additional cementitious products (Golewski 2022; Kang et al. 2022; Wang and Ishida 2019). Although some voids remain due to the absence of NRL, the unimpeded hydration enables the development of a cohesive and well-bonded matrix. This results in the highest compressive strengths among the mixes, as the structure benefits from complete gel formation without interference from polymer films.

Figure 4.9(b) ($r/b = 0.5\%$) represents the optimal latex dosage, showing a compact and refined microstructure. The matrix is densely packed with granular C-S-H and well-integrated FA particles. The inset magnification reveals thin NRL films bridging microvoids and bonding hydration products, which improve flexural performance through crack-bridging effects. While some porosity persists, the synergistic effect of FA and moderate latex dosage fosters both pozzolanic reactivity and matrix reinforcement. The structure is optimized for bending resistance, explaining its superior flexural strength at this dosage. In **Figure 4.9(c)** ($r/b = 2\%$), the matrix deteriorates visibly. The microstructure is porous, with disconnected gel phases and clusters of unreacted or partially reacted FA particles. Thick, continuous latex films dominate the surface, forming barriers around hydration sites. These films restrict water movement and reduce the efficiency of hydration and pozzolanic reactions, leading to a fragmented and weakly bonded matrix (Naseem et al. 2023; Yaowarat et al. 2021). The excess polymer acts more as an insulator than a reinforcing agent, correlating with the lowest compressive strength among the mixes.

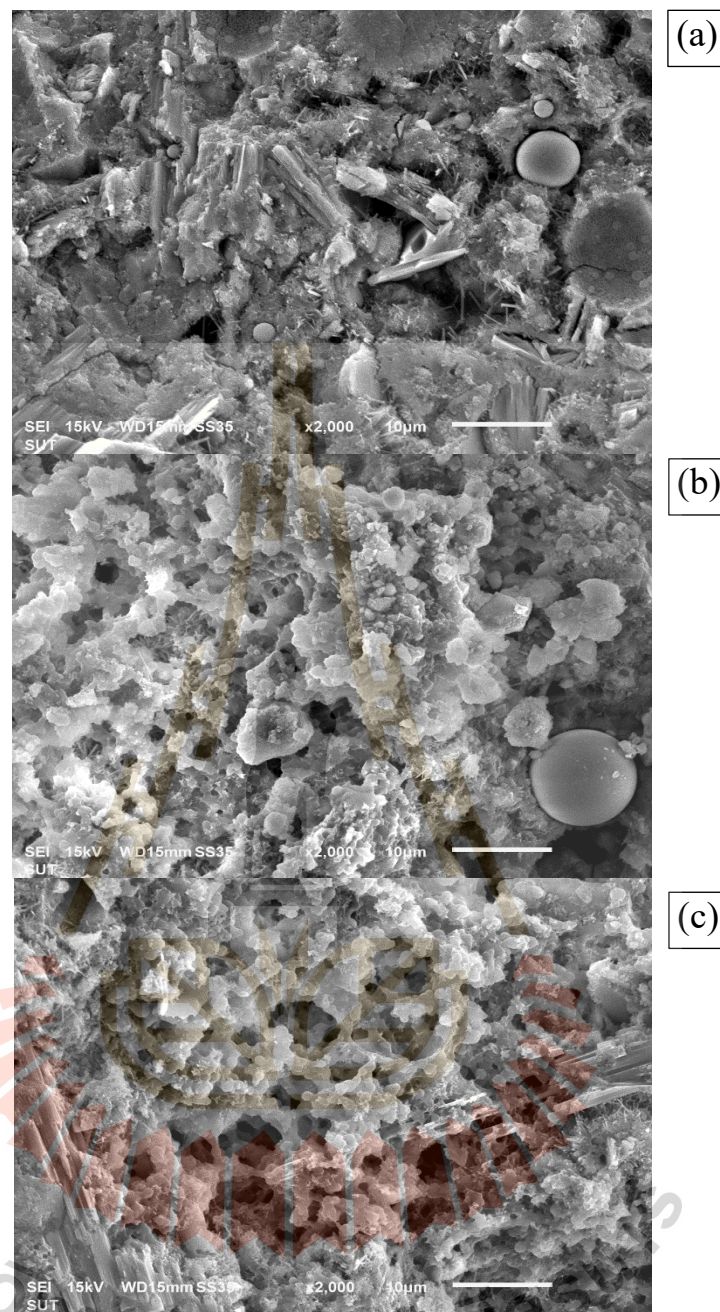


Figure 4.8 SEM images of FA-RCA-NRL concrete at 28 days with 25% fly ash replacement and r/b ratios of (a) 0%, (b) 0.5% (optimal), and (c) 2%

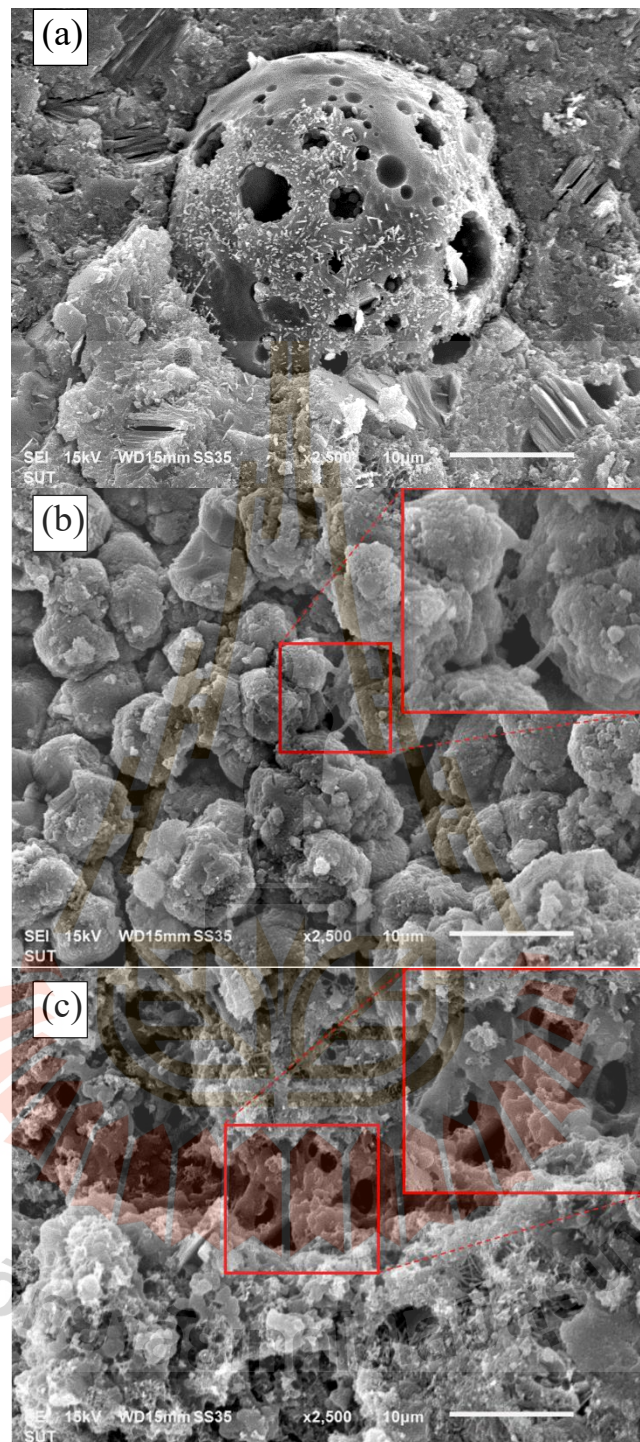


Figure 4.9 SEM images of FA-RCA-NRL concrete at 56 days with 25% fly ash replacement and r/b ratios of (a) 0%, (b) 0.5% (optimal), and (c) 2%

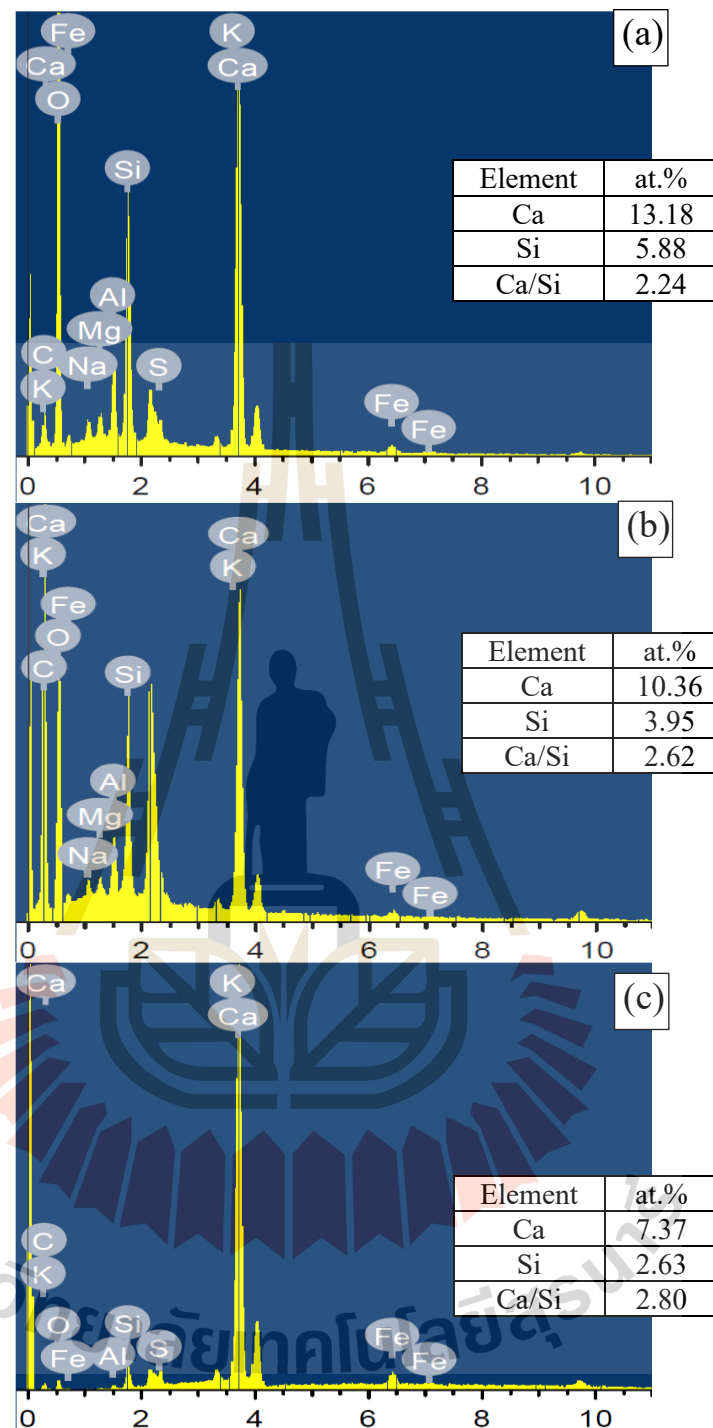


Figure 4.10 EDS images of FA-RCA-NRL concrete at 56 days with 25% fly ash replacement and r/b ratios of (a) 0%, (b) 0.5% (optimal), and (c) 2%

Figure 4.10 presents the EDX spectra of FA-RCA-NRL concretes at 56 days with 25% FA replacement for different r/b ratios. The dominant elements identified across

all samples were Ca, Si, and Al, confirming the formation of C-S-H and C-A-S-H phases that govern the strength development of pozzolanic cementitious systems (Tokpatayeva et al. 2022; Wang and Ishida 2019; Wang et al. 2021). In the NRL-free mixture ($r/b = 0\%$), the peaks of Ca, Si, and Al were most prominent, indicating a high degree of cement hydration and active pozzolanic reaction between FA and the liberated calcium hydroxide, which corresponds to the dense microstructure and high compressive strength observed in SEM analysis. As the r/b ratio increased to 0.5% and 2.0%, the relative intensities of Si and Al declined, while the carbon (C) peak-associated with the latex polymer (Rippel et al. 2002) -became increasingly pronounced, reflecting the growing presence of polymer films within the matrix. Quantitative EDX analysis further revealed that the Ca/Si ratio increased from 2.24 in the control mix ($r/b = 0\%$) to 2.62 at $r/b = 0.5\%$ and 2.80 at $r/b = 2.0\%$, indicating a progressive shift toward a Ca-rich C-S-H composition and reduced silica incorporation from FA. This trend suggests that higher NRL contents tend to suppress the pozzolanic reaction and the formation of secondary C-S-H, leading to a chemically less refined microstructure. Nevertheless, the $r/b = 0.5\%$ mixture, despite its moderately higher Ca/Si ratio, exhibited the greatest compressive, flexural, and fatigue strengths, implying that the physical benefits of latex film formation-such as crack bridging, improved ITZ bonding, and enhanced energy dissipation-can outweigh the less favorable chemical composition at this dosage. Conversely, at $r/b = 2.0\%$, the combination of an excessively high Ca/Si ratio and the porous, polymer-rich morphology observed in SEM images reflects severe hydration inhibition and weakened matrix connectivity, explaining the marked reduction in mechanical and fatigue performance at this dosage.

4.5 CARBON EMISSION AND COST ANALYSES

The life-cycle assessment (LCA) in this study followed a cradle-to-gate system boundary, encompassing raw material extraction, processing, transportation, and concrete production up to the batching stage. The emission factors used for the calculations are summarized in Table 4 and were primarily obtained from published literature sources (McLellan et al., 2011; Ekundayo et al., 2019; Alzard et al., 2020; Usubharatana and Phungrassami, 2018; Kanagaraj et al., 2025). The selected emission

values fall within the ranges reported by internationally recognized databases, notably the IPCC (2006) Guidelines (Eggleston et al. 2006; IPCC 2006), thereby confirming their consistency with established life-cycle inventory data for cement, aggregates, and industrial by-products. Consequently, the results represent the embodied carbon of the concrete mixtures, excluding service-life and end-of-life stages. To reflect realistic local production conditions in Thailand, it was assumed that all raw materials were sourced within a 50 km radius of the batching plant and transported by diesel trucks with an average emission factor of 0.10 kg CO₂-e per ton·km. The cost and transport data were based on average 2024 market values in the Nakhon Ratchasima region, including fuel, handling, and delivery. These assumptions ensure that both the emission and cost assessments represent typical regional supply chains under Thai conditions.

Figure 4.11 illustrates the total CO₂-equivalent emissions (kg CO₂-e), material cost (USD/m³) and fatigue life (cycles at SR = 60%) of seven FA-RCA-NRL concrete mixtures, incorporating FA replacement levels of 0%, 15%, 20%, and 25%, with and without 0.5% NRL. The emissions and material cost were calculated based on the factors for each material, as presented in **Table 4.4**. It should be noted that the comparison in **Figure 4.11** focuses on mixtures with $r/b = 0.5\%$, since this dosage was identified as the optimum latex content. At this level, both f_c and f_f consistently satisfied the minimum requirements for rigid pavement specified by the Department of Highways, Thailand ($f_c \geq 32$ MPa, $f_f \geq 4.2$ MPa), while higher r/b ratios (≥ 1.0) led to performance reductions below the standard. Therefore, $r/b = 0.5\%$ was selected as the representative condition for evaluating the balance among mechanical performance, fatigue resistance, emissions, and material cost.

The results of **Figure 4.11(a)** revealed that cement dominated the carbon footprint, contributing over 98% of total emissions in each mix. The reference mix with FA = 0% (Youromphruk et al. 2025) recorded the highest CO₂ emissions at 402.83 kg CO₂-e. In comparison, as FA content increased 15% to 25%, cement consumption and total CO₂ emissions decreased progressively, with the lowest emission observed in the RCA+25% FA mixture (304.20 kg CO₂-e). The addition of 0.5% NRL marginally increased emissions by about 0.42 kg CO₂-e per mix. For example, RCA+0.5%NRL+15%FA emitted

344.08 kg CO₂-e compared to 343.66 kg CO₂-e for the NRL-free equivalent, and this small increase was consistent across all FA replacement levels. Importantly, if RCA was entirely replaced with natural aggregate (NA) at the same dosage of 1018 kg per cubic meter, the total CO₂ emissions per mix would increase by approximately 35.6 kg CO₂-e, highlighting the environmental benefit of using RCA over NA.

Table 4.4 Emission factors (kg CO₂-e/kg) and Material Cost of concrete mix materials

Material	Emission factor (kg CO ₂ -e/kg)	Material Cost (USD/kg)
Cement (kg)	0.86 (McLellan et al. 2011)	0.114 (Egemen et al. 2024)
Fly ash (kg)	0.007 (McLellan et al. 2011)	0.0124 (Reiner and Rens 2006)
Sand	0.006 (Ekundayo et al. 2019)	0.0062 (Hamada et al. 2023)
RCA	0.000667 (Alzard et al. 2020)	0.0055 (Prasittisopin et al. 2025)
NRL	0.095 (Usubharatana and Phunggrassami 2018)	1.92 (Yaowarat et al. 2021)
NA	0.035 (Kanagaraj et al. 2025)	0.042 (Kanagaraj et al. 2025)

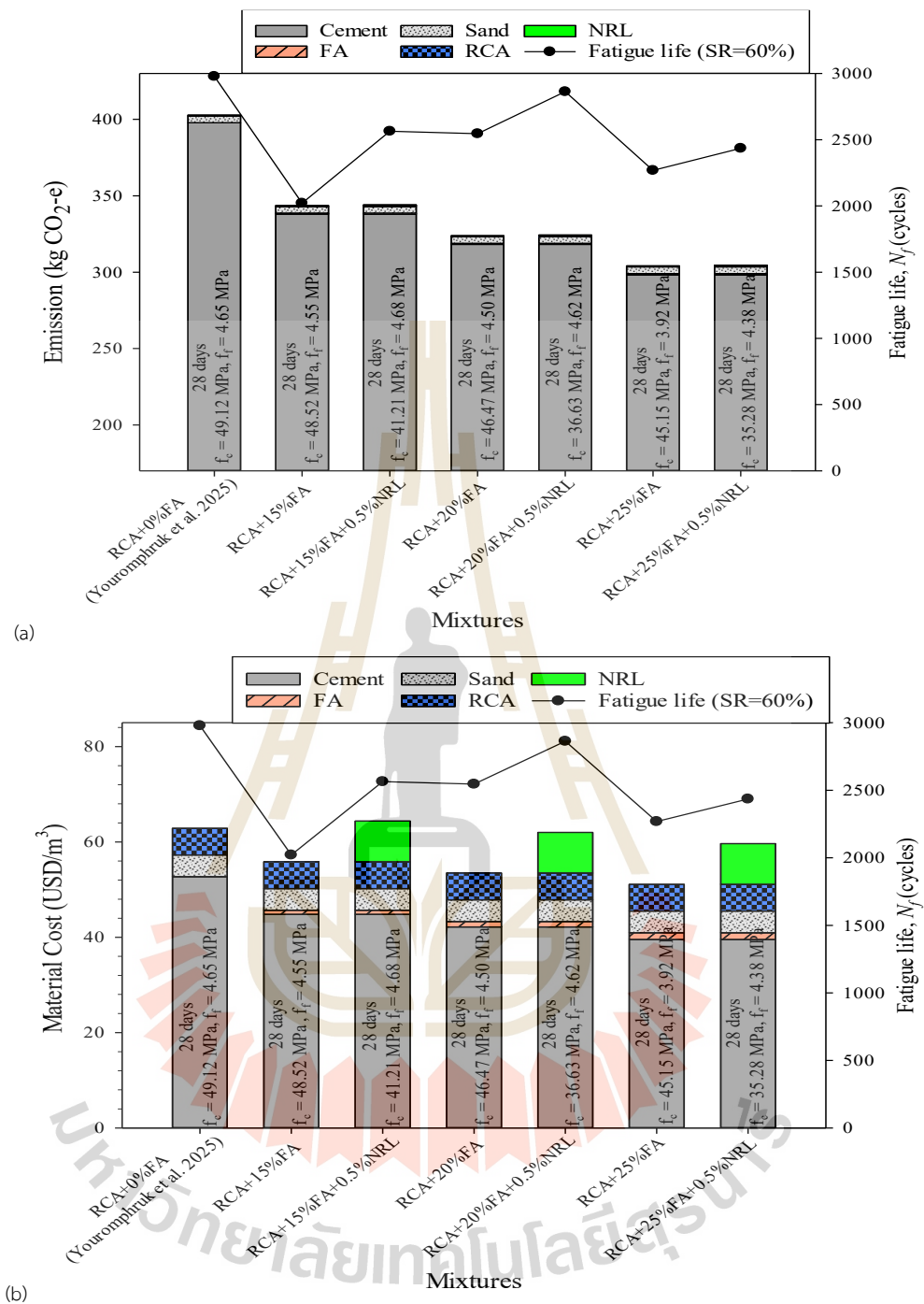


Figure 4.11 FA-RCA-NRL concrete mixtures and corresponding 28-day compressive strength, flexural strength and fatigue life: (a) CO₂ emissions and (b) material cost.

When engineering performance is considered together with emissions, the results show that flexural strength at 28 days and fatigue life at SR = 60% were broadly comparable among the FA-blended mixtures and the FA = 0% reference. The FA = 0% mix achieved the highest values, with $f_f = 4.65$ MPa and a fatigue life of 2978 cycles, but at the cost of the largest footprint (402.83 kg CO₂-e). By contrast, FA substitution reduced emissions substantially while maintaining acceptable performance. For example, at 15% FA, the r/b = 0% mix recorded $f_f = 4.55$ MPa and 2022 cycles, while the addition of 0.5% NRL slightly increased flexural strength (4.68 MPa) and improved fatigue life to 2564 cycles, although emissions rose marginally. At 20% FA, the r/b = 0% mix achieved $f_f = 4.50$ MPa and 2546 cycles, and with 0.5% NRL, flexural strength remained comparable (4.62 MPa) while fatigue life increased to 2863 cycles, again with only a small emission penalty. At 25% FA, the r/b = 0% concrete recorded lower values ($f_f = 3.92$ MPa, 2269 cycles), yet the incorporation of 0.5% NRL enhanced both flexural strength (4.38 MPa) and fatigue resistance (2436 cycles), narrowing the gap with the FA = 0% baseline while still achieving the lowest footprint (304.20–304.63 kg CO₂-e).

A similar trend was observed for material cost (**Figure 11(b)**). The FA = 0% reference mix (Youromphruk et al. 2025) recorded the highest cost at 62.87 USD/m³, which can be attributed to its full reliance on cement, the most expensive binder at 0.114 USD/kg. In contrast, partial replacement of cement with FA (unit cost = 0.0124 USD/kg) reduced the overall cost substantially, down to 51.13 USD/m³ for the RCA+25%FA mix. This highlights the strong economic benefit of FA substitution, since FA costs less than one-ninth of cement per kilogram. The addition of NRL, which has the highest unit cost among the considered materials (1.92 USD/kg), increased the total cost of mixtures by about 8–9 USD/m³. For instance, RCA+0.5%NRL+25%FA costs 59.67 USD/m³ compared with 51.13 USD/m³ for RCA+25%FA. This trend was consistent across all FA replacement levels.

In terms of engineering performance, the FA = 0% mixture achieved the highest f_c (49.12 MPa), f_f (4.65 MPa), and N_f (2978 cycles) at 28 days (Youromphruk et al., 2025), outperforming FA-blended concretes. Nevertheless, FA-based mixtures demonstrated only slightly lower strengths (e.g., 48.52 MPa, 4.55 MPa, and 2022 cycles for RCA+15%FA), while offering significant environmental and cost benefits. The addition

of NRL improved f_f and N_f at moderate levels (e.g., 4.68 MPa and 2564 cycles for RCA+0.5%NRL+15%FA). However, these benefits came at the expense of higher material cost and a moderate reduction in compressive strength.

These findings emphasize that partial replacement of cement with FA not only reduces the environmental impact but also lowers material cost. For example, CO₂ emissions decreased from 402.83 kg CO₂-e and a cost of 62.87 USD/m³ in the FA = 0% reference mix to as low as 304.20 kg CO₂-e and 51.13 USD/m³ in the RCA+25%FA mixture. Although the compressive and flexural strengths of FA-blended concretes (e.g., 45.15 MPa and 3.92 MPa at 28 days for RCA+25%FA) were slightly lower than the FA = 0% baseline (49.12 MPa and 4.65 MPa), the trade-off is offset by substantial sustainability and economic gains. The incorporation of a low dosage of NRL further enhanced flexural strength (e.g., 4.68 MPa for RCA+0.5%NRL+15%FA) but increased costs (to 64.36 USD/m³) and reduced compressive strength (41.21 MPa). Overall, the compressive and flexural strength values annotated on each bar confirm that FA substitution strikes a favorable balance between lower CO₂ emissions, reduced cost, and adequate mechanical performance, while NRL addition offers flexural benefits at the expense of higher cost and moderate compressive strength loss.

When considering sustainability and economics under the Thai pavement criteria ($f_c \geq 32$ MPa, $f_f \geq 4.2$ MPa), two mixes stand out as optimal choices. For minimizing emissions, the RCA+0.5%NRL+25%FA mix achieved the lowest CO₂ footprint while still meeting the requirements, recording 304.63 kg CO₂-e/m³, with $f_c = 35.28$ MPa, $f_f = 4.38$ MPa, and a cost of 59.67 USD/m³. In contrast, for minimizing cost, the RCA+20%FA mix offered the most economical option at 53.48 USD/m³, while also maintaining acceptable environmental and mechanical performance (323.93 kg CO₂-e/m³, $f_c = 46.47$ MPa, $f_f = 4.50$ MPa). These results highlight that RCA+0.5%NRL+25%FA is the most sustainable mix in terms of emissions, whereas RCA+20%FA provides the best balance for cost efficiency.

4.6 CONCLUSION

This study highlights the synergistic effects of fly ash (FA) and natural rubber latex (NRL) on the mechanical, microstructural, and durability performance of RCA-

based pavement concrete. Moderate NRL dosages ($r/b = 0.5\text{--}1.0\%$) combined with higher FA contents (20-25%) improved flexural strength and fatigue resistance, attributed to thin latex films that bridged microvoids and strengthened the interfacial transition zone. In contrast, excessive NRL ($r/b \geq 1.5\%$) inhibited hydration, producing a porous, Ca-rich matrix with reduced Si and Al contents as shown by SEM-EDX. The optimum mix ($r/b = 0.5\%$, FA=25%) achieved the best balance of strength, ductility, and fatigue performance for pavement applications.

From a sustainability perspective, cement was the primary source of CO₂ emissions, but this impact was substantially reduced through FA substitution. Increasing FA content progressively lowered both emissions and cost, with RCA+25%FA achieving the lowest cost (51.13 USD/m³) and the lowest footprint among FA-only mixes. The inclusion of NRL slightly increased emissions (~ 0.42 kg/m³) and raised costs by about 8–9 USD/m³ due to its higher unit price (1.92 USD/kg), as seen in RCA+0.5%NRL+25%FA (59.67 USD/m³). When considering sustainability and economics under the Thai pavement criteria ($f_c \geq 32$ MPa, $f_r \geq 4.2$ MPa), two mixes were identified as optimal. The RCA+0.5%NRL+25%FA mix provided the lowest CO₂ footprint (304.63 kg CO₂-e/m³), with adequate strength ($f_c = 35.28$ MPa, $f_r = 4.38$ MPa), and a cost of 59.67 USD/m³. While the RCA + 20% FA mix offered the most economical solution (53.48 USD/m³) with balanced environmental and mechanical performance (323.93 kg CO₂-e/m³, $f_c = 46.47$ MPa, $f_r = 4.50$ MPa). Overall, the former is recommended for maximum sustainability, whereas the latter provides the best cost–performance balance for pavement concrete applications. It should be noted that the CO₂ emission and cost analyses are based on local Thai production and transport conditions, and the quantitative results may vary under different regional supply chains or energy systems. Nevertheless, the comparative trends and identified optimal mix proportions remain valid for sustainable pavement concrete design.

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CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary and conclusions

This thesis consists of two main objectives.

The first is to investigate the influence of natural rubber latex (NRL) on the compressive and flexural strength development of recycled concrete aggregate (RCA) pavement concrete. RCA was used as the coarse aggregate, river sand as the fine aggregate, and the dry rubber-to-cement ratio (r/c) was varied at different water-to-cement ratios (w/c). The Two-Stage Mixing Approach (TSMA) was adopted to improve the coating and bonding of RCA. The mechanical behavior was examined through compressive and flexural strength tests, flexural stiffness–deflection response, and microstructural analysis via SEM–EDX and XRD.

The second objective is to develop sustainable pavement concrete by incorporating fly ash (FA) as a supplementary cementitious material (SCM) together with NRL. The influence of FA replacement ratio (FA/c), dry rubber-to-binder ratio (r/b), and curing time on compressive strength, flexural strength, fatigue resistance, microstructure, carbon emissions, and material cost was systematically investigated. The conclusions can be drawn as follows.

5.1.1 Compressive and Flexural Strength of Natural Rubber Latex-Modified Pavement Concrete Utilizing Recycled Concrete

This chapter presents the development of RCA–NRL concrete at w/c ratios of 0.3–0.5. The results indicated that the incorporation of NRL significantly altered the hydration behavior, mechanical strength, and ductility of the concrete. The flexural strength increased with increasing r/c ratio until reaching an optimum value, after which the strength decreased. The optimum r/c ratio depended strongly on w/c :

- 1) $w/c = 0.3$: optimum at $r/c = 1.0\%$
- 2) $w/c = 0.4$: optimum at $r/c = 0.5\%$

3) $w/c = 0.5$: NRL addition did not provide benefits, and all mixes fell below the flexural requirement of the Department of Highways (DOH).

Improvement in flexural strength is attributed to the formation of thin NRL films bridging microcracks and enhancing the tensile resistance of the cement matrix. At the optimum r/c , the specimens also demonstrated significantly improved stiffness and ductility.

However, when the r/c exceeded the optimum, thick NRL films formed, which enveloped the cement matrix and impeded hydration, causing reductions in both compressive and flexural strengths. SEM-EDX and XRD analyses confirmed reduced C-S-H formation and decreased portlandite intensity at higher r/c ratios. Based on Thailand DOH pavement requirements (28-day $f_c \geq 32$ MPa, $f_f \geq 4.2$ MPa), the workable range for structural pavement applications was $w/c \leq 0.4$ and $r/c \leq 1.0\%$. NRL-modified concrete at these levels demonstrates promising potential for improving pavement ductility and crack resistance.

5.1.2 Chapter 4: Fly Ash and Natural Rubber Latex Modified Recycled Aggregate Concrete as Sustainable Rigid Pavement Surface

This chapter evaluates the combined effects of fly ash (FA) and NRL on RCA concrete with a fixed w/b ratio of 0.4. The study investigated FA replacement levels of 15%, 20%, and 25% and r/b ratios ranging from 0–2%. The compressive strength (f_c) of all concretes increased with curing time, and the long-term strength (56 days) was dominated by the pozzolanic reaction of FA. While FA reduced early-age strength, mixes with 20–25% FA achieved the highest long-term strength due to additional C-S-H and C-A-S-H formation. SEM-EDX confirmed that silica-rich FA refined the matrix and produced denser microstructures over time. NRL affected strength depending on dosage.

1) $r/b = 0.5\%$ consistently produced the highest flexural strength and fatigue life.

2) $r/b \geq 1.5\%$ caused significant reductions in f_c and f_f due to thick polymer films inhibiting hydration.

The flexural strength at 28 days met the Thai pavement requirement ($f_f \geq 4.2$ MPa) when:

- 1) $FA \leq 20\%$ with $r/b \leq 1.0\%$
- 2) $FA = 25\%$ with $r/b = 0.5\%$

Fatigue testing at stress ratios (SR) of 60–80% showed that mixes with 0.5% NRL provided superior fatigue resistance due to enhanced ductility and crack-bridging. Higher FA content (20–25%) further improved fatigue performance at 56 days through microstructural refinement. The fatigue life trends closely followed the PCA model but with improved resistance at optimal r/b . The life-cycle assessment revealed that cement contributed over 98% of total CO₂ emissions. Replacing cement with FA significantly reduced emissions and material cost. RCA+25%FA achieved the lowest CO₂ emissions (≈ 304 kg CO₂-e/m³) and lowest cost (51.13 USD/m³) among FA blends. Adding NRL increased cost (due to high unit price) but improved mechanical performance.

Two optimal mixes were identified:

- 1) Most sustainable: RCA + 25% FA + 0.5% NRL (lowest carbon footprint).
- 2) Most economical: RCA + 20% FA (lowest cost with acceptable strength).

Overall, FA–NRL–RCA concrete provides a viable and sustainable pavement material when the r/b ratio is optimized at 0.5%.

5.2 Recommendations for future work

1) NRL and Other Polymer Alternatives

This study focused on natural rubber latex. Other elastomeric or water-soluble polymer modifiers—such as ethylene-vinyl acetate (EVA), styrene-butadiene rubber (SBR), or bio-based latexes—should be explored to compare their effects on hydration, ductility, and long-term durability.

2) Alternative Pozzolanic Materials

FA was used as the principal SCM. Future studies may investigate bagasse ash, rice husk ash, metakaolin, volcanic ash, or limestone calcined clay to evaluate variations in pozzolanic reactivity and environmental performance.

3) Durability Under Aggressive Environments

The chemical resistance of NRL-modified RCA concrete should be examined under:

- 3.1) sulphate attack
- 3.2) acid exposure
- 3.3) chloride ion penetration
- 3.4) freeze–thaw cycles

4) Field-Scale Validation and Long-Term Monitoring

Full-scale pavement trials should be conducted to validate fatigue life predictions, drying shrinkage behavior, and long-term surface deterioration.

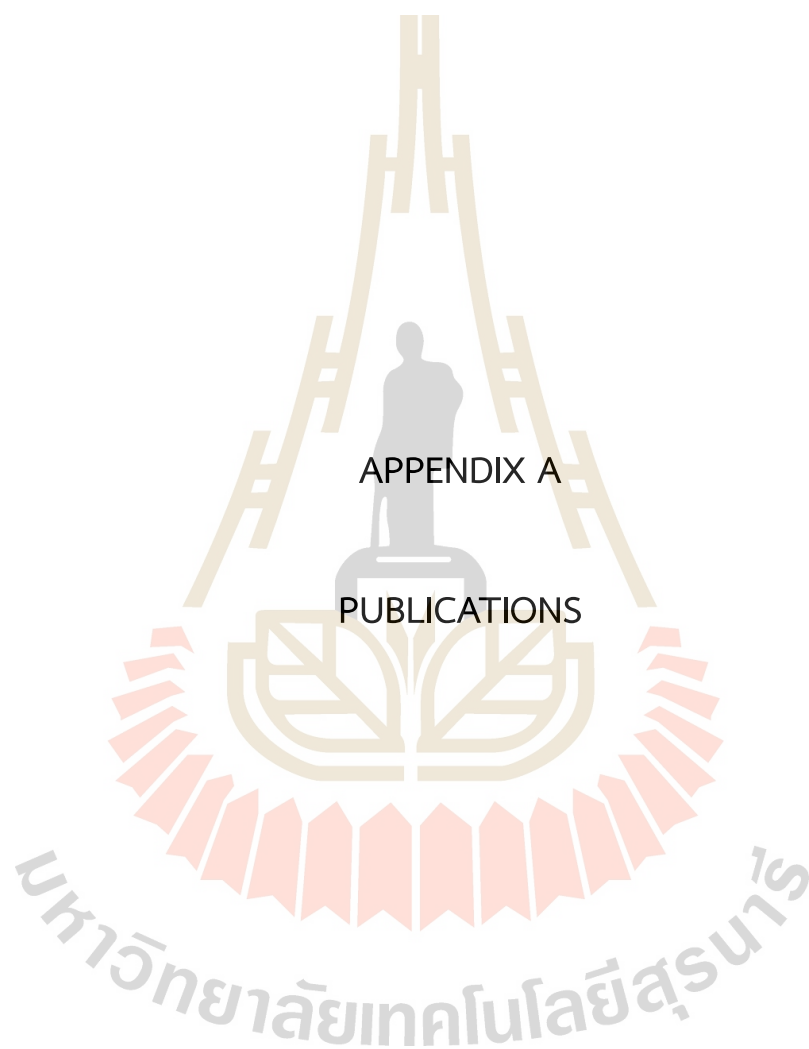
5) Optimization of FA–NRL Interaction

Additional rheological and kinetic studies may clarify how NRL interferes with FA hydration, particularly for high FA content (>25%). Modeling hydration with calorimetry or machine learning can support predictive mix design.

6) Life-Cycle Cost and Carbon Modeling for Pavement Design

Integrating mechanical performance with environmental and economic indices would allow development of a unified pavement design guide for RCA–NRL–FA concrete under Thai DOH specifications.





List of Publications

INTERNATIONAL JOURNAL PAPERS

- Youromphruk, C., Yaowarat, T., Horpibulsuk, S., Buritatum, A., Suddeepong, A., Phunpeng, V., Hoy, M., and Arulrajah, A. (2025), “Enhancing the Flexural strength of concrete pavements with recycled aggregate using natural rubber latex additive”, *Journal of Materials in Civil Engineering*. 37(11), 04025391.
- Horpibulsuk, S., Youromphruk, C., Yaowarat, T., Buritatum, A., Suddeepong, A., Hoy, M., Akkharawongwhatthana, K., Aiamsri, K., Kantatham, K., Zhao, L.-S., and Rashid, A. S. A. (2026), “Fly ash and natural rubber latex modified recycled aggregate concrete as sustainable rigid pavement surface”, *Construction and Building Materials*, 511, 145291.



Enhancing the Flexural Strength of Concrete Pavements with Recycled Aggregate Using Natural Rubber Latex Additive

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Abstract: The use of recycled concrete aggregate (RCA) in infrastructure activities has surfaced as a feasible strategy to reduce the reliance on natural aggregates and address environmental concerns related to construction waste disposal. This study aligns with the recent trends in sustainability by evaluating the enhancement of RCA properties through the incorporation of natural rubber latex (NRL), specifically for concrete pavement applications. Compressive strength (f_c) and flexural (f_t) strength assessments, microstructural examinations via energy-dispersive X-ray spectroscopy (EDX) and X-ray diffraction (XRD) analyses of RCA-NRL concretes were conducted. The dominant factors investigated were the ratios of dry rubber to cement (r/c) and water to cement (w/c). The presence of NRL retards cementitious products, resulting in reduced f_c at all r/c levels but enhanced f_t and ductility when r/c ratios were less than or equal to the optimum ratio. The RCA-NRL concretes, with $w/c = 0.3$ at $r/c \leq 1.0$ and $w/c = 0.4$ at $r/c = 0.5$, consistently met the prescribed compressive strength ($f_c \geq 34.3$ MPa) and flexural strength ($f_t \geq 4.2$ MPa) requirements outlined by the local authority. However, when $w/c > 0.5$, the addition of NRL led to a decrease in both f_c and f_t . The microstructural analysis confirmed the existence of NRL films in all concrete specimens containing RCA and NRL, which effectively contribute to the development of f_t , particularly when the r/c ratio was lower than the optimal level. EDX and XRD analyses revealed the lower portlandite phase with a higher r/c value, indicating hydration retardation. Profound insights derived from this study underscore the intricate relationship between NRL and RCA, offering valuable guidance for optimizing NRL-modified concrete blends to achieve enhanced performance and environmental sustainability in construction projects. DOI: 10.1061/JMCEE7.MTENG-19894. © 2025 American Society of Civil Engineers.

Author keywords: Natural rubber latex; Recycled material; Flexural characteristic; Compression strength; Microstructure; Rigid pavement.

26 3 Introduction

The construction sectors have demonstrated significant attention to the use of waste materials as viable alternatives to naturally derived materials, underscoring a robust commitment to waste recycling and the subsequent reduction of environmental impacts. Consequently, the development of advanced techniques and management methodologies, aimed at establishing comprehensive guidelines, serves as a catalyst for achieving sustainable economic and social progress. Presently, aggregate derived from construction and demolition

waste (CDW) is extensively adopted in the sustainable concrete development. The mechanical properties of concrete containing recycled concrete aggregate (RCA) are notably affected by the quality of the aggregate, given that the percentage of RCA in this type of concrete generally varies between 70% and 80% of the total aggregate volume (Omary et al. 2016).

RCA is manufactured substituting conventional natural aggregate (NA) in concrete through the conversion of aggregate derived from CDW. According to Omary et al. (2016), this practice has been shown to effectively mitigate the accumulation of concrete

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Note. This manuscript was submitted on July 23, 2024; approved on February 20, 2025. **No Epub Date.** Discussion period open until 0, 0; separate discussions must be submitted for individual papers. This paper is part of the *Journal of Materials in Civil Engineering*, © ASCE, ISSN 0899-1561.

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waste in landfills, contributing to sustainable construction practices. However, the performance of RCA concrete is highly sensitive to various factors, including the source and type of RCA, its physico-chemical and mechanical properties, and the methodology employed for mix proportioning (Omary et al. 2016). Silva et al. (2014) reported that these factors significantly affected the permeability and overall quality of the recycled aggregate, thereby influencing the performance of the resulting concrete. While RCA has the potential to replace NA, previous studies have identified some limitations, such as a relatively low compressive strength (f_c), high absorption, and low elastic modulus (Silva et al. 2014), which are strongly influenced by the adhered mortar content and aggregate quality. For instance, RCA derived from low-quality CDW or improperly processed aggregate often results in suboptimal mechanical properties.

The mechanical strength of RCA concrete is critically determined by the abrasion resistance of the recycled aggregate, typically assessed using the Los Angeles test. Variability in abrasion resistance between RCA sources can lead to significant differences in performance. Additionally, the tensile strength of RCA concrete is governed by the porosity and characteristics of the cement mortar adhering to the recycled coarse aggregate, as noted by Omary et al. (2016). These variations underline the importance of controlling the properties of RCA and optimizing mix design methodologies to achieve consistent and reliable concrete performance. Without considering these variables, generalizing the outcomes of RCA studies could lead to misconceptions about its suitability for specific applications.

Previous studies have substantiated the practicality and effectiveness of incorporating RCA as a viable substrate in civil infrastructures (Arulrajah et al. 2015). Dilbas et al. (2014) proposed an optimal RCA content of around 30% of the total aggregate when incorporated into concrete composites. The findings, derived from past investigations, have shed light on various properties of RCA, showcasing its potential as a reliable alternative to NA (Dilbas et al. 2014). Importantly, RCA has demonstrated the ability to produce concrete that exhibits the desired properties typically associated with conventional structural concrete (Behera et al. 2014). These observations underscore the significant contribution that RCA makes to fostering sustainable construction practices and mitigating the construction industry's environmental footprint.

To enhance the f_c of concrete containing RCA, Tam et al. (2005) proposed the two-stage mixing approach (TSMA). This method involves a premixing phase, where a portion of cement and water is mixed with RCA to form a cement slurry coating, improving the aggregate's surface quality and reducing porosity. In the second stage, the remaining cement, water, and other ingredients are added to complete the mix. This approach enhances the bond strength at the interfacial transition zone (ITZ), resulting in improved compressive strength and durability compared to conventional mixing methods. Additionally, Jansen et al. (2012) investigated how superplasticizers reduce water demand and improve workability in RCA concrete, while Plank et al. (2015) studied their impact on reducing hydraulic conductivity, thereby enhancing the durability of the concrete. These studies highlight specific improvements in the mechanical and durability properties of RCA concrete. The TSMA significantly enhances f_c by improving the quality of the ITZ, while investigations into superplasticizer types reveal their role in reducing water absorption and hydraulic conductivity, thereby improving durability and long-term performance. These findings are directly relevant to advancing the use of RCA in sustainable and resilient construction applications.

In the context of conventional concrete pavement design, the evaluation of flexural strength (f_r) assumes utmost significance

as it facilitates the determination of the minimum pavement thickness necessary to endure deflection resulting from bending (Yaowarat et al. 2021). The current body of research regarding the f_r and elastic modulus of concrete incorporating RCA consistently demonstrates diminished values as compared to concrete manufactured with natural aggregates (Danish and Mosaberpanah 2022; Etxeberria et al. 2007; Makul et al. 2021; Xu et al. 2022). The potential for f_r enhancement in concrete can be achieved through the addition of reinforcing materials and additives. A viable method for augmenting the f_r of RCA-based concrete has been identified as the incorporation of polypropylene fibers (Ye et al. 2022). Additionally, a soluble polymer type, specifically polyvinyl alcohol (PVA) that dissolved at a 1% concentration in water, was found to improve the f_r of cement mortar (Knapien and Van Gemert 2015). PVA has been effectively employed as an additive in RCA to promote the advancement of environmentally friendly pavement solutions with the objective of improving f_r (Yaowarat et al. 2018, 2019).

Natural rubber latex (NRL), derived from rubber trees (*Hevea brasiliensis*), is a milky white fluid primarily composed of water and rubber particles suspended within the liquid. As a renewable resource, NRL is produced through natural processes, offering advantages such as a lower carbon footprint over its life cycle compared to synthetic polymers. Although the cultivation of rubber trees necessitates careful land management to address environmental concerns like deforestation, sustainable tapping practices ensure long-term resource availability without causing significant harm to the trees. Due to the abundance of rubber trees in Thailand, NRL is a more environmentally sustainable additive compared to recycled rubber, which often requires energy-intensive processing prior to its use in concrete (Yaowarat et al. 2021). Chemically, NRL belongs to the class of natural polymers known as copolymers, comprising long chains of organic molecules. Its high concentration of rubber hydrocarbons is integral to its exceptional physical properties, including elasticity, durability, and resilience (Hoy et al. 2023a).

The NRL films formed by the evaporation of the liquid medium heighten the engineering properties of cement-stabilized soil, which is commonly employed in subbase and base construction applications (Buritatun et al. 2020). It has been demonstrated that using NRL to fortify cement-stabilized soil increased its resistance to severe environments. Enhanced durability against cyclic wetting and drying is indicative of this development (Buritatun et al. 2020, 2021). In addition, the NRL additive could improve engineering characteristics of cement-stabilized recycled materials, including RCA and steel slag (SS). Multiple research studies (Hoy et al. 2023b; Nhieu et al. 2023; Tran et al. 2022) have reported that the NRL additive resulted in enhanced fatigue life and rutting resistance in the aforementioned materials. Furthermore, promising results have been observed with the incorporation of NRL into cement pastes as a natural polymer to increase f_r (Sukmak et al. 2020). The enhancement of f_r in concrete pavement through the use of NRL was reported by Yaowarat et al. (2021).

A comprehensive review of existing literature highlights a significant scarcity of studies investigating the application of NRL for enhancing flexural properties of RCA-based concretes. Thus, the present study was conducted with the primary aim of addressing this gap by focusing on improving RCA concrete's flexural properties through the use of NRL. The f_c and f_r of RCA concrete samples prepared using the TSMA mixing method were assessed to evaluate the influence of the dried rubber-to-cement ratio (r/c) and water-to-cement ratio (w/c). The comprehensive examination of the role of NRL incorporation on the microstructure of RCA-NRL concretes was carried out by employing advanced assessments like scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS). Additionally, a thorough evaluation was performed on

the f_c and f_t of RCA-NRL concrete samples in order to confirm that they met the standards established by the Thailand Department of Highways.

Material and Methods

Materials

Type I ordinary portland cement (OPC) was employed as a cementing agent in this research. Its specific gravity was determined to be 3.15. Table 1 provides the chemical compositions of the OPC.

A river sand was utilized as the fine aggregate. Its specific gravity was recorded as 2.65 in saturated surface dry (SSD) state. Sand characteristics, determined according to ASTM C128, included a water absorption rate of 1.10%, a fineness modulus of 2.46 (ASTM C136), and a void percentage of 43.6 (ASTM C29). The RCA used as the coarse aggregate in this study, sourced from crushed cubic concrete specimens obtained from the Department of Rural Roads, had dimensions ranging from 4.75 mm to 19 mm, meeting the specifications of ASTM C33. The fineness modulus of RCA was 6.3 (ASTM C136), while its specific gravity, tested in accordance with ASTM C127, was 2.67. The RCA exhibited a water absorption of 5.5% (ASTM C127), a voids percentage of 54% (ASTM C29), and a Los Angeles abrasion resistance of 34% (ASTM C131). The residual mortar content of the RCA was determined to be 29.3%, measured using the acid dissolution method in accordance with the procedure outlined by Akbarzadeh et al. (2013). Fig. 1 illustrates particle size distribution curves of RCA, river sand, and RCA + sand, with the two dashed lines representing the upper and lower gradation limits for aggregate in concrete as specified by ASTM C33.

In Table 2, NA sourced locally from Nakhon Ratchasima province was included as a benchmark to evaluate the properties and

performance of RCA. The NA used in this study had a maximum size of 19 mm and a minimum size of 4.75 mm, with a fineness modulus of 7.1 and a specific gravity of 2.76. The NA demonstrated superior physical characteristics compared to the RCA, including a significantly lower water absorption rate (1.13%) and void percentage (51%), indicative of its higher density and lower porosity. Furthermore, the NA exhibited better durability, with a Los Angeles abrasion resistance of 22.7%, which is considerably lower than the 34% observed for the RCA, highlighting its reduced susceptibility to wear and fragmentation. These comparisons provide a clear context for assessing the feasibility and performance of RCA in sustainable concrete applications.

NRL was implemented as an additive to accumulate the flexural characteristics of RCA-based concretes. The NRL utilized in this investigation was authorized by the Rubber Authority of Thailand, ensuring adherence to manufacturing regulations. Table 3 provides the chemical composition of NRL. A water-reducing concrete admixture or superplasticizer, specifically Sika Plastocrete-907, was incorporated to regulate the workability of the concrete and mitigate the issue of low slump value. The properties of Sika Plastocrete-907 align with ASTM C494 Type D & G specifications.

Samples Preparation

To produce the RCA-NRL concrete samples, various w/c ratios were incorporated: 0.3, 0.4, and 0.5. The NRL additive was employed with an r/c ratio varying from 0% to 2% via increments of 0.5, 1.0, and 1.5. The selection of these r/c ratios was guided by the findings of Yaowarat et al. (2021), which demonstrated the effectiveness of similar ranges in enhancing the mechanical properties, providing a solid foundation for their application in this study. According to Table 3, the NRL chemical composition consists of approximately 52% dry rubber, 45% water, and 3% nonrubber constituents. To maintain the specified w/c value, it was necessary to adjust the amount of water used in the concrete mixing process to align with the water present in the NRL mix.

In this research, NRL was used in liquid form and mixed with distilled water to prepare the concrete specimens. The method followed ensures accurate incorporation of NRL into the mix while maintaining the specified w/c and r/c ratios. Specifically, the distilled water was partially replaced by NRL to achieve the target w/c ratio, as suggested by previous studies (Yaowarat et al. 2021). Considering the dry rubber content of NRL (52%), each kilogram

Table 1. Chemical composition of Type I portland cement

Component	Percent
Silicon dioxide (SiO ₂)	20.9
Aluminum oxide (Al ₂ O ₃)	4.7
Iron oxide (Fe ₂ O ₃)	3.4
Calcium oxide (CaO)	65.4
Magnesium oxide (MgO)	1.2
Sulfur trioxide (SO ₃)	2.7
Loss on ignition	0.9

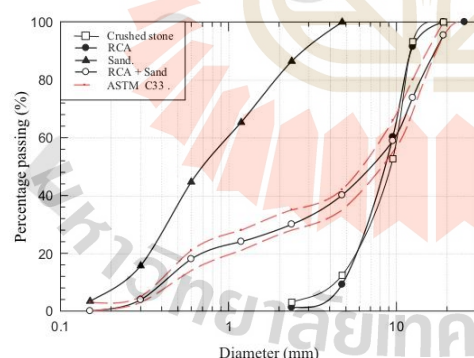


Fig. 1. Particle size distributions of sand, crushed limestone, RCA, and RCA + sand.

Table 2. RCA and NA properties

Properties	RCA	NA
Maximum size (mm)	19	19
Minimum size (mm)	4.75	4.75
Fineness modulus	6.3	7.1
Specific gravity	2.67	2.76
Water absorption (%)	5.5	1.13
Voids (%)	54	51
Los Angeles abrasion (%)	34	22.7

Table 3. Chemical analysis of natural rubber latex

Property	Value
Total solid content	55.11%
Dry rubber content	52.04%
Nonrubber content	3.07%
Volatile fatty acid	0.07%
Alkalinity (NH ₃)	0.69%
pH	10.42%
Mechanical stability time	7,440 s

Table 4. Mixing proportions of RCA-NRL concrete

		Mixing proportions of RCA-NRL concrete (kg/m ³)						w/c	Slump (mm)
T4:2	Mix	Cement	Sand	RCA	Water	NRL	SP		
T4:3	WC3-NRL0.0	617	603	1,018	185.10	0.00	3.70	0.3	50
T4:4	WC3-NRL0.5	617	603	1,018	183.62	5.93	3.70	0.3	60
T4:5	WC3-NRL1.0	617	603	1,018	182.14	11.86	3.70	0.3	60
T4:6	WC3-NRL1.5	617	603	1,018	180.66	17.80	3.70	0.3	50
T4:7	WC3-NRL2.0	617	603	1,018	179.18	23.73	3.70	0.3	40
T4:8	WC4-NRL0.0	462.5	734	1,018	185.00	0.00	2.78	0.4	80
T4:9	WC4-NRL0.5	462.5	734	1,018	183.89	4.45	2.78	0.4	90
T4:10	WC4-NRL1.0	462.5	734	1,018	182.78	8.89	2.78	0.4	90
T4:11	WC4-NRL1.5	462.5	734	1,018	181.67	13.34	2.78	0.4	70
T4:12	WC4-NRL2.0	462.5	734	1,018	180.56	17.79	2.78	0.4	60
T4:13	WC5-NRL0.0	370	814	1,018	185.00	0.00	2.22	0.5	130
T4:14	WC5-NRL0.5	370	814	1,018	184.11	3.56	2.22	0.5	150
T4:15	WC5-NRL1.0	370	814	1,018	183.22	7.12	2.22	0.5	150
T4:16	WC5-NRL1.5	370	814	1,018	182.34	10.67	2.22	0.5	130
T4:17	WC5-NRL2.0	370	814	1,018	181.45	14.23	2.22	0.5	120

of NRL consists of 520 g of dry rubber and 480 g of water. The mixing water for the concrete was calculated using the formula $\{(w/c)C - 0.48[(r/c)/100]C\}$, where C represents the required cement in kilograms. This approach ensured precise adjustments to the water content while accounting for the water contribution from the liquid NRL, facilitating uniform mixing and consistent results.

The mix proportion of the RCA-NRL concretes was meticulously designed according to the American Concrete Institute (ACI) method, as specified in Table 4. As an effective replacement for natural aggregate, RCA was fully incorporated into the mix design, with sand and RCA carefully proportioned by mass to achieve sand-to-RCA ratios of 37.2:62.8, 41.9:58.9, and 44.4:55.6 for mixtures with w/c ratios of 0.3, 0.4, and 0.5, respectively. These proportions were selected in accordance with the recommended upper and lower gradation limits specified by ASTM C33 (ASTM 2023). To ensure the desired slump value of the concretes within the designated control limits, the superplasticizer was employed. The designated slump measurements for w/c = 0.3, 0.4, and 0.5 were 40–60 mm, 60–100 mm, and 100–150 mm, respectively. In order to rectify the intrinsic deficiencies of RCA aggregate, which included porosity and cracking that occurred during the pulverizing phase, the RCA-NRL concrete samples were fabricated using the TSMA method, as suggested by Tam et al. (2005). This technique aims at improving the quality of RCA, with the ultimate goal of enhancing the properties of the concrete.

The high cement content in the RCA-NRL concrete mixtures was necessary to meet the mechanical property requirements for pavement-grade concrete. However, it is recognized that this increases the carbon intensity of the mixtures, potentially conflicting with sustainability goals. To address this, future studies could explore the partial replacement of cement with supplementary cementitious materials (SCMs) such as fly ash or slag, which reduce CO₂ emissions while maintaining performance. Additionally, further optimization of the RCA content could help minimize cement usage, aligning with sustainability objectives by promoting the reuse of construction waste.

Engineering and Microstructural Investigation

Initial and Final Setting Periods

A comprehensive analysis was performed on cement-NRL paste to examine how the concentration of NRL affected its hardening manner, with a particular emphasis on the initial and final setting periods. The assessment was carried out utilizing Method A, which involved the manual operation of a Vicat needle apparatus, in adherence to the guidelines specified in ASTM C191 (ASTM 2021a)

regarding cement pastes. In the study, an analysis was conducted to compare the effects of various r/c ratios (0%, 0.5%, 1%, 1.5%, and 2.0%) at w/c ratios of 0.3, 0.4, and 0.5. To ensure precision, each sample underwent two tests. The initial setting period was determined by penetrating a 1-mm-diameter Vicat needle into cement-NRL paste at 25 mm within a duration of 30 s. On the contrary, the final setting period was established as the instant when the Vicat needle ceased to be able to penetrate the cement-NRL paste.

Compressive Strength (f_c) and Flexural Strength (f_t)

The RCA-NRL concrete samples were prepared in accordance with the ACI 211.1 method (Dixon et al. 1991), with the objective of achieving a predetermined target f_c of 34.3 MPa. The different w/c ratios of 0.3, 0.4, and 0.5 were selected to investigate their influence on the resulting strength, with the expectation that higher w/c ratios would result in lower compressive strength values, as detailed in Table 4. A comprehensive blending operation was executed utilizing a rotary drum mixer in order to guarantee the uniformity of every constituent. The evaluation of the concrete mixture's workability was conducted using the slump test in accordance with ASTM C143 (ASTM 2015). To evaluate the f_c , cubic concrete samples with dimensions of 150 × 150 × 150 mm³ were cast in accordance with the guidelines specified in the BS 1881 Part 3 (BSI 1983). In order to measure the f_t , beam-shaped concrete samples with dimensions of 100 mm × 100 mm × 400 mm were prepared in accordance with ASTM C78 (ASTM 2021b), as presented in Fig. 2. The samples were formed by pouring the fresh RCA-NRL concrete into formwork in three layers and compacting each layer using a 1.8-kg (4-lb) steel ram with 35 strokes per layer, following the methodology described in ASTM C192 (ASTM 2019). The cured concrete samples were carefully preserved in a moist water environment at a controlled temperature ranging between 27°C and 29°C. Following a period of aging of 7 days and 28 days, the samples underwent f_c evaluation using either BS 1881 Part 4 (BSI 1983) or ASTM C39 (ASTM 2021c) standards. To assess f_t , the beam samples were subjected to a bending test using two loads positioned to divide the beam span into three equal parts. This experimental procedure adhered to the guidelines outlined in ASTM C78 (ASTM 2021b). Following this, the f_t of the RCA-NRL concretes was assessed utilizing the following equation:

$$\text{Flexural strength (ff)} = \frac{PL}{bd^2} \quad (1)$$

where P is the maximum load; L is the span length; and b and d are the average width and depth of the sample.

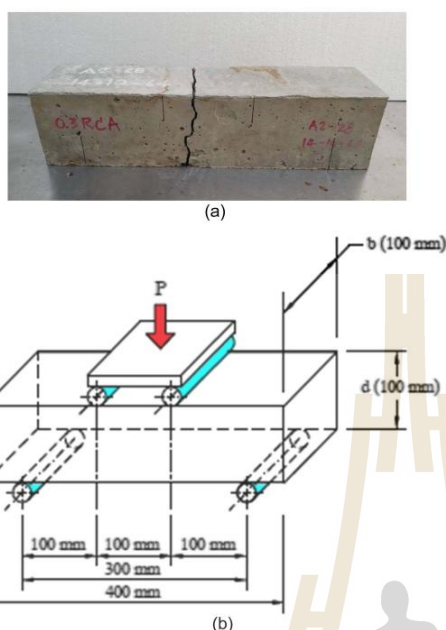


Fig. 2. (a) Specimen; and (b) schematic diagram for flexural test.

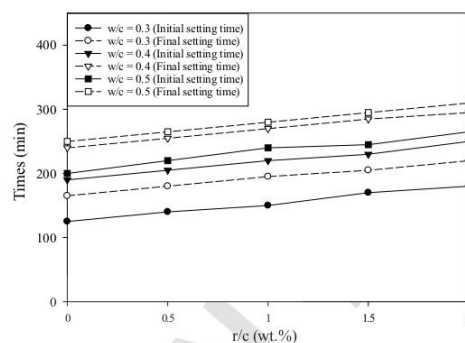


Fig. 3. Initial and final setting times of cement-NRL paste.

F3:1

the identical w/c ratio. For example, at a w/c ratio of 0.4, the initial setting periods for r/c = 0, 0.5, 1.0, 1.5, and 2.0 were 190 min, 205 min, 220 min, 230 min, and 250 min, respectively. Likewise, the final setting times for the corresponding r/c ratios were 240 min, 255 min, 270 min, 285 min, and 295 min, respectively.

Experimental conditions incorporating w/c ratios of 0.4, 0.5, and 0.6 at an r/c ratio of 2% resulted in delays of approximately 55 min, 60 min, and 65 min in the initial setting time and 55 min, 55 min, and 60 min in the final setting time, respectively, compared to the control cement paste. The increased setting times can be attributed to the nonrubber components in the NRL, including proteins and phospholipids, which form a coating around cement particles. This coating hinders hydration reactions and retards the formation of calcium silicate hydrate (C-S-H) gel, thereby delaying both initial and final setting times (Yaowarat et al. 2018, 2019, 2021).

Compressive Strength (f_c) of RCA-NRL Concretes

The f_c of RCA-NRL concretes at different w/c and r/c levels is illustrated in Fig. 4. When the w/c ratio increased, the f_c of RCA concretes (r/c = 0) decreased, whereas it increased with curing time. Fig. 4(a) illustrates that the f_c of RCA concretes for w/c = 0.3, 0.4, and 0.5 at the end of a 7-day curing period were 45.8 MPa, 42.8 MPa, and 36.8 MPa. Furthermore, the f_c of the RCA-NRL concretes decreased as the r/c ratio increased, regardless of the w/c ratio. As an illustration, the f_c of RCA concretes was assessed at 52.4 MPa, 48.1 MPa, and 43.7 MPa, for w/c = 0.3, 0.4, and 0.5, respectively, after 28 days of curing [Fig. 4(b)]. However, when the r/c = 2%, the f_c values for w/c = 0.3, 0.4, and 0.5 were 42.7 MPa, 31.0 MPa, and 23.7 MPa, respectively. The pronounced reduction in f_c at higher w/c ratios can be attributed to the combined effects of increased porosity and the hydration-retarding properties of NRL (Knapen and Van Gemert 2015). At higher w/c ratios, the cement matrix becomes more porous, reducing its overall density and strength. Additionally, the NRL's nonrubber constituents form a film around the cement particles, further delaying the hydration process and weakening the development of calcium silicate hydrate (C-S-H) gel, which is critical for strength. This effect is magnified at elevated w/c ratios, where the weaker cementitious bonds exacerbate the reduction in compressive strength. It is also observed that the incorporation of NRL into the RCA concrete mixture influences the ability to achieve the targeted strength at 28 days.

F2:1

The mean values of f_c and f_t were calculated using data collected from three test samples. These values underwent a thorough assessment to verify dependability and uniformity of the test results within the standard deviation (SD) boundaries, using the criterion $SD/\bar{X} < 10\%$. In this context, $\bar{X}$ denotes the mean value of either the f_t or f_c .

Scanning Electron Microscopy, Energy-Dispersive X-Ray Spectroscopy, and X-Ray Diffraction

An examination of the f_c and f_t development in relation to the w/c and r/c ratios was conducted utilizing scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDX), and X-ray diffraction (XRD). For facilitating SEM and EDX analyses, a protective layer of gold was applied to a thin section of the specimen subsequent to its freezing at -195°C in liquid nitrogen. This preparation ensured optimal specimen quality for SEM imaging (Yaowarat et al. 2018). The XRD test on powder specimen was to acquire microstructural insights concerning crystalline and amorphous phases. The XRD scans were performed utilizing a Bruker D8 ADVANCE instrument, over a spectrum of 0° – $90^\circ 2\theta$.

Results

Initial and Final Setting Periods

The initial and final setting periods are illustrated in Fig. 3 for cement paste containing NRL and the control cement paste, at different ratios of w/c to r/c. The Vicat apparatus was employed to determine the average setting periods of the pastes using two samples per batch. As compared to the control paste, both setting periods of the cement-NRL paste were significantly prolonged. Extended setting periods were attributed to greater r/c ratios for

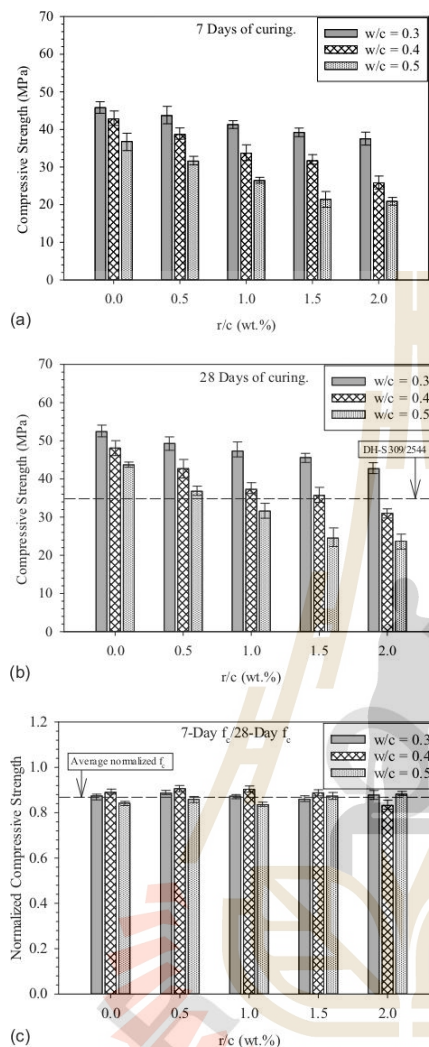


Fig. 4. Compressive strength of RCA-NRL concretes at: (a) 7 days; (b) 28 days; and (c) normalized 7-day f_c / 28-day f_c .

As illustrated in Fig. 4(b), the dashed line represents the strength criterion assigned to rigid pavement by the local authority (DH-S309/2544). In accordance with this specification, which stipulates a 28-day f_c of ≥ 35 MPa, the RCA concretes (excluding NRL) fulfill the criterion for all w/c ratios. However, at w/c = 0.5 the r/c ratios were ≤ 0.5 , while at w/c = 0.4 the r/c ratios were ≤ 1.0 . At w/c = 0.3 for all r/c ratios, the NRL enabled the compliance of RCA-NRL concretes with the requirement. Even with the longer setting periods, it should be noted that the NRL insignificantly

affected the rate of strength development after 7 days of curing. As shown in Fig. 4(c), the normal compressive strength (7-day f_c to 28-day f_c ratio) for all r/c levels is essentially the same, approximately 0.83.

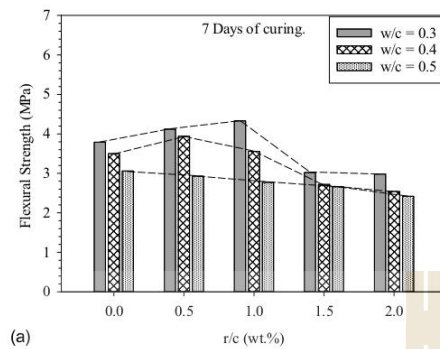
The observed pattern in compressive strength can be attributed to the dual influence of NRL on the hydration process and microstructure of RCA concretes. The incorporation of NRL introduces a film of natural rubber and nonrubber constituents, which coats the cement particles and delays hydration, particularly at higher r/c ratios. This delay reduces the early strength gain and, at higher w/c ratios, further weakens the cementitious matrix due to increased porosity. However, the consistent strength development rate after 7 days suggests that hydration stabilizes once the effects of the NRL film diminish. Additionally, at lower w/c ratios, the denser matrix partially offsets the strength reduction caused by the NRL, enabling RCA-NRL concretes to meet the required strength criteria under specific conditions. This balance highlights the importance of optimizing both w/c and r/c ratios for achieving the desired performance in RCA-NRL concretes.

Flexural Strength (f_t) of RCA-NRL Concretes

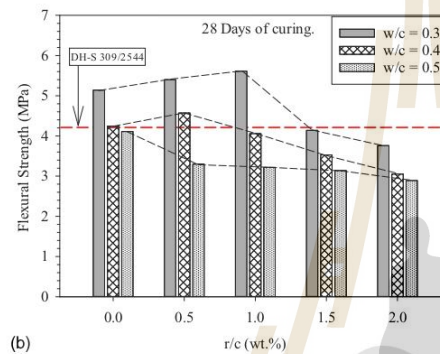
The f_t of the samples at different curing periods, w/c ratios, and r/c ratios is illustrated in Fig. 5. Changes in peak strengths observed during different curing periods for each w/c ratio are denoted by the dashed lines. The pattern of development of f_t in RCA concretes exhibited similarities to that noted in the f_c . The f_t for a given w/c ratio increased with the raised curing period but declined with the raised w/c ratio. The f_t of RCA-NRL concrete exhibited a progressive increase as the r/c ratio was augmented, reaching its highest value at the optimized ratio. Further augmentation of the r/c ratio beyond this ratio resulted in a decline in f_t . To illustrate, the 7-day and 28-day f_t values reached their maximum values with the optimized r/c ratios being 1.0 and 0.5 for w/c = 0.3 and 0.4, accordingly. The maximal 7-day f_t was 4.33 MPa for w/c = 0.3 with r/c = 1.0 and 3.94 MPa for w/c = 0.4 with r/c = 0.5. Similarly, the maximal 28-day f_t was 5.40 MPa for w/c = 0.3 with r/c = 1.0 and 5.61 MPa for w/c = 0.4 with r/c = 0.5. Comparing RCA-NRL concretes with w/c = 0.3 and r/c = 1.0 to those with w/c = 0.4 and r/c = 0.5, respectively, at identical w/c levels, f_t increased by 8.40% and 7.22%, respectively, when compared to RCA concretes with r/c = 0.

Fig. 5(c) shows the normalized 7-day f_t / 28-day f_t of RCA-NRL concretes at various r/c values. It is important to note that the rate of flexural strength development RCA concretes and RCA-NRL concretes was similar at a specific w/c. However, an increase in w/c ratio was correlated with an accelerated rate of flexural strength development. This observation suggests that, when using RCA-NRL concrete with higher w/c ratio, its flexural strength approached the 28-day f_t at earlier age. The flexural capacities of RCA concretes (excluding NRL) at w/c = 0.3 and 0.4 were determined to achieve local authority's specification where the f_t was > 4.2 MPa (indicated by the dashed line). On the contrary, it was observed that RCA-NRL concretes did not achieve the specification at w/c = 0.5 for all r/c ratios. They did satisfy the specification for w/c = 0.3 at r/c ≤ 1.0 and w/c = 0.4 at r/c = 0.5.

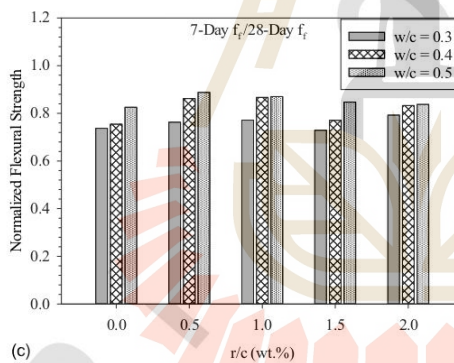
The correlation between flexural stress and deflection in flexural beam experiments performed on samples with varying w/c ratios (Fig. 6) revealed that RCA-NRL concretes exhibited notable enhancements in stiffness and toughness. As indicated by the slope of the relationship, the stiffness of the specimens increased progressively as the r/c ratio increased, reaching its optimal value at r/c = 1.0 for w/c = 0.3 and r/c = 0.5 for w/c = 0.4, while no optimal r/c ratio was observed for w/c = 0.5. Beyond the optimum r/c ratio, however, an observed decrease in stiffness occurred.



(a)

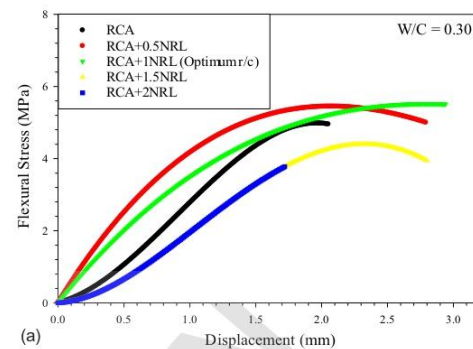


(b)

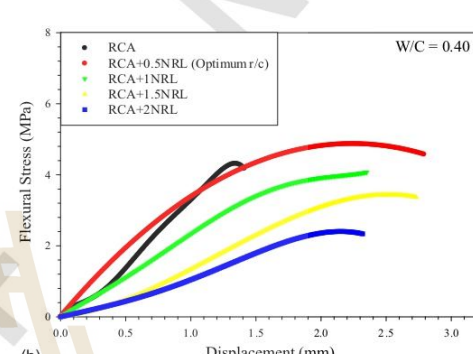


(c)

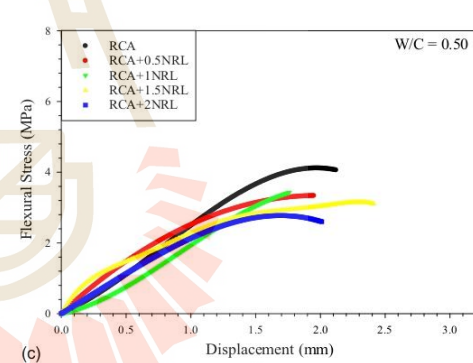
Fig. 5. Flexural strength of RCA-NRL concrete at: (a) 7 days; (b) 28 days; and (c) normalized 7-day f_t /28-day f_t .



(a)



(b)



(c)

Fig. 6. Flexural stress versus midspan displacement of specimens cured for 28 days at w/c ratios of: (a) 0.30; (b) 0.40; and (c) 0.50.

The midspan deflections of the RCA-NRL concretes were larger than those of RCA concretes for all w/c ratios except w/c of 0.5. As an illustration, the deflections were found to be 2.35 mm and 2.95 mm for $r/c = 0$ and 1.0, respectively, at $w/c = 0.3$. In the same way, at $w/c = 0.4$, the deflection was measured to be 1.40 mm and 3.00 mm at $r/c = 0$ and 0.5, respectively. In comparison with the RCA concrete ($r/c = 0$), the deflection exhibited

an approximate 25.5% and 114% increase at $w/c = 0.3$ and 0.4, correspondingly. The area under the flexural stress versus displacement graph provides a better representation of toughness. At the optimal r/c ratios of 1.0 for $w/c = 0.3$ and 0.5 for $w/c = 0.4$, this area was observed to be the largest, indicating enhanced toughness in RCA-NRL concretes.

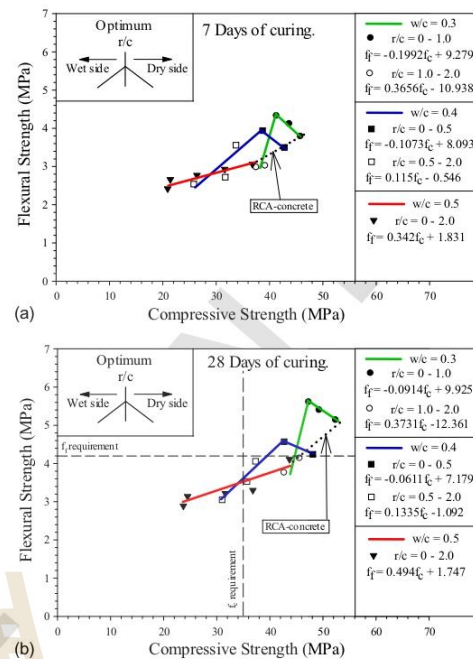
Table 5. Flexural modulus of elasticity of RCA-NRL concrete

		Flexural modulus of elasticity (E) (MPa)		
		w/c = 0.3	w/c = 0.4	w/c = 0.5
T5:2	Mix			
T5:3	RCA	396.75	362.4	309.9
T5:4	RCA + 0.5NRL	783.3	573.6	457.95
T5:5	RCA + 1NRL	621.75	330.3	203.1
T5:6	RCA + 1.5NRL	163.35	131.85	388.8
T5:7	RCA + 2NRL	134.55	127.35	339.15

The results clearly demonstrate that NRL enhances the toughness and stiffness (rigidity) of RCA concretes. The improved stiffness is evidenced by the steeper slope of the flexural stress versus displacement graph at the optimal r/c ratios (1.0 for $w/c = 0.3$ and 0.5 for $w/c = 0.4$), indicating increased resistance to deformation under load. This behavior can be attributed to the formation of NRL films within the concrete matrix, which act as a reinforcing network. These films enhance the bond between the aggregates and the cement paste, distributing stresses more evenly and improving load transfer.

The flexural modulus of elasticity (E) values, calculated using flexural stress and strain curve in accordance with ASTM C78 and D790 standards, reveal distinct trends across various w/c ratios, as shown in Table 5. These results highlight the significant influence of mix composition. At a w/c ratio of 0.3, the highest modulus is observed in RCA-NRL concrete with $r/c = 0.5$, achieving 783.3 MPa, followed by $r/c = 1$ at 621.75 MPa. The lowest values are recorded for $r/c = 1.5$ and $r/c = 2$, at 163.35 MPa and 134.55 MPa, respectively. For $w/c = 0.4$, RCA-NRL concrete with $r/c = 0.5$ again shows the highest modulus at 573.6 MPa, with RCA concrete ($r/c = 0$) achieving 362.4 MPa, while the lowest values are seen in $r/c = 1.5$ and $r/c = 2$, at 131.85 MPa and 127.35 MPa, respectively. At a w/c ratio of 0.5, the RCA-NRL concrete with $r/c = 0.5$ continues to lead with 457.95 MPa, followed by RCA concrete ($r/c = 0$) at 309.9 MPa. The lowest modulus is recorded for $r/c = 1$ at 203.1 MPa, while $r/c = 1.5$ and $r/c = 2$ show moderately higher values at 388.8 MPa and 339.15 MPa, respectively. These findings emphasize the critical role of w/c ratio and RCA-NRL proportions in influencing the flexural modulus of elasticity.

The correlations between f_t and f_c at 7 and 28 days of curing are depicted in Fig. 7. These correlations account for different ratios of w/c and r/c . As expected, the f_t of RCA concretes increased in tandem with the f_c as a result of the strengthened cementation bond, demonstrated by the dashed line. Conversely, at $w/c = 0.3$ and 0.4, the correlation between f_t and f_c for NRL-RCA concretes revealed two distinct regions: the dry region and the wet region of the optimal r/c ratio. An increase in f_t was observed when the f_c reduced on the dry region. On the contrary, a reduction in f_t was noted as f_c decreased on the wet region, exhibiting a pattern comparable to that of RCA concrete. This observation indicates that both the cementation bonds and the NRL films have an impact on the f_t of the NRL-RCA concretes. An augmentation in the r/c ratio led to a greater concentration of NRL films within a given w/c ratio; this, in turn, enhanced the RCA-NRL-concrete matrix reinforcement. However, the higher r/c ratio caused a lower strength of the cementation bonds due to the hydration retardation. In the dry region, the abatement in bond strength was offset by the contribution of NRL films. Thus, at w/c ratios of 0.3 and 0.4 with the r/c ratio less than the optimum value, the f_t of the NRL-RCA concretes demonstrated a positive correlation while a negative trend was observed in f_t . Both f_t and f_c , however, decreased when the r/c ratio was greater than the optimum value. In the case of a w/c ratio of 0.5, the NRL in the mixture resulted in an abatement in both f_c and f_t at all r/c ratios.

**Fig. 7.** Flexural strength versus compressive strength at various r/c ratios at: (a) 7 days; and (b) 28 days.

The incorporation of NRL significantly influenced the flexural performance of RCA concretes, as evidenced by enhanced flexural strength and increased midspan deflections under flexure. The optimized r/c ratio contributed to improved matrix reinforcement through NRL films, leading to higher flexural capacities. At the same curing time, larger midspan deflections observed in RCA-NRL concretes demonstrated improved ductility, allowing the material to deform more before failure. This enhanced ductility can be attributed to the cohesive nature of the NRL films, which distributed stresses more effectively across the matrix. However, exceeding the optimum r/c ratio resulted in reduced stiffness and strength, emphasizing the need to find an optimal r/c ratio to achieve the best possible flexural performance without compromising the structural stability of the concrete.

Based on the fracture face images presented in Fig. 8, the failure patterns of the NRL-RCA concrete specimens with $w/c = 0.3$ at different r/c ratios provide critical insights into crack propagation mechanisms through the RCA and NRL/virgin aggregate interfaces. For $r/c = 0$ [Fig. 8(a)], the fracture face primarily exhibits cracks propagating through the cementitious matrix rather than the virgin aggregate interface, indicating relatively weak bonding between the matrix and the aggregates, which may limit the overall structural performance. In contrast, the optimal mix at $r/c = 1.0$ [Fig. 8(b)] demonstrates cracks propagating both through the RCA and the cementitious matrix interface, reflecting a more balanced load transfer mechanism and satisfactory bonding between the RCA and the surrounding matrix. This mix highlights an efficient interaction between the components, contributing to enhanced structural

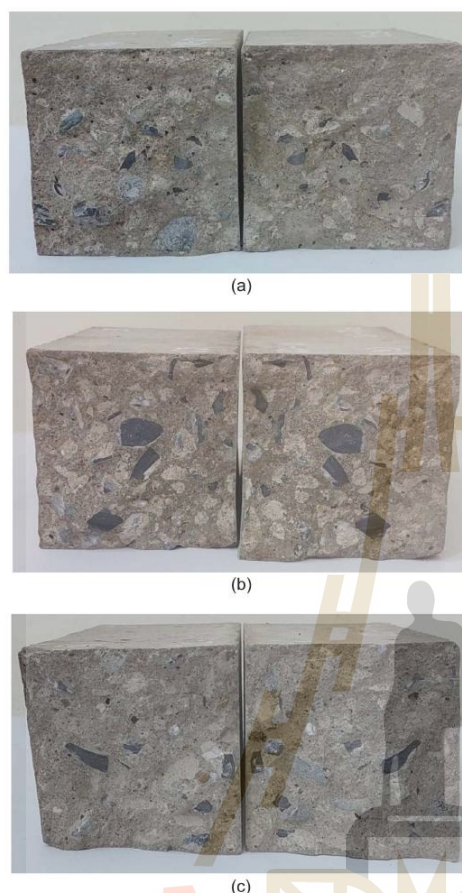


Fig. 8. Fracture surface morphology of NRL-RCA concrete beams for $w/c = 0.3$ at 28 days: (a) $r/c = 0$; (b) $r/c = 1.0$ (optimal); and (c) $r/c = 2.0$.

integrity. However, at $r/c = 2.0$ [Fig. 8(c)], cracks predominantly propagate along the RCA and the RCA-matrix interface, revealing weakened bonding that is primarily influenced by the r/c ratio and the interaction between the RCA, NRL, and the cementitious matrix. This weakened bonding, combined with the inherent porosity and preexisting microcracks within the recycled aggregates, significantly impacts the material's load-bearing capacity. Additionally, some fractures in the $r/c = 2.0$ mix appear to traverse weak zones within the RCA itself, reflecting the complex interactions at the aggregate-matrix interface. These findings suggest that the r/c ratio plays a critical role in influencing the mechanical behavior of the composite.

578 Microstructural Analysis

Morphological analyses were performed on NRL-RCA concretes in order to investigate their microstructures. This was achieved utilizing a 15-kV scanning electron microscope that was outfitted with

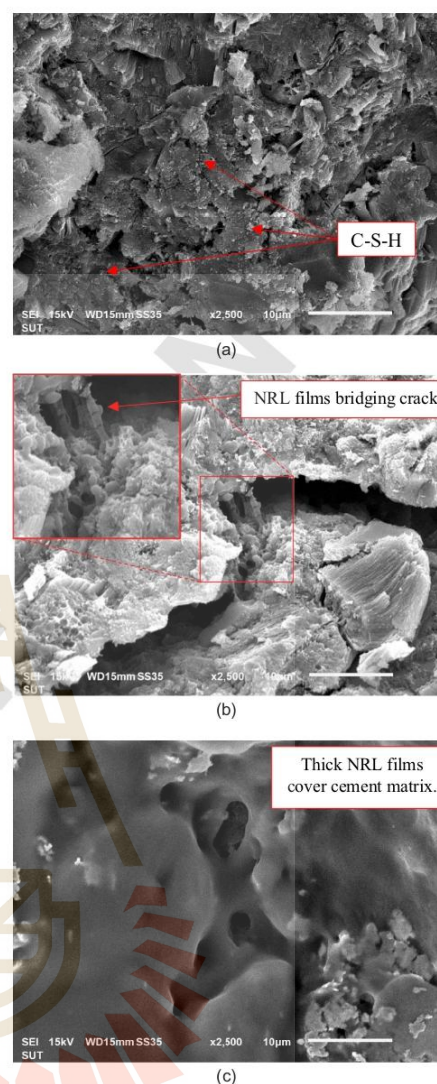


Fig. 9. SEM images of NRL-RCA concretes for $w/c = 0.3$ at: (a) $r/c = 0$; (b) $r/c = 1$ (optimal); and (c) $r/c = 2$.

selenium detectors. Analyzing the microstructural evolution of the concrete mixtures was the objective of the investigation. Fig. 9 presents SEM images of RCA-NRL-concrete specimens, magnified at 2,500 times, after 28-day curing with a w/c of 0.3 and varying r/c levels of 0%, 1% (optimum r/c), and 2%. The calcium silicate hydrate (C-S-H) gel was distinctly visible in the RCA concrete (excluding NRL), as illustrated in the SEM image [Fig. 9(a)]. The formation of the C-S-H, which functions as the principal

590 cementitious product, is the essential mechanism through which
591 strength is enhanced in cement-based materials.

592 Additionally, the SEM images revealed the existence of thin
593 NRL films in the RCA-NRL concrete specimen with a r/c ratio
594 of 1% [Fig. 9(b)]. These thin NRL films acted as reinforcement
595 and contributed to improved crack resistance and enhanced flexi-
596 bility of the concrete. This observation implies that the NRL films
597 possess a substantial impact on the flexural strength of RCA-NRL
598 concretes through their efficient reinforcement of the material's
599 structural integrity. Fig. 9(c) ($r/c = 2\%$) unequivocally indicates
600 the existence of substantial NRL films enveloping the cement
601 matrix. These films played a negative role in the microstructure of
602 RCA-NRL concrete, infiltrating and forming a dense layer within
603 the cement matrix. The progression of the cementitious products was
604 hindered by them. Similar to previous studies on synthetic polymer-
605 concrete (Afridi et al. 2003; Mayhoub et al. 2022; Xiao et al. 2018;
606 Yaowarat et al. 2018, 2019), the synthetic polymer films were found
607 to embed in the concrete matrix. The reductions in f_c and f_t resulted
608 from the inhibition of cementitious products formation within the
609 matrix due to the presence of synthetic polymer or NRL films.

610 To verify the inhibition of C-S-H gels in RCA-NRL concrete
611 specimens at different r/c ratios (0%, 1%, and 2%) while keeping
612 the w/c ratio constant at 0.3, EDX analysis was conducted and
613 its results are presented in Fig. 10. The three notable elements
614 were detected in every specimen—calcium (Ca), silicon (Si), and
615 aluminum (Al)—demonstrating the existence of C-S-H and
616 calcium aluminosilicate hydrate (C-A-S-H). Significantly, the RCA
617 concrete specimen ($r/c = 0\%$) exhibited the highest peak intensi-
618 ties of Ca, Si, and Al as shown in Fig. 10(a). On the other hand,
619 Figs. 10(b and c) ($r/c = 1\%$ and 2%) demonstrated a decrease in
620 the intensities of Ca, Si, and Al, with increased r/c levels from 1%
621 to 2% compared to the RCA concrete. These main components
622 were observed to have the lowest intensities in the specimen with
623 a 2% r/c ratio. On the contrary, it was observed that the quantity
624 of C, which serves as the predominant element of NRL, increased
625 as the r/c ratio raised.

626 XRD patterns were employed to validate the retardation of
627 cementitious products in RCA-NRL concretes at different r/c
628 levels, in addition to EDX analysis. The XRD patterns of 28-day
629 cured specimens are illustrated in Fig. 11. The specimens under-
630 went testing with $r/c = 0\%$, 1%, and 2% at $w/c = 0.3$. The
631 XRD patterns showed amorphous phase and broad peaks that
632 extended over a range of 17° to $35^\circ 2\theta$, which is consistent with
633 findings from previous studies (Abo-El-Enain et al. 2015; Hoy
634 et al. 2016; Kontoleon et al. 2013; Lothenbach et al. 2011).
635 As the r/c ratio increased, the XRD results revealed a decline in
636 the portlandite phase, which was indicative of a reduction in
637 hydration products. The broad peaks observed at approximately
638 $29.5^\circ 2\theta$ in the XRD patterns of the RCA concrete specimens
639 (excluding NRL) indicated the substantial presence of C-S-H
640 (Alizadeh 2009; Qi et al. 2017; Xin et al. 2017), which coincided
641 with calcite [Fig. 11(a)]. In comparison, the broad peak at approx-
642 imately $29.5^\circ 2\theta$ on the XRD pattern of the RCA-NRL concrete
643 specimen [Fig. 11(b)] with a $w/c = 0.3$ and a $r/c = 1$ was less
644 intense, suggesting a diminished quantity of C-S-H products.
645 The observed phenomenon may be ascribed to the existence of
646 NRL films that were encased and interwoven throughout the
647 cement matrix. The specimen of RCA-NRL concrete with a $r/c =$
648 2.0 exhibited the smallest number of cementitious products, as
649 indicated by its XRD pattern [Fig. 11(c)].

650 The microstructural analysis confirmed the formation of NRL
651 films, which effectively established interconnections and enhanced
652 the reinforcement of the cement matrix. The f_t of the NRL-RCA
653 concrete was enhanced by this film formation, particularly when

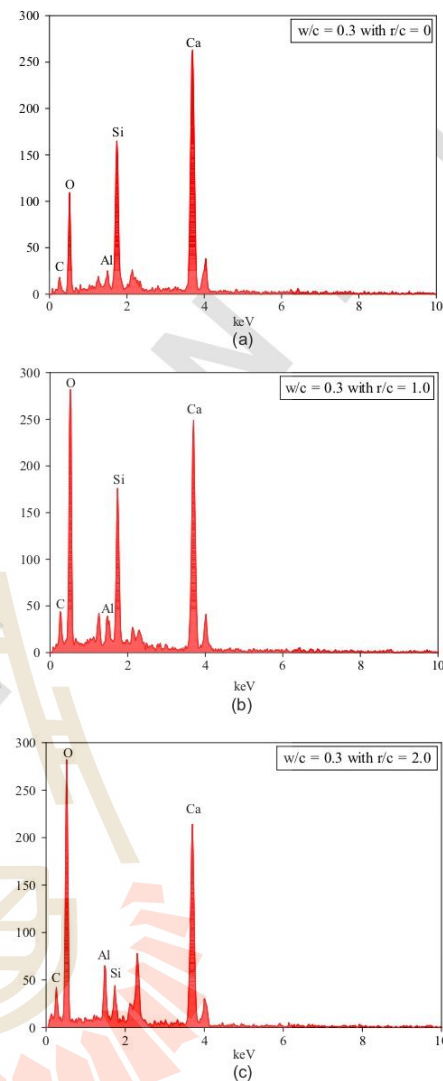


Fig. 10. EDX results of RCA-NRL concretes for $w/c = 0.3$ at: (a) $r/c = 0$; (b) $r/c = 1$ (optimal); and (c) $r/c = 2$.

the r/c ratios were below the optimal value. Notwithstanding, a noticeable decrease in the number of cementitious products was detected when the r/c ratios escalated to excessively high levels. Despite the fact that the NRL films led to the enhanced cohesion, they did not adequately offset the decline in strength of cementation bonds, ultimately leading to a decrease in f_t .

Although this study provides valuable insights into the use of NRL and RCA in concrete, it has some limitations that warrant

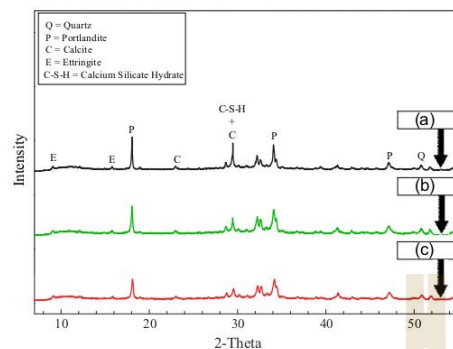


Fig. 11. X-ray diffraction pattern of NRL-RCA concretes at: (a) $w/c = 0.3$, $r/c = 0$; (b) $w/c = 0.3$, $r/c = 1$ (optimal); and (c) $w/c = 0.3$, $r/c = 2$ at 28 days.

further exploration. The research primarily focuses on short-term properties and specific mix compositions, leaving long-term performance such as durability, creep, and shrinkage unexamined. Additionally, the interfacial bonding mechanisms between RCA, NRL, and the cementitious matrix were not analyzed in detail. Future studies should investigate long-term performance under various environmental conditions, explore microstructural bonding mechanisms, and expand mechanical testing to include tensile strength and fatigue behavior. Life-cycle assessments and field validations are also recommended to evaluate the environmental benefits and practical application of NRL-RCA concrete.

673 Conclusions

The incorporation of NRL in RCA concretes resulted in notable effects on their microstructure and mechanical properties. The NRL films were observed to cover the cement matrix, playing a significant role in the microstructure of the NRL-RCA concretes. The presence of these films impeded the cementitious products' hardening process, resulting in a decreased f_c . However, the NRL films also acted as reinforcement and bridged cracks, improving the RCA-NRL-concrete matrix reinforcement and flexibility of the concretes. The correlation between deflection and flexural stress revealed that an optimal ratio of r/c enhanced f_t , whereas an excessive r/c (wet side) decreased both f_c and f_t . The impedance of cementitious products in RCA-NRL concretes was confirmed by the EDX and XRD patterns, which revealed a reduction in the portlandite phase and the appearance of C-S-H. In general, the incorporation of NRL at optimum r/c ratio into RCA concretes demonstrated promise in improving their flexural strength and resistance to deformation. The outcomes of this research provide a clear picture of the mechanical characteristics of RCA concretes modified with NRL. These results could potentially be used as a reference for research and development in the field of sustainable pavement concrete technology.

695 Data Availability Statement

Some or all data, models, or code that support the finding of this study are available from the corresponding author upon reasonable request.

698 Acknowledgments

This work was financially supported by the National Research Council of Thailand under the Chair Professor Program (Grant No. N42A670631) and Suranaree University of Technology. This research was also supported under the Australian Research Council's Linkage Projects funding scheme (Project No. LP220200548).

Author Contributions

Chatree Youromphruk: Conceptualization; Data curation; Writing—original draft. Teerasak Yaowarat: Investigation; Methodology; Writing—review and editing. Suksun Horpibulsuk: Writing—review and editing. Apinun Buritatum: Formal analysis. Apichat Suddepong: Investigation; Resources. Veena Phunpeng: Software. Menglim Hoy: Validation. Arul Arulrajah: Validation.

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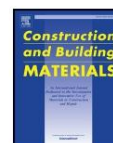
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Contents lists available at ScienceDirect

Construction and Building Materials

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

Fly ash and natural rubber latex modified recycled aggregate concrete as sustainable rigid pavement surface

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ARTICLE INFO

Keywords:

Natural rubber latex
Recycled concrete aggregate
Fly ash
CO₂ emissions
Flexural fatigue
Microstructure
Sustainable pavement materials

ABSTRACT

An integration of Recycled Concrete Aggregate (RCA) and Fly Ash (FA) into concrete represents a practical solution for sustainable construction by minimizing the use of natural resources and lowering carbon emissions. This research investigated the effects of incorporating Natural Rubber Latex (NRL) into FA-RCA concrete mixtures on both mechanical properties and environmental performance as a greener pavement concrete. Experimental evaluations included compressive strength (f_c), flexural strength (f_t), flexural fatigue behavior, and microstructural analysis using Scanning Electron Microscopy (SEM), and Energy-Dispersive X-ray spectroscopy (EDX). In addition, total CO₂-equivalent emissions were calculated based on the emission factors of each mix constituent. Results showed that moderate NRL content ($r/b = 0.5$ – 1.0 %) improved f_t and fatigue life, particularly at FA replacement levels of 15–25 %, while higher r/b ratios led to diminished strength due to hydration retardation. SEM and EDX analyses revealed enhanced microstructural densification at optimal NRL dosages, while excessive latex introduced film barriers, limiting hydration. Furthermore, replacing cement with 25 %FA and 0.5 % r/b resulted in the lowest emissions (304.63 kg CO₂-e/m³) and the greatest fatigue life at 56 days (2863 cycles), whereas 20 %FA provided the most cost-efficient option (53.48 USD/m³); all mixes satisfied the Thai pavement strength requirements. The findings confirm that careful optimization of NRL and FA content in RCA-based concrete can simultaneously improve structural performance and reduce carbon footprint, supporting the development of low-carbon pavement surface materials.

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<https://doi.org/10.1016/j.conbuildmat.2026.145291>

Received 27 September 2025; Received in revised form 13 January 2026; Accepted 14 January 2026

Available online 20 January 2026

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1. Introduction

The construction industry has increasingly embraced sustainable approaches to mitigate the environmental impact of infrastructure development [24]. The utilization of recycled materials has gained significant attention as an alternative to conventional raw materials, aligning with global efforts to promote circular economy practices. Among the various waste-derived materials, recycled concrete aggregate (RCA) has emerged as a viable substitute for natural aggregate (NA), e.g., fiber or nano-materials in concrete applications [1]. The incorporation of RCA contributes to waste reduction by diverting construction and demolition waste from landfills while conserving natural resources. However, despite its advantages, RCA-based concrete often exhibits inferior mechanical properties compared to conventional concrete due to the porous nature of RCA and the presence of adhered cementitious mortar [47]. Although RCA can be directly used to replace natural coarse aggregate, even at 100 % replacement levels, numerous studies have reported reductions in strength, stiffness, and durability compared with natural aggregate concrete due to the attached mortar and higher porosity of RCA. Therefore, the incorporation of supplementary materials or modification techniques such as fly ash, slag, or polymer latex is often recommended to enhance the mechanical performance and long-term durability of RCA-based concrete, particularly for structural and pavement applications. These considerations highlight the need for optimizing RCA concrete through material modification to achieve a balance between sustainability and mechanical performance.

Natural rubber latex (NRL), an organic polymer obtained from *Hevea brasiliensis*, has demonstrated potential in improving the mechanical properties of RCA-based concrete. Due to its elastomeric nature, NRL contributes to enhanced flexibility, adhesion, and durability when incorporated into cementitious systems [26]. Previous research has highlighted its ability to modify the interfacial transition zone (ITZ) between aggregate and cement paste, thereby affecting compressive strength (f_c) and flexural strength (f_f) [51]. Nevertheless, some studies have reported reductions in strength when higher dosages of NRL are used, as excessive latex content can disrupt cement hydration and lead to a porous matrix [62]. To address these limitations, the present study investigates the incorporation of fly ash (FA) as a pozzolanic material to refine the microstructure and enhance the long-term performance of NRL-RCA concrete.

FA, a byproduct of coal combustion in thermal power plants, has been extensively used in cement-based materials due to its ability to improve workability, strength, and durability [33]. As a supplementary cementitious material, FA undergoes a pozzolanic reaction with calcium hydroxide ($\text{Ca}(\text{OH})_2$) released during cement hydration, forming additional calcium silicate hydrate (C-S-H) gel [41]. This secondary hydration process enhances the density of the cement matrix, refines pore structure, and contributes to improved mechanical performance over time [20]. Several studies have demonstrated that FA incorporation enhances the compressive strength of RCA-based concrete by mitigating the adverse effects associated with RCA's porous nature and weak ITZ [39]. Furthermore, the long-term benefits of FA, including reduced permeability and enhanced resistance to sulfate attack, make it a promising solution for addressing the durability concerns of RCA concrete [2].

The application of FA in RCA-based concrete has been widely studied, yet limited research has explored its synergistic role with NRL in enhancing pavement concrete performance. In pavement applications, concrete is subjected to significant tensile and bending stresses, making flexural strength a critical parameter [62]. Previous studies have indicated that pozzolanic reactions associated with FA contribute to microstructural refinement, thereby improving bonding within the cementitious system [38]. Moreover, the gradual strength development provided by FA can help offset the early-age reduction in strength often observed in NRL-modified concretes, potentially resulting in a more durable and resilient pavement material [54].

Another key aspect of FA incorporation is its impact on hydration kinetics and the overall microstructure of concrete. RCA, due to its previous exposure to hydration cycles, contains residual cementitious compounds that influence the hydration behavior of new cementitious matrix [15]. The interaction between FA and RCA may lead to variations in reaction kinetics, affecting setting time, strength gain, and overall durability. Advanced analytical techniques, such as scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDS), and X-ray diffraction (XRD), have been employed to evaluate the microstructural characteristics of RCA-based concrete [11]. These methods provide insights into phase composition, elemental distribution, and the formation of hydration products, facilitating a deeper understanding of the mechanisms governing strength development in FA-modified NRL-RCA concrete [13,14].

In addition to mechanical performance, the environmental and economic implications of FA utilization warrant consideration. The increasing generation of FA as an industrial byproduct necessitates sustainable disposal solutions [28]. By integrating FA into concrete formulations, the construction sector can contribute to waste valorization while reducing the demand for Portland cement, which is associated with high carbon emissions [41]. From an economic perspective, FA is often more cost-effective than ordinary Portland cement, making it a viable option for large-scale infrastructure projects [63]. The combination of RCA, NRL, and FA thus presents an innovative approach to sustainable concrete production, aligning with global efforts to promote eco-friendly construction practices [60,61].

Despite the potential benefits, challenges associated with FA incorporation must be acknowledged. The variability in FA composition, influenced by factors such as coal source and combustion conditions, can impact its reactivity and performance in concrete [39]. Furthermore, the optimal dosage of FA must be carefully determined to balance workability, early-age strength, and long-term durability. Excessive FA content may lead to delayed strength gain, which could pose limitations in applications requiring rapid construction cycles [47].

Another critical aspect in evaluating pavement materials is their behavior under cyclic or repeated loading. Unlike static tests, cyclic tests simulate the real service conditions of pavements, which are continuously subjected to traffic-induced stresses and fatigue over their service life. Parameters such as resilient modulus, permanent deformation, and flexural fatigue life provide essential insights into the long-term performance and durability of concrete materials under repeated loads [59]. However, limited research has investigated the cyclic performance of FA-modified NRL-RCA concrete. Addressing this gap is crucial for assessing the feasibility of such mixtures in pavement applications, where resistance to fatigue and deformation directly governs service life.

Previous studies have mainly examined fly ash (FA) or natural rubber latex (NRL) separately in recycled concrete aggregate (RCA) or conventional concrete systems. In contrast, this study systematically investigates the combined FA-NRL modification of RCA-based concrete for rigid pavement applications, integrating mechanical performance, flexural fatigue behavior, microstructural (SEM-EDX) analysis, and environmental and cost assessments. The results establish a clear link between microstructural characteristics and fatigue performance, enabling identification of an optimal FA-NRL combination that meets pavement strength requirements while reducing carbon emissions and material cost.

By building upon the limitations of earlier studies, the present work advances the understanding of sustainable pavement concrete through a unified investigation of mechanical, fatigue, microstructural, and environmental behaviors. Whereas previous research has often examined FA or NRL separately, this study explores their combined effect within an RCA-based system specifically designed for rigid pavement applications. The research emphasizes the optimization of material proportions that satisfy Thai pavement strength standards while simultaneously minimizing CO_2 emissions and material costs. The findings are expected to offer practical guidelines for producing high-performance, low-carbon

pavement concrete and to support the broader adoption of recycled aggregate technology in sustainable infrastructure development.

2. Material and methods

2.1. Materials

Ordinary Portland cement (OPC) was utilized as the primary cementing material, possessing a specific gravity of 3.15. The detailed chemical composition of the OPC is presented in Table 1.

FA used in this research was sourced from a cement manufacturing plant in Nakhon Ratchasima Province, located in northeastern Thailand. According to its chemical composition (Table 1), FA contained 39.18 % silicon dioxide (SiO_2), 22.64 % aluminum oxide (Al_2O_3), and 15.45 % iron oxide (Fe_2O_3), which are key contributors to its pozzolanic activity. With a high calcium oxide (CaO) content of 11.3 %, the FA was classified as Class C in accordance with ASTM C618 standards [8]. The specific gravity of FA was measured at 2.39, and the particle size distribution is illustrated in Fig. 1.

River sand was selected as the fine aggregate in this study. Under a saturated surface dry (SSD) condition, it exhibited a specific gravity of 2.65. Additional properties of the sand included a water absorption capacity of 1.10 %, a fineness modulus of 2.46, and a void content of 43.6 %. The coarse aggregate used was recycled concrete aggregate (RCA), ranging in size from 4.75 to 19 mm. The RCA had a fineness modulus of 6.3 and a specific gravity of 2.67. It exhibited a water absorption rate of 5.5 %, a porosity of 54 %, and a Los Angeles abrasion value of 34 %. A visual representation of the particle characteristics of both RCA and river sand is illustrated in Fig. 1.

Natural rubber latex (NRL) was introduced as an additive to enhance the flexural performance of RCA-based concrete mixtures. The NRL utilized in this study was certified by the Rubber Authority of Thailand, ensuring compliance with industry production standards. The chemical composition of NRL is outlined in Table 2.

To maintain adequate workability and address low slump values, a water-reducing admixture, specifically Sika® Plastocrete®-907, was incorporated into the concrete mix. This admixture meets the ASTM C494 Type D & G specifications and aids in improving the overall flowability of the concrete.

2.2. Specimens preparation

FA-NRL-RCA concrete specimens were prepared with a fixed water-to-binder ratio (w/b) of 0.4, while varying the dried rubber content-to-binder ratio (r/b). The NRL additive was incorporated at five different percentages relative to the binder (cement + FA) weight e.g. 0 %, 0.5 %, 1 %, 1.5 %, and 2.0 % to evaluate its influence on workability and water retention in concrete, as referenced by Kim and Robertson [32]. FA was introduced as a partial cement replacement at three levels: 15 %, 20 %, and 25 % (FA/c). According to Table 2, the chemical composition of NRL consisted of approximately 52 % dry rubber and 48 % water. To maintain the designated w/c ratio, adjustments were made to the total mixing water to account for the water content present in the NRL mix.

In this research, NRL was used in liquid form and mixed with distilled water to prepare the concrete specimens. The method followed ensures accurate incorporation of NRL into the mix while maintaining the specified w/b and r/b ratios. Specifically, the distilled water was

partially replaced by NRL to achieve the target w/b ratio, as suggested by previous studies [62]. Considering the NRL contains 52 % dry rubber, each kilogram of liquid NRL consists of 520 g of dry rubber and 480 g of water. The required NRL dosage for each r/b ratio was determined using the formula $((r/b)/100)B^*(1/0.52)$, where B represents the total binder content (OPC + FA) in kilograms. To maintain the targeted w/b ratio, the mixing water for the concrete was adjusted using the equation $[(w/b)B - 0.48((r/b)/100)B]$, ensuring that the water introduced through NRL was properly accounted for in the overall mix design.

The mix proportions of the FA-NRL-RCA concretes were meticulously designed following the American Concrete Institute (ACI) methodology, as detailed in Table 3. RCA was fully utilized as a substitute for natural aggregate, with the fine and coarse aggregate proportions set at 44 % and 56 %, respectively, adhering to the upper and lower limits prescribed by ASTM C33 [6]. A superplasticizer was incorporated to ensure that the slump values remained within the target range of 40–60 mm for the w/c ratio of 0.4. To mitigate the inherent deficiencies of RCA, such as increased porosity and microcracking caused by the crushing process, the FA-NRL-RCA concrete mixtures were produced using the Two-Stage Mixing Approach (TSMa) as recommended by Tam et al. [52]. This method is specifically employed to enhance RCA quality, ultimately improving the overall mechanical and durability properties of the concrete.

The cement was partially replaced by FA on a mass basis to maintain consistency with the reference RCA-NRL concrete used for comparison. Although mass-based replacement can introduce slight volumetric variation due to the lower specific gravity of FA, the mix proportions were carefully adjusted to ensure a total volume of approximately 1.00 m³ for all mixtures, as shown in Table 3. This approach allows a direct evaluation of FA's influence on hydration behavior, microstructural refinement, and long-term performance while maintaining comparable batch volumes. A total binder content of approximately 450 kg/m³ was adopted for the mix design to meet the requirements of rigid pavement applications in accordance with the Department of Highways, Thailand specification (DH-S309/2544), which specifies minimum strengths of $f_c \geq 32$ MPa and $f_t \geq 4.2$ MPa at 28 days. This relatively high binder content was selected to ensure adequate fatigue resistance and workability for pavement-grade concrete while compensating for the higher porosity and water absorption of RCA.

2.3. Engineering and microstructural investigation

2.3.1. Compressive strength (f_c) and flexural strength (f_f)

The FA-RCA-NRL concrete specimens were prepared following the ACI method, aiming to achieve a f_c of 350 ksc (34.3 MPa) at w/c = 0.4, as presented in Table 3. A rotary drum mixer was employed to ensure uniform distribution of all components throughout the mixing process. The workability of the fresh concrete mixture was assessed using the slump test, conducted in accordance with ASTM C143 [4]. To evaluate the f_c , cubic concrete specimens measuring 150 × 150 × 150 mm³ were cast following the standards outlined in BS 1881 Part 3 [12]. Similarly, for f_f , testing beam-shaped specimens of 100 × 100 × 400 mm³ were prepared. The fresh FA-RCA-NRL concrete was poured into molds in three layers, with each layer compacted using a 4-pound steel ram, applying 35 strokes per layer, as specified in ASTM C192 [5]. The specimens were cured in a moist environment at a controlled temperature of 27° – 29° to ensure proper hydration and strength development. After 7, 28 and 56 days, f_c testing was performed following either BS 1881 Part 4 (1983) or ASTM C39 [7] standards. For f_f evaluation, the beam specimens underwent a third-point loading test, where two loads were applied to divide the beam span into three equal sections, adhering to ASTM C78 [9]. The f_f values of the FA-RCA-NRL concretes were subsequently calculated using the relevant equation based on these experimental procedures.

Table 1
Chemical compositions of OPC and Fly Ash.

Materials	Composition (%)						
	SiO_2	SO_3	Fe_2O_3	Al_2O_3	CaO	MgO	LOI
Cement	20.9	2.7	3.32	4.7	65.4	2.54	0.9
FA	39.18	4.29	15.45	22.64	11.3	1.69	1.61

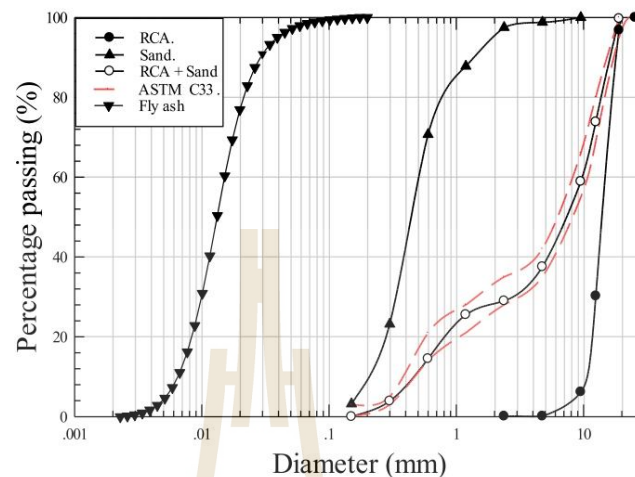


Fig. 1. Particle size distributions of Sand, RCA, RCA+Sand and FA.

Table 2
Chemical Analysis of Natural Rubber Latex.

Property	Value
Total solid content (TSC)	55.11 %
Dry rubber content (DRC)	52.04 %
Non rubber contents (NRC)	3.07 %
Volatile fatty acid (VFA)	0.07 %
Alkalinity (NH ₃)	0.69 %
pH	10.42 %
Mechanical stability time (MST)	7440 s

$$\text{Flexural strength}(ff) = \frac{PL}{2bd^2} \quad (1)$$

where P is the maximum load, L is the span length, and b and d are the average width and depth of the specimen.

The average values of f_c and f_t were determined based on data obtained from three test specimens. To ensure the reliability and consistency of the results, these values were rigorously evaluated within the standard deviation (SD) threshold, following the criterion $SD/\bar{X} < 10\%$,

where $\bar{X}$ represents the mean value of either f_t or f_c .

2.3.2. Flexural Fatigue

The three-point flexural fatigue test was conducted on FA-RCA-NRL concrete specimens, maintaining the same mix proportions and dimensions as those used in flexural strength testing. A 500 kN electro-hydraulic servo testing machine equipped with an autonomous data recorder was utilized to evaluate fatigue performance. The impact of NRL and FA incorporation on the fatigue resistance of concrete beams was evaluated across all r/b and FA replacement ratios by applying cyclic vertical loads at stress ratio (SR) levels of 60 %, 70 %, and 80 %, referenced to their flexural strength (f_t). To ensure a consistent loading condition throughout the test, a stress-controlled approach was implemented to maintain a constant load at the target SR.

The stress ratio (SR), which accounts for both applied flexural stress and concrete strength, was determined using the equation proposed by Smith and Roesler [48]

$$SR = \frac{\sigma}{f_t} \quad (2)$$

Table 3
The mix proportions of the FA-NRL-RCA concretes.

Mix	r/b (wt.%)	OPC (kg/m ³)	FA (kg/m ³)	Sand (kg/m ³)	RCA Coarse Agg. (kg/m ³)	Water (kg/m ³)	NRL (kg/m ³)	SP (kg/m ³)	volume (m ³)
0 %FA	0.0	462.5	0	734	1018	185	0	2.78	0.99008
15 %FA	0.0	393.125	69.375	734	1018	185.00	0.00	2.36	0.99708
15 %FA + 0.5 %NRL	0.5	393.125	69.375	734	1018	182.87	4.45	2.36	0.99708
15 %FA + 1.0 %NRL	1.0	393.125	69.375	734	1018	180.73	8.89	2.36	0.99495
15 %FA + 1.5 %NRL	1.5	393.125	69.375	734	1018	178.60	13.34	2.36	0.99281
15 %FA + 2.0 %NRL	2.0	393.125	69.375	734	1018	176.46	17.79	2.36	0.99068
20 %FA	0.0	370	92.5	734	1018	185.00	0.00	2.22	0.98855
20 %FA + 0.5 %NRL	0.5	370	92.5	734	1018	182.87	4.45	2.22	0.99942
20 %FA + 1.0 %NRL	1.0	370	92.5	734	1018	180.73	8.89	2.22	0.99942
20 %FA + 1.5 %NRL	1.5	370	92.5	734	1018	178.60	13.34	2.22	0.99728
20 %FA + 2.0 %NRL	2.0	370	92.5	734	1018	176.46	17.79	2.22	0.99515
25 %FA	0.0	346.875	115.625	734	1018	185.00	0.00	2.08	0.99301
25 %FA + 0.5 %NRL	0.5	346.875	115.625	734	1018	182.87	4.45	2.08	0.99088
25 %FA + 1.0 %NRL	1.0	346.875	115.625	734	1018	180.73	8.89	2.08	1.00175
25 %FA + 1.5 %NRL	1.5	346.875	115.625	734	1018	178.60	13.34	2.08	1.00175
25 %FA + 2.0 %NRL	2.0	346.875	115.625	734	1018	176.46	17.79	2.08	0.99962

where σ represents the applied flexural stress, and f_t denotes the flexural strength of the FA-RCA-NRL concrete.

To simulate the vehicular traffic loading conditions expected in pavement applications, a haversine loading pulse with a frequency of 10 Hz was applied to the FA-RCA-NRL concrete specimens.

To improve the reliability and transparency of the experimental findings, all bar charts illustrating compressive strength, flexural strength, and fatigue life included error bars representing one standard deviation (SD), derived from three specimens per mix condition. This addition highlights the reproducibility of the results and provides a clearer visualization of data variability across the tested mixtures.

2.3.3. Scanning electron microscopy (SEM) and Energy-Dispersive X-ray spectroscopy (EDX)

The development of f_c and f_t in relation to varying r/b and FA replacement ratios was analyzed using scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDX). To facilitate SEM and EDX examinations, a thin section of the specimen was first frozen at -195°C in liquid nitrogen and subsequently coated with a protective gold layer, ensuring optimal image quality for SEM analysis [60].

2.3.4. Calculation of carbon emissions

Life cycle assessment is an analytical method used to evaluate the environmental impacts associated with the stages of a product's life, which is from raw material extraction through materials processing, manufacture, distribution, and use. The carbon is a dominant category to assess the environment impacts compared to other impact categories [34,44]. The carbon footprint is a key greenhouse gas that drives global climate change and global warming effect [25]. In practice, the evaluation of carbon footprint of a product is the key process for the life cycle assessment. Carbon emissions was calculated using the following equation:

$$\sum \text{CO}_2 = V \times EF \quad (3)$$

where V is the amount of tested materials (kg), and EF is the emission factors of tested materials (kg $\text{CO}_2\text{-e/kg}$).

In this study, the life-cycle assessment adopted a cradle-to-gate system boundary, covering raw material extraction, processing, transportation, and concrete production up to the batching stage. The emission factors used in this study, summarized in Table 4, were obtained from established literature sources [18,36] [55,29], and their values fall within the ranges reported by internationally recognized databases, including the IPCC Guidelines [17,27]. This alignment ensures that the carbon assessment is consistent with widely accepted life-cycle inventory data for cementitious materials, aggregates, and industrial by-products.

3. Results

3.1. Compressive strength of FA-RCA-NRL concrete

Fig. 2 illustrates the compressive strength (f_c) development of FA-RCA-NRL concrete specimens cured for 7, 28, and 56 days, with FA replacement levels of 0 % [64], 15 %, 20 %, and 25 %, and various r/b

ranging from 0.0 % to 2.0 %, under a constant w/b ratio of 0.4. At all curing periods, the specimens without NRL ($r/b = 0$ %) exhibited the highest f_c . As expected, the f_c of all mixtures increased with longer curing durations, while it decreased with an increasing r/b ratio. For instance, at 7 days (Fig. 2(a)), the f_c of the control mix ($r/b = 0$ %) reached 42.80 MPa for FA = 0 % [64], which was higher than the corresponding values of 41.14 MPa, 38.32 MPa, and 37.52 MPa for FA replacement levels of 15 %, 20 %, and 25 %, respectively. However, when the r/b ratio was increased to 2.0 %, the f_c values dropped markedly to 25.80 MPa for FA = 0 % and to 25.68 MPa, 24.44 MPa, and 23.32 MPa for FA = 15 %, 20 %, and 25 %, respectively. A similar trend was observed at 28 days (Fig. 2(b)), where the control mixes continued to outperform the NRL-modified ones. The f_c values at $r/b = 0$ % were 49.10 MPa for FA = 0 % [64], followed by 48.52 MPa, 46.47 MPa, and 45.15 MPa for FA levels of 15 %, 20 %, and 25 %, respectively. In contrast, at the highest NRL content ($r/b = 2.0$ %), the f_c values decreased to 31.00 MPa for FA = 0 % and to 28.92 MPa, 28.43 MPa, and 27.57 MPa for FA = 15 %, 20 %, and 25 %, respectively.

Interestingly, the 56-day strength results (Fig. 2(c)) reveal a noteworthy gain in f_c , particularly for higher FA replacement levels. For example, the control mix ($r/b = 0$ %) demonstrated increasing strength with increasing FA content, reaching 53.35 MPa, 55.78 MPa, and 59.63 MPa for 15 %, 20 %, and 25 % FA, respectively. This long-term strength gain is attributed to the pozzolanic reaction of FA, which becomes more pronounced over time. Despite the strength reductions observed at early ages with higher r/b ratios, the 56-day strength results for NRL-modified mixes showed measurable improvement. At $r/b = 2.0$ %, f_c improved to 33.10 MPa, 33.76 MPa, and 32.76 MPa for FA contents of 15 %, 20 %, and 25 %, respectively indicating that the delayed strength development associated with NRL and FA can be partially recovered over time.

The horizontal dotted line in Fig. 2(b) indicates the minimum f_c requirement for rigid pavement, as specified by the Department of Highways, Thailand ($f_c > 32$ MPa at 28-day) [DH-S309/2544]. It was observed that the control mixtures without NRL ($r/b = 0$ %) met the requirement for all levels of FA replacement. In particular, the FA = 0 % mix achieved the highest compressive strength at 28 days (49.1 MPa), clearly surpassing the minimum requirement and outperforming the FA-blended concretes. For mixes incorporating NRL, the requirement was still satisfied at $r/b \leq 1.0$ % for FA = 15 % and FA = 20 %, with f_c of 41.21 MPa and 36.63 MPa at $r/b = 0.5$ %, and 37.63 MPa and 32.78 MPa at $r/b = 1.0$ %, respectively. However, for FA = 25 %, only the mixes with $r/b = 0.5$ % (35.28 MPa) met the standard. Mixes with $r/b \geq 1.5$ % for all FA replacement levels fell below the required 32 MPa threshold, highlighting that higher NRL content adversely affected strength development at 28 days. This suggests that, for applications requiring compliance with the Department's rigid pavement criteria, the allowable r/b ratio should be limited according to the FA content: up to 1.0 % for FA levels below 20 %, and restricted to 0.5 % when FA content reaches 25 %.

3.2. Flexural strength of FA-RCA-NRL concrete

Fig. 3 presents the f_t development of FA-RCA-NRL concrete specimens at 7, 28, and 56 days with different FA replacement levels (0 %, 15 %, 20 %, and 25 %) and r/b ratios of 0.0 %, 0.5 %, 1.0 %, 1.5 %, and 2.0 %, under a constant w/b ratio of 0.4. The results indicated that at a given r/b ratio and FA content, f_t increased over time, with the highest values observed at 56 days, similar to the compressive strength trend. At 7 days (Fig. 3(a)), the control mix ($r/b = 0$ %) exhibited the highest f_t , reaching 4.15 MPa for FA = 0 % [64], which was slightly higher than the values of 4.00 MPa, 3.80 MPa, and 3.66 MPa for FA levels of 15 %, 20 %, and 25 %, respectively. With the incorporation of NRL, the f_t decreased across all FA contents, particularly at $r/b \geq 1.5$, where the f_t values dropped to 3.55 MPa for FA = 0 % [64] and to 3.26 MPa, 3.22 MPa, and 2.75 MPa for FA = 15 %, 20 %, and 25 %, respectively.

Table 4
Emission factors (kg $\text{CO}_2\text{-e/kg}$) and Material Cost of concrete mix materials.

Material	Emission factor (kg $\text{CO}_2\text{-e/kg}$)	Material Cost (USD/kg)
Cement (kg)	0.86 [36]	0.114 [16]
Fly ash (kg)	0.007 [36]	0.0124 [45]
Sand	0.006 [18]	0.0062 [22]
RCA	0.000667 (Alzard et al. 2020)	0.0055 [43]
NRL	0.095	1.92 [62]
	Usubharatana, Phunggrassami [55]	
NA	0.035 [29]	0.042 [29]

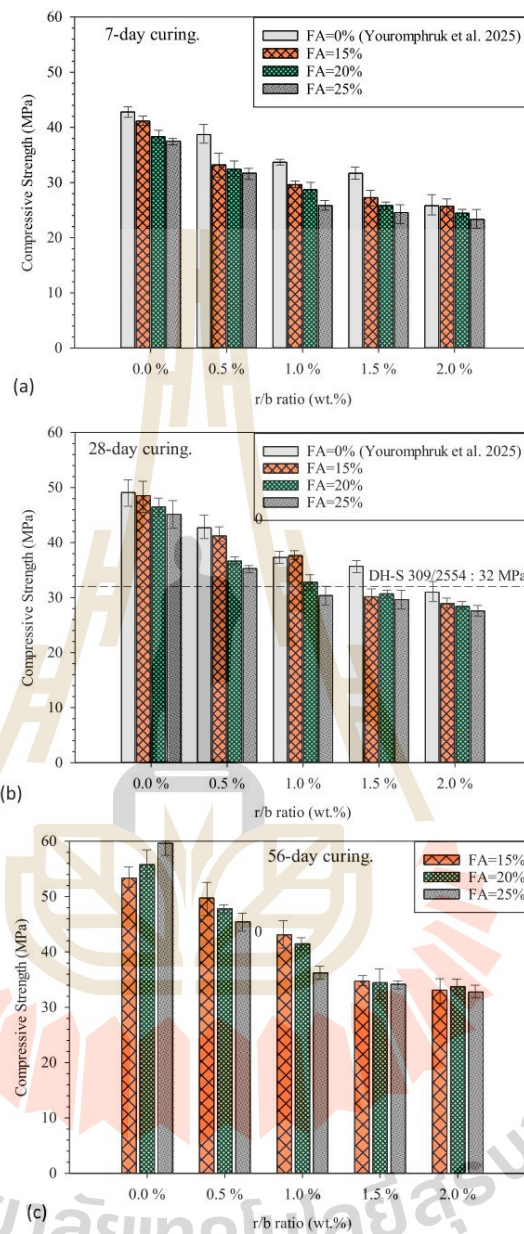


Fig. 2. Compressive strength of FA-RCA-NRL concrete at. (a) 7 days; (b) 28 days; (c) 56 days.

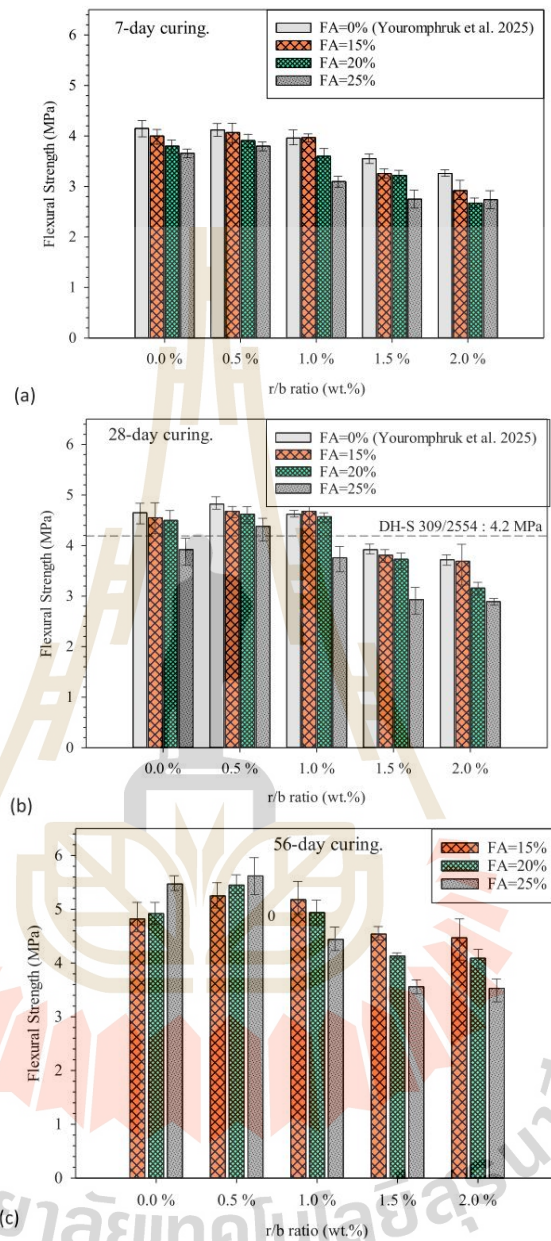


Fig. 3. Flexural strength of FA-RCA-NRL concrete at: (a) 7 days; (b) 28 days; (c) 56 days.

At 28 days (Fig. 3(b)), an increase in f_t was observed across all mixes. The control concrete ($r/b = 0\%$) achieved 4.65 MPa for FA = 0% [64], compared with 4.55 MPa, 4.50 MPa, and 3.92 MPa for FA replacement levels of 15%, 20%, and 25%, respectively. The highest f_t was recorded at $r/b = 0.5$, where f_t exceeded that of the control mix, reaching 4.82 MPa for FA = 0% [64] and 4.57 MPa, 4.62 MPa, and 4.38 MPa for FA = 15%, 20%, and 25%, respectively. At $r/b = 1.0$, a slight reduction was noted, with corresponding values of 4.62 MPa for FA = 0% [64] and at 4.68 MPa, 4.57 MPa and 3.76 MPa for FA = 15%, 20% and 25%, respectively. Beyond this level, a consistent decline in f_t was evident, with $r/b = 2.0$ producing the lowest values: 3.72 MPa for FA = 0% [64] and to 3.69 MPa, 3.16 MPa, and 2.89 MPa for FA = 15%, 20%, and 25%, respectively. These results suggest that a low-to-moderate NRL dosage ($r/b = 0.5$ – 1.0%) enhances flexural performance, whereas higher dosages ($r/b \geq 1.5\%$) negatively affect strength development, likely due to changes in the cementitious matrix and bond structure.

At 56 days (Fig. 3(c)), the highest f_t was recorded, with f_t exceeding 5.0 MPa for some mixes. The control mix ($r/b = 0\%$) exhibited 4.82 MPa, 4.92 MPa, and 5.47 MPa for FA replacement levels of 15%, 20%, and 25%, respectively. The highest recorded f_t was 5.62 MPa at $r/b = 0.5\%$ and FA = 25%, suggesting that a moderate addition of NRL contributed positively to long-term strength development. However, a decline was noted for $r/b \geq 1.5$, where f_t values dropped to 4.13 MPa, 4.54 MPa, and 3.56 MPa at FA levels of 15%, 20%, and 25%, respectively.

The f_t of FA-RCA-NRL concrete exhibited ages-dependent trends rather than a single distinct pattern. At 7 days, f_t generally decreased with increasing r/b ratio for all FA levels, which is attributed to the insufficiently developed cementitious matrix at early age; consequently, NRL is not yet effective and higher latex contents can even disrupt hydration. At 28 days, an optimum emerged: mixes with $r/b \approx 0.5$ – 1.0% achieved equal or higher f_t than the $r/b = 0\%$ control for FA = 15–20% (with the peak at $r/b = 1.0\%$), while the FA = 25% series benefited only at $r/b = 0.5\%$ and declined beyond this dosage. By 56 days, the optimum shifted toward $r/b \approx 0.5\%$ for all FA levels, after which f_t decreased markedly at higher r/b ratios of $\geq 1.5\%$. This evolution reflects the combined effects of latex-film coalescence and the delayed pozzolanic reaction of FA, which enhance matrix integrity at moderate NRL dosages.

The horizontal dotted line in Fig. 3(b) represents the minimum f_t requirement for rigid pavements, as per the Department of Highways, Thailand ($f_t > 4.2$ MPa at 28-day) [DH-S309/2544]. The control concrete ($r/b = 0\%$) met this requirement for FA = 0%, 15% and 20% at 28 days but failed for FA = 25%. Among the NRL-modified concretes, the requirement was satisfied for $r/b \leq 1.0\%$ at FA = 0%, 15% and 20%, achieving f_t above 4.2 MPa. For FA = 25%, only the mix with $r/b = 0.5\%$ met the standard, recording 4.38 MPa at 28 days, while $r/b \geq 1.5\%$ failed to meet the requirement across all FA levels. When evaluating both f_c and f_t requirements, the control concrete ($r/b = 0\%$) met the requirement when FA < 20%, while FA-RCA-NRL-concrete met the requirement when $r/b \leq 1.0\%$ for FA < 20%, and when $r/b = 0.5\%$ for FA < 25%. These findings suggest that while NRL improves workability and water retention, its proportion must be optimized to ensure compliance with structural performance standards. Moreover, the inclusion of FA contributes long-term benefits through its pozzolanic reaction, which improves the microstructure, enhances durability, and supports continued strength development beyond 28 days, thereby improving the overall service life of RCA-based pavement concrete.

3.3. Fatigue performance

Fig. 4 illustrates the fatigue performance of FA-RCA-NRL concrete at 28 days of curing, incorporating various levels of FA replacement (15%, 20%, and 25%) and r/b , under three applied stress ratios (60%, 70%, and 80%). It should be noted that the fatigue behavior of the FA = 0%

mixtures was not further investigated in this study, since the research objective focused on reducing cement consumption to lower material costs and mitigate greenhouse gas emissions. In addition, the results of compressive and flexural strength tests confirmed that concretes with FA replacement levels of 15–25% still satisfied the minimum requirements of the Department of Highways, Thailand with superior long-term performance, ensuring their suitability for pavement applications.

In general, fatigue life decreased as the stress ratio increased, regardless of FA content or r/b ratio. For example, at FA = 15% (Fig. 4(a)), the fatigue life of unmodified concrete ($r/b = 0\%$) was 2022, 750, and 122 cycles at stress ratios of 60%, 70%, and 80%, respectively. The inclusion of NRL at $r/b = 0.5\%$ significantly enhanced the fatigue life to 2564, 895, and 263 cycles under the same stress levels. However, increasing the r/b ratio beyond 1.0% resulted in a gradual reduction in fatigue life, reaching the lowest values of 1507, 562, and 55 cycles at $r/b = 2.0\%$, likely due to excessive NRL content retarding hydration and limiting pozzolanic reaction.

A similar trend was observed at FA = 20% (Fig. 4(b)), where the fatigue life of the unmodified mix ($r/b = 0\%$) was 2546, 988, and 253 cycles at 60%, 70%, and 80% stress ratios, respectively. The optimum fatigue performance was again recorded at $r/b = 0.5\%$, where fatigue life increased to 2868, 1263, and 364 cycles, demonstrating that moderate NRL content improves resistance to cyclic loading. Beyond this point, further increases in r/b caused a decline in fatigue life, with the lowest values at $r/b = 2.0\%$ being 1954, 659, and 126 cycles, similar to the pattern found with 15% FA. At FA = 25% (Fig. 4(c)), all mixes exhibited generally lower fatigue life compared to those with 15% and 20% FA replacement ratios. The unmodified mix ($r/b = 0\%$) recorded fatigue lives of 2269, 785, and 62 cycles at the respective stress ratios. As with the other FA levels, the addition of NRL at $r/b = 0.5\%$ improved performance to 2436, 863, and 87 cycles. However, as the r/b ratio increased further, fatigue life diminished, with $r/b = 2.0\%$ yielding the lowest recorded values of 1544, 201, and 39 cycles.

Fig. 5 illustrates the fatigue performance of FA-RCA-NRL concrete at 56 days of curing, incorporating various levels of FA replacement (15%, 20%, and 25%) and different r/b ratios, under three applied stress ratios (60%, 70%, and 80%). At 15% FA replacement ratio (Fig. 5(a)), the unmodified concrete ($r/b = 0\%$) exhibited moderate fatigue resistance, recording 3567, 1265, and 532 cycles at stress ratios of 60%, 70%, and 80%, respectively. These values reflect limited long-term performance, particularly under high-stress conditions, likely due to the relatively low pozzolanic reactivity at this replacement level. Importantly, the incorporation of NRL at an optimum dosage ($r/b = 0.5\%$) extended the fatigue life to 3856, 1584 and 689 cycles at stress ratios of 60%, 70%, and 80%, respectively, confirming the beneficial interaction of latex film formation and FA-induced microstructural refinement at later ages. However, when the r/b ratio increased to 2.0, the fatigue life significantly decreased to 2247, 1101, and 386 cycles, suggesting that excessive NRL content impaired hydration and weakened bonding within the cementitious matrix.

At 20% FA replacement (Fig. 5(b)), the unmodified concrete ($r/b = 0\%$) showed a marked improvement, achieving 3862, 1416, and 696 cycles at the respective stress levels. In this case, the addition of NRL at $r/b = 0.5\%$ further enhanced fatigue performance to 3896, 1756 and 852 cycles at stress ratios of 60%, 70%, and 80%, respectively, particularly under low-to-moderate stress ratios, highlighting the synergistic effect of FA's pozzolanic activity and latex bridging in prolonging fatigue life. Although a reduction in fatigue life was observed at $r/b = 2.0\%$, with values of 2136, 1306, and 463 cycles, the overall performance remained acceptable—especially under lower and moderate stress ratios. This indicates that the higher pozzolanic activity at 20% FA helped mitigate the negative effects of elevated NRL dosage.

The trend continued at 25% FA (Fig. 5(c)), where the unmodified concrete ($r/b = 0\%$) achieved the highest fatigue life among all tested groups: 4596, 2305, and 1253 cycles at 60%, 70%, and 80% stress ratios, respectively. At this FA level, the presence of NRL at $r/b = 0.5\%$

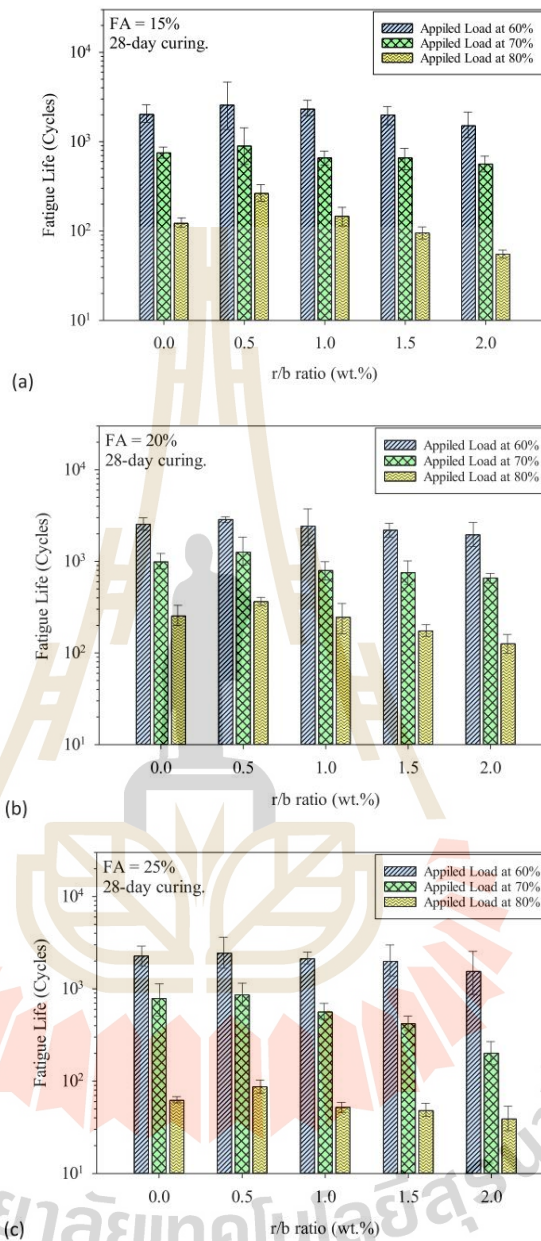


Fig. 4. Fatigue life of FA-RCA-NRL concrete at 28 days for FA replacement levels of (a) 15 %, (b) 20 %, and (c) 25 %.

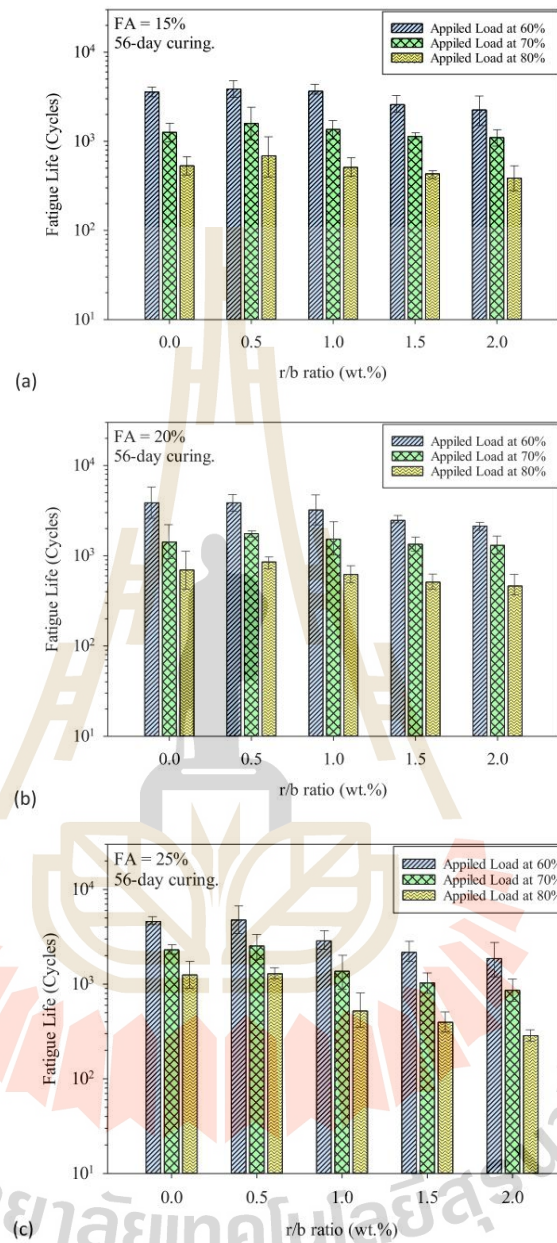


Fig. 5. Fatigue life of FA-RCA-NRL concrete at 56 days for FA replacement levels of. (a) 15 %, (b) 20 %, and (c) 25 %.

sustained high fatigue resistance even beyond the control mix, with values of 4768, 2534, and 1288 cycles, underscoring the strong synergy between high-volume FA and moderate latex addition. Notably, even at $r/b = 2.0$, the fatigue performance remained relatively robust, with 1863, 862, and 286 cycles. Although this represented a reduction compared to the unmodified mix, the decline was more gradual, suggesting that high-volume FA contributes to improved matrix resilience and can partially offset the detrimental impact of excessive latex content. Overall, these findings emphasize the critical role of FA replacement level in moderating the influence of NRL on fatigue life, especially over extended curing periods.

In addition to fatigue life, Fig. 6 illustrates the displacement response of FA-RCA-NRL concrete under flexural fatigue loading at a stress ratio of 60 %, incorporating 25 % FA replacement and a constant w/c ratio of 0.4 across various r/b ratios. The number of cycles to failure is plotted along the x-axis, while the y-axis represents the total displacement at the center of the beam during cyclic loading. The unmodified concrete ($r/b = 0$ %) exhibited moderate fatigue life, with a notable increase in displacement toward the final stages of loading, indicating failure after about 80 % of its fatigue life. In contrast, the mix with $r/b = 0.5$ % showed the highest fatigue life and noticeably lower displacement accumulation than the mixes with $r/b = 1.5$ %, and 2.0 %, identifying it as the optimum r/b ratio for this mix. This trend is consistent with the findings of Suddeepong et al. [50], which demonstrated that low dosages of NRL can enhance ductility, energy absorption, and fatigue resistance by improving the microstructural bond and limiting micro-crack propagation. However, further increases in r/b ratio to 1.0, 1.5, and 2.0 led to a noticeable decline in fatigue performance, as seen in the lower fatigue life and greater displacement accumulation. This behavior is attributed to the adverse effects of excessive latex, which can retard hydration, disrupt matrix formation, and increase plastic deformation. The shape of the displacement curves also reflects the typical three-phase fatigue behavior observed in cementitious materials: an initial phase of crack initiation, a stable crack propagation phase, and a final phase characterized by rapid displacement growth leading to failure. The $r/b = 0.5$ % mix maintained a prolonged stable phase with low deformation progression, suggesting superior crack control and energy dissipation under repeated loading.

Fig. 7 presents the flexural fatigue performance of FA-RCA-NRL concrete at 56 days of curing under stress ratios of 60 %, 70 %, and 80 %, with varying r/b ratios and FA replacement levels of 15 %, 20 %, and 25 %, compared with the PCA [42] fatigue model. The results show that the NRL-modified RCA concretes scatter closely around the PCA model line, confirming that SR predominantly governs fatigue life. The results clearly showed that fatigue life was strongly influenced by both the r/b ratio and the applied stress ratio. At FA = 15 %, the unmodified mix ($r/b = 0$ %) recorded fatigue lives of 3567, 1265, and 532 cycles at stress ratios of 60 %, 70 %, and 80 %, respectively. The fatigue life increased at $r/b = 0.5$ % to 3856, 1584, and 689 cycles, confirming an optimum dosage that enhances resistance to cyclic loading. However, further increases in r/b ratio led to decreased performance, with the lowest fatigue life observed at $r/b = 2.0$ % (2247, 1101, and 386 cycles). A similar trend was observed at FA = 20 %, where the unmodified mix achieved 3862, 1416, and 696 cycles. The peak performance was again at $r/b = 0.5$ % (3996, 1756, and 852 cycles), suggesting an optimum NRL dosage. Beyond this point, fatigue life progressively declined, particularly at $r/b = 2.0$ %, where the fatigue life dropped to 2136, 1306, and 463 cycles. These findings align with Suddeepong et al. [50], who demonstrated that NRL-modified concrete at optimum r/b ratios exhibits superior flexural fatigue resistance compared with conventional concrete, due to reduced plastic deformation and improved ductility.

Fig. 8 presents the regression analysis between the logarithmic fatigue life ($\log N_f$) and the applied stress ratio (SR) for the FA-NRL-RCA concrete. The derived relationship closely followed the trend of the Portland Cement Association (PCA) [42] fatigue model but exhibited a lower slope, indicating a more gradual rate of fatigue degradation. This

behavior demonstrates the beneficial effect of optimal NRL incorporation in improving the fatigue resistance of FA-RCA concrete. The strong correlation between the measured and predicted fatigue lives further confirms that the proposed regression model reliably represents the fatigue behavior of the developed mixtures.

From a mechanistic design perspective, the Department of Highways (DH-S309/2544) specifies fatigue life as a controlling factor in rigid pavement performance. For normal concretes, fatigue life is strongly governed by the stress ratio (SR) in accordance with the PCA model. However, recent studies indicate that in NRL-concretes, this relationship is modified: at equivalent SR, the presence of latex films improves crack resistance and extend fatigue life beyond conventional predictions. This suggests that mix design for NRL-concrete pavement should not only satisfy compressive ($f_c > 32$ MPa) and flexural strength ($f_t > 4.2$ MPa) requirements but also optimize the r/b ratio at ~ 0.5 to achieve superior fatigue performance. By adopting this approach, pavement thickness can potentially be reduced without compromising service life, offering both economic and sustainability benefits, consistent with design recommendations by Suddeepong et al. [50] and Yaowarat et al. [62].

4. Microstructural analysis

To understand the microstructural characteristics of FA-RCA-NRL concrete, scanning electron microscope (SEM) analysis was performed at 28 days of curing. The SEM was operated at 15 kV with secondary electron imaging to characterize the morphology of the concrete surface. Fig. 8 illustrates the microstructure of FA-RCA-NRL concrete incorporating 25 % FA as a partial cement replacement and varying r/b ratios of 0 %, 0.5 %, and 2 %. In Fig. 8(a) ($r/b = 0$ %), the microstructure displays a relatively dense matrix with well-formed C-S-H gel and needle-like ettringite crystals, reflecting active early-age hydration [40,61]. Smooth and spherical FA particles are embedded in the matrix, indicating partial pozzolanic reaction [19,21,3]. In the absence of NRL, no polymer films are observed, allowing for uninterrupted hydration and gel formation. In Fig. 8(b), corresponding to the optimal r/b ratio of 0.5 %, the microstructure appears more homogeneous and compact compared to the $r/b = 0$ % mix (Fig. 8(a)). Thin and continuous NRL films were evident, interwoven with the hydration products and bridging microvoids within the matrix. These films likely fill capillary pores and reinforce interfacial zones, resulting in enhanced flexural strength and fatigue life due to the improved ductility and crack-bridging capability of the latex [26,35,49]. The smoother surface texture and denser C-S-H gel formation suggest a favorable interaction between pozzolanic FA reaction and moderate latex addition. The microstructure at this dosage reflects a balanced synergy: sufficient hydration, strong inter-particle bonding, and enhanced toughness from the polymer network [60,62].

In contrast, Fig. 8(c), representing a higher r/b ratio of 2.0 %, shows a more porous and disrupted morphology. Thicker NRL films are visible, particularly around unreacted or partially hydrated FA particles and hydration products. These films appear to cluster or isolate phases, forming physical barriers that retard water transport and ion exchange, which are essential for continued hydration [23,31,33,58]. The resulting structure is less cohesive, with poorly developed C-S-H gel and visible voids. This morphology correlates with a reduction in compressive strength, as the excessive latex interferes with the formation of continuous cementitious bonds. Moreover, the plastic nature of the excess NRL may have introduced internal weaknesses that compromise the material's load-bearing capacity under compression [10].

In Fig. 9(a) ($r/b = 0$ %), the matrix revealed a dense and well-developed microstructure, featuring numerous etched spherical FA particles and needle-like ettringite crystals embedded within a continuous C-S-H gel network. The pronounced surface dissolution of the FA indicates active and advanced pozzolanic reaction, contributing to the formation of additional cementitious products [21,30,56]. Although some voids remain due to the absence of NRL, the unimpeded hydration

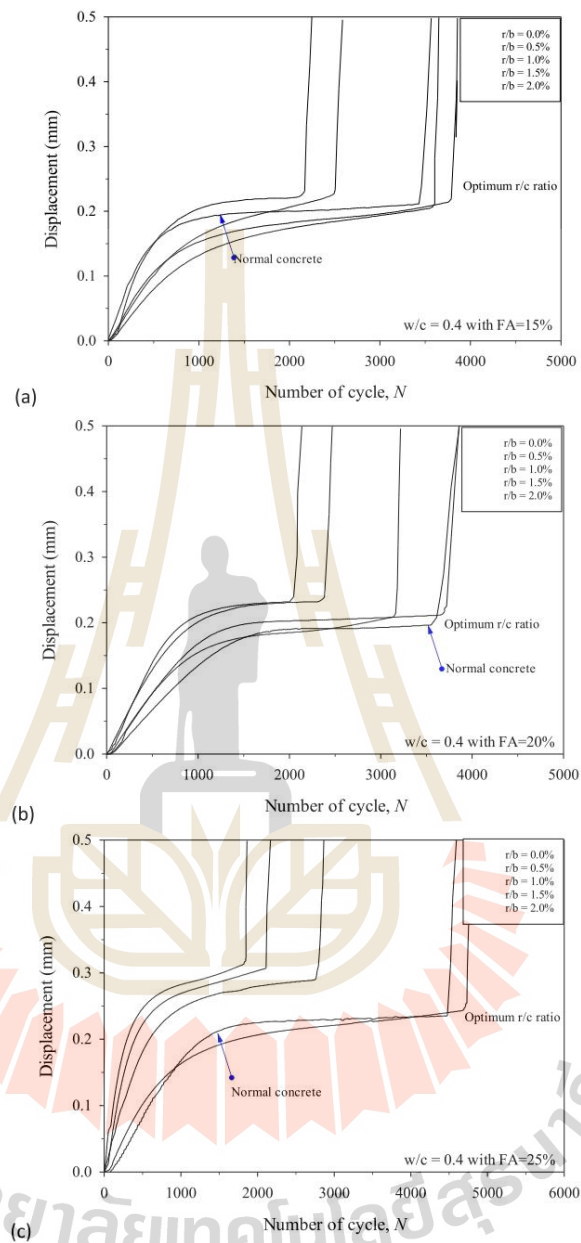


Fig. 6. Flexural fatigue response of FA-RCA-NRL concrete under a stress ratio of 60% after 56 days for FA replacement levels of (a) 15%, (b) 20%, and (c) 25%.

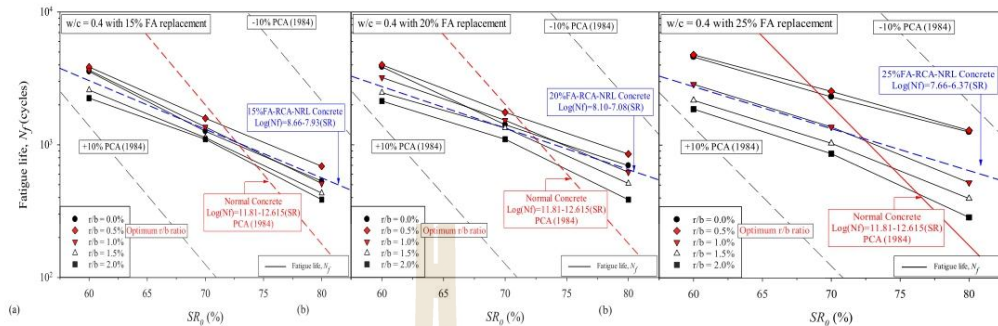


Fig. 7. Effect of r/b ratio on fatigue life versus SR_0 relationship of FA-RCA-NRL concrete at 56 days for varying fly ash replacement levels: (a) 15 %, (b) 20 %, and (c) 25 %.

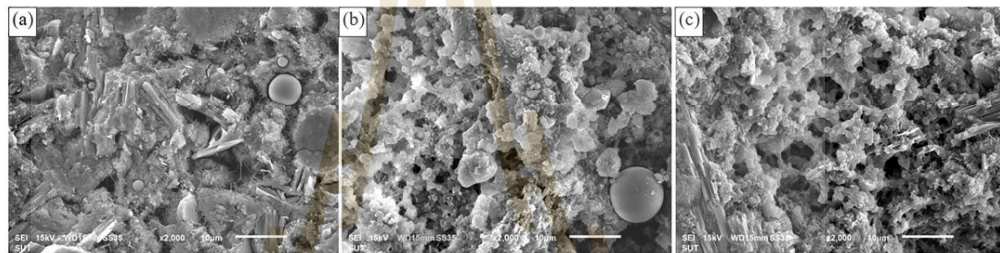


Fig. 8. SEM images of FA-RCA-NRL concrete at 28 days with 25 % fly ash replacement and r/b ratios of (a) 0 %, (b) 0.5 % (optimal), and (c) 2 %.

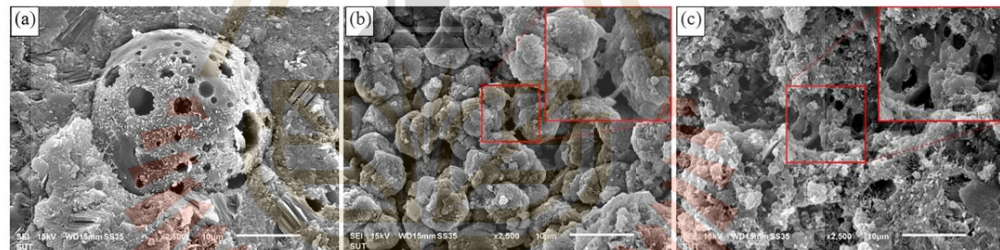


Fig. 9. SEM images of FA-RCA-NRL concrete at 56 days with 25 % fly ash replacement and r/b ratios of (a) 0 %, (b) 0.5 % (optimal), and (c) 2 %.

enables the development of a cohesive and well-bonded matrix. This results in the highest compressive strengths among the mixes, as the structure benefits from complete gel formation without interference from polymer films.

Fig. 9(b) ($r/b = 0.5$ %) represents the optimal latex dosage, showing a compact and refined microstructure. The matrix is densely packed with granular C-S-H and well-integrated FA particles. The inset magnification reveals thin NRL films bridging microvoids and bonding hydration products, which improve flexural performance through crack-bridging effects. While some porosity persists, the synergistic effect of FA and moderate latex dosage fosters both pozzolanic reactivity and matrix reinforcement. The structure is optimized for bending resistance, explaining its superior flexural strength at this dosage. In Fig. 9(c) ($r/b = 2$ %), the matrix deteriorates visibly. The microstructure is porous, with

disconnected gel phases and clusters of unreacted or partially reacted FA particles. Thick, continuous latex films dominate the surface, forming barriers around hydration sites. These films restrict water movement and reduce the efficiency of hydration and pozzolanic reactions, leading to a fragmented and weakly bonded matrix [37,62]. The excess polymer acts more as an insulator than a reinforcing agent, correlating with the lowest compressive strength among the mixes.

Fig. 10 presents the EDX spectra of FA-RCA-NRL concretes at 56 days with 25 % FA replacement for different r/b ratios. The dominant elements identified across all samples were Ca, Si, and Al, confirming the formation of C-S-H and C-A-S-H phases that govern the strength development of pozzolanic cementitious systems [53,56,57]. In the NRL-free mixture ($r/b = 0$ %), the peaks of Ca, Si, and Al were most prominent, indicating a high degree of cement hydration and active pozzolanic

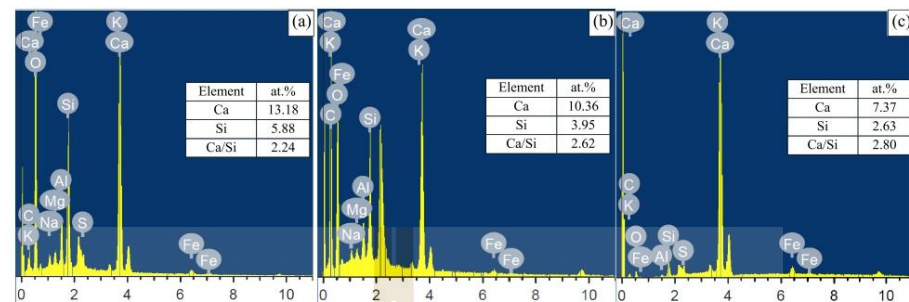


Fig. 10. EDS images of FA-RCA-NRL concrete at 56 days with 25% fly ash replacement and r/b ratios of (a) 0%, (b) 0.5% (optimal), and (c) 2%.

reaction between FA and the liberated calcium hydroxide, which corresponds to the dense microstructure and high compressive strength observed in SEM analysis. As the r/b ratio increased to 0.5% and 2.0%, the relative intensities of Si and Al declined while the carbon (C) peak, associated with the latex polymer [46], became increasingly pronounced, reflecting the growing presence of polymer films within the matrix.

To support the SEM-EDX analysis, the elemental compositions and Ca/Si ratios are summarized in Table 5. Quantitative EDX analysis further revealed that the Ca/Si ratio increased from 2.24 in the control mix ($r/b = 0\%$) to 2.62 at $r/b = 0.5\%$ and 2.80 at $r/b = 2.0\%$, indicating a progressive shift toward a Ca-rich C-S-H composition and reduced silica incorporation from FA. This trend suggests that increasing NRL content suppresses the pozzolanic reaction and limits the formation of secondary C-S-H, resulting in a chemically less refined matrix. Nevertheless, the $r/b = 0.5\%$ mixture, despite its moderately higher Ca/Si ratio, exhibited the greatest compressive, flexural, and fatigue strengths. This implies that the physical benefits of latex film formation, such as crack bridging, improved ITZ bonding, and enhanced energy dissipation, can outweigh the less favorable chemical composition at this dosage. Conversely, at $r/b = 2.0\%$, the combination of an excessively high Ca/Si ratio and the porous, polymer-rich morphology observed in SEM images reflects severe hydration inhibition and weakens matrix connectivity, explaining the marked reduction in mechanical and fatigue performance at this dosage.

5. Carbon emission and cost analyses

The results in Table 4 represent the embodied carbon of the concrete mixtures, excluding service-life and end-of-life stages. To reflect realistic Thai production conditions, it was assumed that all materials were sourced within a 50 km radius of the batching plant and transported by diesel trucks with an average emission factor of 0.10 kg CO₂-e per ton-km. Cost and transportation assumptions were based on 2024

market values in Nakhon Ratchasima, including fuel, handling, and delivery. The resulting calculations therefore represent the embodied (upstream) carbon of the mixtures, excluding service-life and end-of-life stages.

Fig. 11 illustrates the total CO₂-equivalent emissions (kg CO₂-e), material cost (USD/m³) and fatigue life (cycles at SR = 60%) of seven FA-RCA-NRL concrete mixtures, incorporating FA replacement levels of 0%, 15%, 20%, and 25%, with and without 0.5% NRL. The emissions and material cost were calculated based on the factors for each material, as presented in Table 4. It should be noted that the comparison in Fig. 11 focuses on mixtures with $r/b = 0.5\%$, since this dosage was identified as the optimum latex content. At this level, both f_c and f_t consistently satisfied the minimum requirements for rigid pavement specified by the Department of Highways, Thailand ($f_c \geq 32$ MPa, $f_t \geq 4.2$ MPa), while higher r/b ratios (≥ 1.0) led to performance reductions below the standard. Therefore, $r/b = 0.5\%$ was selected as the representative condition for evaluating the balance among mechanical performance, fatigue resistance, emissions, and material cost.

The results of Fig. 11(a) revealed that cement dominated the carbon footprint, contributing over 98% of total emissions in each mix. The reference mix with FA = 0% [64] recorded the highest CO₂ emissions at 402.83 kg CO₂-e. In comparison, as FA content increased 15–25%, cement consumption and total CO₂ emissions decreased progressively, with the lowest emission observed in the RCA+25% FA mixture (304.20 kg CO₂-e). The addition of 0.5% NRL marginally increased emissions by about 0.42 kg CO₂-e per mix. For example, RCA+0.5% NRL+15%FA emitted 344.08 kg CO₂-e compared to 343.66 kg CO₂-e for the NRL-free equivalent, and this small increase was consistent across all FA replacement levels. Importantly, if RCA was entirely replaced with natural aggregate (NA) at the same dosage of 1018 kg per cubic meter, the total CO₂ emissions per mix would increase by approximately 35.6 kg CO₂-e, highlighting the environmental benefit of using RCA over NA. When engineering performance is considered together with emissions, the results showed that flexural strength at 28 days and fatigue life at SR = 60% were broadly comparable among the FA-blended mixtures and the FA = 0% reference. The FA = 0% mix achieved the highest values, with $f_t = 4.65$ MPa and N_f of 2978 cycles, but at the cost of the largest footprint (402.83 kg CO₂-e). By contrast, FA substitution reduced emissions substantially while maintaining acceptable performance. For example, at 15% FA, the $r/b = 0\%$ mix recorded $f_t = 4.55$ MPa and $N_f = 2022$ cycles, while the addition of 0.5% NRL slightly increased flexural strength (4.68 MPa) and improved N_f to 2564 cycles, although emissions rose marginally. At 20% FA, the $r/b = 0\%$ mix achieved $f_t = 4.50$ MPa and $N_f = 2546$ cycles, and with 0.5% NRL, flexural strength remained comparable (4.62 MPa) while N_f increased to 2863 cycles, again with only a small emission penalty. At 25% FA, the $r/b = 0\%$ concrete recorded lower values ($f_t = 3.92$ MPa, and $N_f = 2269$ cycles), yet the incorporation of 0.5% NRL enhanced both flexural

Table 5
EDX elemental composition and Ca/Si ratio of FA-RCA-NRL concrete at 56 days (25% FA).

r/b ratio (%)	0	0.5 (optimum)	2
Ca (%)	13.18	10.36	7.37
Si (%)	5.88	3.95	2.63
C (%)	6.4	7.97	9.37
O (%)	68.4	70.1	73.56
Na (%)	0.48	0.6	0.63
Mg (%)	0.96	1.19	1.25
Al (%)	1.87	2.32	0.48
K (%)	0.69	0.86	1.91
Fe (%)	2.14	2.67	2.8
Ca/Si	2.24	2.62	2.8

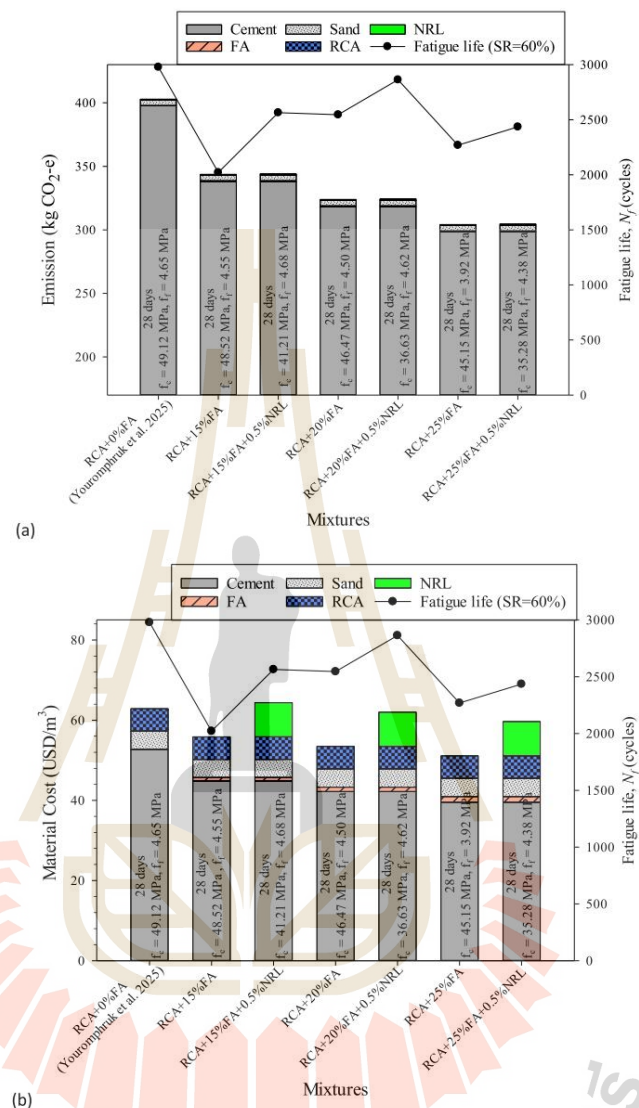


Fig. 11. FA-RCA-NRL concrete mixtures and corresponding 28-day compressive strength, flexural strength and fatigue life: (a) CO₂ emissions and (b) material cost.

strength (4.38 MPa) and fatigue resistance (2436 cycles), narrowing the gap with the FA = 0 % baseline while still achieving the lowest footprint (304.20–304.63 kg CO₂-e).

A similar trend was observed for material cost (Fig. 11(b)). The FA = 0 % reference mix [64] recorded the highest cost at 62.87 USD/m³, which can be attributed to its full reliance on cement, the most expensive binder at 0.114 USD/kg. In contrast, partial replacement of cement with FA (unit cost = 0.0124 USD/kg) reduced the overall cost substantially,

down to 51.13 USD/m³ for the RCA + 25 %FA mix. This highlights the strong economic benefit of FA substitution, since FA costs less than one-ninth of cement per kilogram. The addition of NRL, which has the highest unit cost among the considered materials (1.92 USD/kg), increased the total cost of mixtures by about 8–9 USD/m³. For instance, RCA + 0.5 %NRL + 25 %FA costs 59.67 USD/m³ compared with 51.13 USD/m³ for RCA + 25 %FA. This trend was consistent across all FA replacement levels.

In terms of engineering performance, the FA = 0 % mixture achieved the highest f_c (49.12 MPa), f_t (4.65 MPa), and N_f (2978 cycles) at 28 days [64], outperforming FA-blended concretes. Nevertheless, FA-based mixtures demonstrated only slightly lower strengths (e.g., f_c = 48.52 MPa, f_t = 4.55 MPa, and N_f = 2022 cycles for RCA+15 %FA), while offering significant environmental and cost benefits. The addition of NRL improved f_t and N_f at moderate levels (e.g., f_t = 4.68 MPa and N_f = 2564 cycles for RCA+0.5 %NRL+15 %FA). However, these benefits came at the expense of higher material cost and a moderate reduction in compressive strength.

These findings emphasize that partial replacement of cement with FA not only reduces the environmental impact but also lowers material cost. For example, CO₂ emissions decreased from 402.83 kg CO₂-e and a cost of 62.87 USD/m³ in the FA = 0 % reference mix to as low as 304.20 kg CO₂-e and 51.13 USD/m³ in the RCA + 25 %FA mixture. Although the compressive and flexural strengths of FA-blended concretes (e.g., f_c = 45.15 MPa and f_t = 3.92 MPa at 28 days for RCA+25 %FA) were slightly lower than the FA = 0 % baseline (f_c = 49.12 MPa and f_t = 4.65 MPa), the trade-off is offset by substantial sustainability and economic gains. The incorporation of a low dosage of NRL further enhanced flexural strength (e.g., f_c = 4.68 MPa for RCA+0.5 %NRL+15 %FA) but increased costs (to 64.36 USD/m³) and reduced compressive strength (41.21 MPa). Overall, the compressive and flexural strength values annotated on each bar confirm that FA substitution strikes a favorable balance between lower CO₂ emissions, reduced cost, and adequate mechanical performance, while NRL addition offers flexural benefits at the expense of higher cost and moderate compressive strength loss.

When considering sustainability and economics under the Thai pavement criteria ($f_c \geq 32$ MPa, $f_t \geq 4.2$ MPa), two mixes stand out as optimal choices. For minimizing emissions, the RCA + 0.5 %NRL + 25 %FA mix achieved the lowest CO₂ footprint while still meeting the requirements, recording 304.63 kg CO₂-e/m³, with f_c = 35.28 MPa, f_t = 4.38 MPa, and a cost of 59.67 USD/m³. In contrast, for minimizing cost, the RCA + 20 %FA mix offered the most economical option at 53.48 USD/m³, while also maintaining acceptable environmental and mechanical performance (323.93 kg CO₂-e/m³, f_c = 46.47 MPa, f_t = 4.50 MPa). These results highlight that RCA + 0.5 %NRL + 25 %FA is the most sustainable mix in terms of emissions, whereas RCA + 20 %FA provides the best balance for cost efficiency.

6. Conclusions

This study highlights the synergistic effects of fly ash (FA) and natural rubber latex (NRL) on the mechanical, microstructural, and durability performance of RCA-based pavement concrete. Moderate NRL dosages (r/b = 0.5–1.0 %) combined with higher FA contents (20–25 %) improved flexural strength and fatigue resistance, attributed to thin latex films that bridged microvoids and strengthened the interfacial transition zone. In contrast, excessive NRL ($r/b \geq 1.5$ %) inhibited hydration, producing a porous, Ca-rich matrix with reduced Si and Al contents as shown by SEM-EDX. The optimum mix (r/b = 0.5 %, FA=25 %) achieved the best balance of strength, ductility, and fatigue performance for pavement applications.

From a sustainability perspective, cement was the primary source of CO₂ emissions, but this impact was substantially reduced through FA substitution. Increasing FA content progressively lowered both emissions and cost, with RCA + 25 %FA achieving the lowest cost (51.13 USD/m³) and the lowest footprint among FA-only mixes. The inclusion of NRL slightly increased emissions (~0.42 kg/m³) and raised costs by about 8–9 USD/m³ due to its higher unit price (1.92 USD/kg), as seen in RCA + 0.5 %NRL + 25 %FA (59.67 USD/m³). When considering sustainability and economics under the Thai pavement criteria ($f_c \geq 32$ MPa, and $f_t \geq 4.2$ MPa), two mixes were identified as optimal. The RCA + 0.5 %NRL + 25 %FA mix provided the lowest CO₂ footprint (304.63 kg CO₂-e/m³), with adequate strength (f_c = 35.28 MPa, and f_t = 4.38 MPa), and a cost of 59.67 USD/m³. While the RCA + 20 %FA mix

offered the most economical solution (53.48 USD/m³) with balanced environmental and mechanical performance (323.93 kg CO₂-e/m³, f_c = 46.47 MPa, and f_t = 4.50 MPa). Overall, the former is recommended for maximum sustainability, whereas the latter provides the best cost–performance balance for pavement concrete applications. It should be noted that the CO₂ emission and cost analyses are based on local Thai production and transportation conditions, and the quantitative results may vary under different regional supply chains or energy systems. Nevertheless, the comparative trends and identified optimal mix proportions remain valid for sustainable pavement concrete design.

In summary, the combined use of FA and low-dosage NRL significantly improved the fatigue performance and sustainability of RCA pavement concrete. An optimum mix of RCA + 0.5 % NRL + 25 % FA achieved the lowest carbon footprint while meeting pavement strength requirements, whereas RCA + 20 % FA provided the most cost-efficient solution. These findings demonstrate a practical pathway for designing low-carbon, high-performance rigid pavement concrete.

CRediT authorship contribution statement

Suksun Horpibulsuk: Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Chattree Youromphruk:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Lin-Shuang Zhao:** Writing – review & editing, Visualization. **Ahmad Safuan Bin Rashid:** Writing – review & editing, Visualization. **Teerasak Yaowarat:** Writing – original draft, Visualization, Validation, Supervision, Project administration, Conceptualization. **Apinun Buritatum:** Writing – original draft, Software, Formal analysis, Data curation. **Apichat Suddeepong:** Writing – original draft, Visualization, Validation, Resources, Methodology. **Krairerk Aiamsri:** Visualization, Validation, Software, Data curation. **Karn Kantatham:** Visualization, Methodology, Investigation. **Menglim Hoy:** Writing – review & editing, Visualization, Validation. **Kongsak Akkharawongwhattana:** Writing – original draft, Validation, Methodology, Investigation, Data curation.

Declaration of Competing Interest

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

Acknowledgements

This work was supported by Suranaree University of Technology (SUT), Thailand Science Research and Innovation (TSRI), and the National Research Council of Thailand under the Chair Professor Program, grant number N42A67063.

Data availability

Data will be made available on request.

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