PERFORMANCE OF NATURAL RUBBER LATEX MODIFIED BOTTOM ASH-BASED GEOPOLYMER STABILIZED RECYCLED CONCRETE AGGREGATE AS PAVEMENT BASE AND SUBBASE MATERIALS

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มหาวิทยาลัยเทคโนโลยีสุรนารี

A Thesis Submitted in Partial Fulfillment of the Requirement for the
Degree of Doctor of Philosophy in Civil Engineering and Construction Management
Suranaree University of Technology
Academic Year 2025

ประสิทธิภาพของเศษคอนกรีตเหลือทิ้งปรับปรุงด้วยเถ้าหนักจีโอโพลีเมอร์และน้ำยางพาราธรรมชาติสำหรับวัสดุชั้นพื้นทาง รองพื้นทาง

นายโชคชัย ไตรยสุทธิ์

มหาวิทยาลัยเทคโนโลยีสุรนารี

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาปรัชญาดุษฎีบัณฑิต
สาขาวิชาวิศวกรรมโยธาและการบริหารงานก่อสร้าง
มหาวิทยาลัยเทคโนโลยีสุรนารี
ปีการศึกษา 2568

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

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โชคชัย ไตรยสุทธิ์ : ประสิทธิภาพของเศษคอนกรีตเหลือทิ้งปรับปรุงด้วยเถ้าหนักจีโอโพลีเมอร์และน้ำยางพาราธรรมชาติสำหรับวัสดุชั้นพื้นทาง รองพื้นทาง (PERFORMANCE OF NATURAL RUBBER LATEX MODIFIED BOTTOM ASH-BASED GEOPOLYMER STABILIZED RECYCLED CONCRETE AGGREGATE AS PAVEMENT BASE AND SUBBASE MATERIALS)
อาจารย์ที่ปรึกษา : รองศาสตราจารย์ ดร. Menglim Hoy, 128 หน้า

คำสำคัญ : เศษคอนกรีต, เถ้าหนัก, น้ำยางพาราธรรมชาติ, จีโอโพลีเมอร์, โครงสร้างจุลภาค, กำลังรับแรงอัดแบบไม่จำกัด, การออกแบบชั้นทาง, การปรับปรุงคุณภาพดิน

วิทยานิพนธ์นี้ศึกษาความเป็นไปได้ในการประยุกต์ใช้เถ้าก้นเตา (Bottom ash, BA) จีโอโพลีเมอร์ และน้ำยางพาราธรรมชาติ (Natural Rubber Latex, NRL) ปรับปรุงคุณภาพเศษคอนกรีต (Recycled Concrete Aggregate, RCA) เพื่อใช้เป็นวัสดุพื้นทาง และรองพื้นทางอย่างยั่งยืน การศึกษาประกอบด้วยการทดสอบทางวิศวกรรม โครงสร้างทางจุลภาค และองค์ประกอบทางเคมี เพื่อให้คลอบคลุมความต้องการสำหรับใช้เป็นวัสดุชั้นพื้นทาง (BASE) และรองพื้นทาง (Subbase) การทดสอบในส่วนแรกเป็นการศึกษาการพัฒนากำลังของ RCA-BA จีโอโพลีเมอร์ การสังเคราะห์ RCA-BA จีโอโพลีเมอร์ โดยใช้สารละลายโซเดียมไฮดรอกไซด์ (NaOH) และสารละลายโซเดียมซิลิเกต (Na_2SiO_3) เป็นสารกระตุ้นส่วนผสม RCA-BA ที่ใช้ในการควบคุมเตรียมขึ้นจากการผสม RCA, BA และน้ำ เพื่อใช้เป็นวัสดุควบคุมในการศึกษาอิทธิพลของสารกระตุ้นต่อกำลังของ RCA-BA จีโอโพลีเมอร์ โดยกำหนดแทนที่ RCA-BA ที่อัตราส่วน 90:10,80:20,70:30,60:40 และ 50:50 อัตราส่วนสารกระตุ้น Na_2SiO_3:NaOH (G/N) ที่ 1:1, 1:1.5 และ 1:2 ตามลำดับ

การทดสอบในส่วนที่สองเป็นการศึกษาอิทธิพลของน้ำยางพาราธรรมชาติ (Natural Rubber Latex, NRL) ต่อกำลังและการเปลี่ยนแปลงโครงสร้างทางจุลภาคของ ระหว่าง RCA-BA และ RCA-BA จีโอโพลีเมอร์ โดยกำหนดอัตราส่วน RCA-BA (70:30) อัตราส่วนสารกระตุ้น Na_2SiO_3: NaOH (G/N) ที่ 1:1, 1:1.5 และ 1:2 และผันแปรปริมาณน้ำยางพาราที่ 0.1,0.2 และ 0.3 โดยน้ำหนักของวัสดุทั้งสองส่วนทำการตรวจวัดกำลังด้วยเครื่องทดสอบกำลังอัดแกนเดียว (UCS) ผลการทดสอบ X-Ray Diffraction (XRD), Scanning Electron Microscope (SEM) และ Energy Dispersive X-Ray Analysis (EDX) ใช้วิเคราะห์โครงสร้างทางจุลภาคและอิทธิพลการชะละลายของสารกระตุ้นที่มีต่อกำลังอัด การเกิดปฏิกิริยาจีโอพอลิเมอร์ไรเซชั่นและการก่อตัวของเจล N–A–S–H และ C–S–H และรอยแตกภายในโครงสร้าง พร้อมทั้งอิทธิพลของปริมาณน้ำยางพาราเคลือบผิวของจีโอโพลีเมอร์ที่มีผลต่อกำลังและโครงสร้างทางจุลภาคของ RCA-BA จีโอโพลีเมอร์ และ NRL-RCA-BA จีโอโพลีเมอร์

ผลการทดลองแสดงให้เห็นว่าส่วนผสม RCA90BA10 ที่มี G/N = 1:2 สามารถพัฒนากำลังอัดได้สูงถึง 9.14 MPa ภายใน 7 วัน ซึ่งสูงกว่ามาตรฐานที่กำหนดโดยกรมทางหลวง ทางหลวงชนบท (2.413 MPa) อย่างมาก และทุกสูตรผสมที่ผ่านการเสริมด้วยจีโอพอลิเมอร์มีค่ากำลังที่สูงกว่ามาตรฐานขั้นต่ำที่กำหนด การทดสอบความเหนียว (Toughness) พบว่า อัตราส่วนนี้มีความสามารถในการดูดซับพลังงานได้สูงถึง 107.89 N·m การวิเคราะห์ด้วยกล้องจุลทรรศน์และการเลี้ยวเบนรังสีเอกซ์

ยืนยันการเกิดปฏิกิริยาจีโอพอลิเมอร์อย่างสมบูรณ์ โดยพบการก่อตัวของเจล N–A–S–H และ C–S–H ที่ช่วยสร้างโครงสร้างที่หนาแน่นและมีความแข็งแรงสูง ขณะเดียวกัน เมื่อมีการเติม NRL ในปริมาณที่เหมาะสม 0.1% ร่วมกับ G/N = 1:1 พบว่ากำลังอัดสูงสุดที่ 28 วันมีค่า 5.17 MPa ซึ่งสูงกว่าข้อกำหนดขั้นต่ำของ AASHTO (2008) สำหรับวัสดุชั้นรองทางอย่างชัดเจน การวิเคราะห์โครงสร้างจุลภาคยืนยันการก่อตัวของเมทริกซ์จีโอพอลิเมอร์ที่หนาแน่นและเป็นเนื้อเดียวกัน โดยฟิล์ม NRL ทำหน้าที่เป็นตัวเชื่อมระหว่างอนุภาค RCA และ BA ช่วยลดความพรุนและป้องกันการแพร่กระจายของรอยแตกร้าว ในขณะที่เจล N–A–S–H และ C–S–H ที่เกิดจากกระบวนการจีโอพอลิเมอร์ช่วยเสริมสร้างความแข็งแรงและความทนทานของวัสดุ อย่างไรก็ตาม การใช้อัตราส่วน G/N ที่สูงเกินไปหรือการเติม NRL ในปริมาณมากเกินไปอาจก่อให้เกิดเจลที่อุดมด้วยซิลิกาและฟิล์มยางที่หนาเกินไป ซึ่งส่งผลให้ประสิทธิภาพของกำลังลดลง

ผลจากการทดลองในวิทยานิพนธ์นี้แสดงให้เห็นว่า RCA-BA จีโอโพลีเมอร์ ทั้งที่มีและไม่มีการปรับปรุงด้วย NRL เป็นวัสดุที่มีศักยภาพสูงสำหรับใช้เป็นชั้นรองพื้นทางในงานก่อสร้างถนน ด้วยสมรรถนะทางวิศวกรรมที่เหนือกว่าวัสดุดั้งเดิม อีกทั้งยังสนับสนุนการใช้ทรัพยากรอย่างคุ้มค่า ลดการใช้มวลรวมธรรมชาติ ลดปริมาณกากอุตสาหกรรมที่ต้องกำจัด และลดการปล่อยก๊าซคาร์บอนไดออกไซด์ จึงถือเป็นแนวทางที่สอดคล้องกับการพัฒนาโครงสร้างพื้นฐานที่ยั่งยืนของประเทศ

มหาวิทยาลัยเทคโนโลยีสุรนารี

สาขาวิชา วิศวกรรมโยธาและการบริหารงานก่อสร้าง ลายมือชื่อนักศึกษา .....
ปีการศึกษา 2568 ลายมือชื่ออาจารย์ที่ปรึกษา .....

CHOKCHAI TRAIYASUT : PERFORMANCE OF NATURAL RUBBER LATEX MODIFIED BOTTOM ASH-BASED GEOPOLYMER STABILIZED RECYCLED CONCRETE AGGREGATE AS PAVEMENT BASE AND SUBBASE MATERIALS.
THESIS ADVISOR : ASSOC. PROF. Dr. Menglim Hoy. 128 PP.

Keyword : Recycled concrete aggregate, Bottom ash, Natural rubber latex, Geopolymer Microstructure, Unconfined compressive strength, Pavement geotechnics Ground improvement

This thesis explores the feasibility of using bottom ash (BA) geopolymer and natural rubber latex (NRL) to enhance the properties of recycled concrete aggregate (RCA) for sustainable pavement base and subbase applications. The study includes two engineering approaches, microstructure analysis and chemical component testing, aiming to thoroughly assess its suitability for pavement base and subbase use.

The first part focused on the strength development of RCA–BA geopolymers. The geopolymer synthesis employed sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) as alkaline activators. RCA–BA mixtures prepared from RCA, BA, and water were used as the control to examine the effect of activators on strength. Replacement ratios of RCA:BA were set at 90:10, 80:20, 70:30, 60:40, and 50:50, with alkaline activator ratios (Na_2SiO_3:NaOH, G/N) of 1:1, 1:1.5, and 1:2 respectively.

The second part examined the influence of NRL on the strength and microstructural characteristics of RCA–BA geopolymers. Mixtures were prepared at an RCA:BA ratio of 70:30 with G/N ratios of 1:1, 1:1.5, and 1:2, incorporating NRL at 0.1%, 0.2%, and 0.3% by weight of aggregate. The strength was evaluated through unconfined compressive strength (UCS) testing, while X-ray diffraction (XRD), scanning electron microscopy (SEM), and energy dispersive X-ray spectroscopy (EDX) were employed to analyze microstructural features, geopolymerization reactions, gel formation (N–A–S–H and C–S–H), microcracking, and the influence of NRL coatings within the geopolymer matrix.

The results showed that the RCA90BA10 mixture with G/N = 1:2 achieved a UCS of 9.14 MPa at 7 days, significantly exceeding the Department of Highways (DOH, Thailand) requirement of 2.413 MPa. All geopolymer-stabilized mixtures surpassed the minimum standards. Toughness testing revealed an energy absorption capacity of 107.89 N·m for the optimal formulation. Microstructural analysis confirmed complete geopolymerization with the formation of dense N–A–S–H and C–S–H gels. Moreover,

the addition of 0.1% NRL with G/N = 1:1 resulted in a maximum UCS of 5.17 MPa at 28 days, far surpassing the AASHTO (2008) requirement of 1.72 MPa for subbase materials. SEM images confirmed the formation of a dense and homogeneous geopolymer matrix, with NRL films bridging RCA and BA particles, reducing porosity, and limiting crack propagation. However, excessively high G/N ratios or excessive NRL content led to silica-rich gels or overly thick NRL films, which hindered geopolymerization and reduced strength.

In conclusion, the findings demonstrate that RCA–BA geopolymers, with or without NRL modification, are highly promising materials for pavement subbase construction. They provide superior engineering performance compared with conventional materials while promoting resource efficiency, reducing the consumption of natural aggregates, minimizing industrial waste disposal, and lowering CO_2 emissions. This approach therefore represents a practical pathway toward sustainable infrastructure development.

มหาวิทยาลัยเทคโนโลยีสุรนารี

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Academic Year 2025 Advisor's Signature.....

ACKNOWLEDGMENT

First and foremost, I want to sincerely thank my advisor, Prof. Dr. Suksun Horpibulsuk, and Assoc. Prof. Dr. Menglim Hoy for their unwavering support of my Ph.D. studies and research, as well as for their patience, motivation, enthusiasm, and extensive knowledge. His guidance has helped me throughout the entire process of research and writing this dissertation, and also influenced my academic life. For my Ph.D. journey, I could not have asked for a better advisor and mentor, who possesses both the attitude and the substance of a genius: he consistently and convincingly inspires a spirit of adventure in research and scholarship, along with excitement for teaching. Without his guidance and persistent help, this dissertation would not have been possible.

Besides my advisor, I would like to express my deepest appreciation to my thesis committee: Prof. Dr. Panich Voottipruex, Dr. Apichat Sudeepong, Dr. Teerasak Yaowarat, Dr. Apinun Buritatum and Dr.Kongsak Akkharawongwhatthanafor their encouragement, insightful comments, and constructive questions. I am grateful to the ISI laboratory team, who supported the materials lab tests until I reached my goals. I also wish to thank all the staff and faculty members, as well as friends at the School of Civil Engineering, Suranaree University of Technology, for their academic, administrative, and technical support during my Ph.D. studies. Last but not least, I would like to thank my family for their love, understanding, and support, both spiritually and emotionally, throughout my Ph.D. studies and life.

CHOKCHAI TRAIYASUT

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SYMBOLS AND ABBREVIATIONS

RCA	=	Recycled Concrete Aggregate
BA	=	Bottom ash
NaOH	=	Sodium Hydroxide
Na_2SiO_3	=	Sodium silicate
Na_2O	=	Sodium oxide
SiO_2	=	Silicon dioxide
UCS	=	Unconfined Compression Strength
SEM	=	Scanning Electron Microscopy
EDS	=	Energy Dispersive X-Ray Spectroscopy
XRD	=	X-ray Diffraction
G/N	=	(Sodium silicate/ Sodium Hydroxide) ratio
OLC	=	Optimum liquid content
OMC	=	Optimum moisture content
RT	=	Room temperature

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CHAPTER I
INTRODUCTION

1.1 Statement of the problem

The construction and maintenance of roadway pavements require substantial amounts of raw materials and energy, resulting in significant environmental impacts. Conventional pavements utilize virgin aggregates and cement, which deplete natural resources and produce greenhouse gas emissions. As a result, there is an urgent need for a sustainable pavement material option that minimizes ecological footprints.

Recent estimates indicate that upgrading roadway infrastructure worldwide requires billions of metric tons of concrete and asphalt (Alamgir et al., 2017). The extraction, processing, and transport of raw virgin materials contribute to resource depletion. Cement production alone is responsible for 5-8% of global carbon dioxide emissions (Ige, Von Kallon, & Desai, 2024). Furthermore, the disposal of old pavement material burdens landfills, exacerbating environmental concerns.

In this context, developing alternative eco-friendly pavement solutions has become a priority. The utilization of industrial by-products and recycled waste materials offers prospects for reducing the reliance on virgin resources. Recycled concrete aggregate (RCA) is acquired through the process of recycling concrete from demolished buildings, road infrastructure, and other concrete structures. The reuse and recycling of RCA in new pavement structures not only contributes to reducing waste in landfills but also conserves natural resources by reducing the need for virgin aggregate materials. However, RCA has some limitations in mechanical performance, necessitating the development of effective geochemical stabilization methods.

The adoption of natural rubber latex (NRL) to modify cement-stabilized RCA has been found to be an innovative approach to enhance the performance and sustainability of pavement base materials (Hoy, Nhieu, et al., 2023; Hoy, Vinh Nhieu, et al., 2023; Nhieu et al., 2023). NRL is a milky white liquid extracted from the bark of the rubber tree (Hevea brasiliensis). It is a natural polymer consisting of rubber particles suspended in an aqueous medium. The composition of NRL includes water (50-70%), rubber particles (30-40%), and small amounts of proteins, lipids, and other substances (Bottier, 2020).

The innovation of using NRL-modified cement stabilization of RCA lies in its ability to address some of the limitations of conventional cement-stabilized RCA, such as brittle manner and low tensile ability. By incorporating NRL into the cement-RCA mixture, the resulting material exhibits improved engineering performance such as higher compressive and tensile strengths, strain capacity, and toughness.

Similar studies (Hoy, Tran, Suddeepong, Horpibulsuk, Buritatum, et al., 2023; Hoy, Tran, Suddeepong, Horpibulsuk, Mobkrathok, et al., 2023; Tran et al., 2022) initiated the innovative utilization of NRL to enhance mechanical properties and service life of cement-stabilized recycled materials, particularly RCA and steel slag blended with lateritic soil. It represents a significant advancement in sustainable pavement engineering. This eco-friendly approach combines the benefits of using recycled materials with the unique properties of NRL to create high-performing, resilient, and durable pavement base layers that can withstand the detrimental effects of wetting and drying cycles. The optimization of NRL content in cement-stabilized recycled materials from demolition wastes is crucial to achieving the desired performance improvements. The optimal NRL-to-cement ratios maximize the beneficial effects of NRL while avoiding excessive amounts that can hinder cement hydration and strength development.

Geopolymer technology represents a revolutionary approach in the field of construction materials, offering a sustainable alternative to traditional cement. Geopolymers are formed by the chemical reaction of aluminosilicate materials, such as fly ash or slag, with alkaline solutions. This reaction produces a dense, three-dimensional network structure that provides excellent mechanical strength, durability, and resistance to chemical attack. The environmental benefits of geopolymer technology are significant, as it utilizes industrial by-products and reduces CO_2 emissions associated with cement production. Several studies have reported on the success of geopolymer-stabilized recycled materials in pavement applications (Mohammadinia et al., 2016; Xie et al., 2024; Zhang et al., 2021).

The widespread adoption of fly ash in Portland cement concrete has led to extensive research on fly ash-based geopolymers, resulting in a comprehensive body of literature (Amran, Debbarma, & Ozbakkaloglu, 2021; Klima, Schollbach, Brouwers, & Yu, 2022; Li et al., 2022; Rathnayaka et al., 2024). However, it was reported that bottom ash (BA)-based geopolymers may exhibit poorer mechanical properties and durability than fly ash-based geopolymers owing to the lower reactivity and coarser particle size of BA (Chindaprasirt, Jaturapitakkul, Chalee, & Rattanasak, 2009; ul Haq, Padmanabhan,

& Licciulli, 2014). These performance concerns have hindered the adoption of bottom ash in geopolymer production.

Within the context of sustainable material innovation, the integration of NRL-modified BA in geopolymer stabilization of RCA opens new avenues for high-performance base materials. The inclusion of NRL in the bottom ash geopolymer matrix introduces unique properties to the pavement base material. NRL, known for its elasticity and water resistance, imparts flexibility and resilience to the geopolymer-stabilized RCA. This modification is particularly beneficial for pavement applications, where pavement materials are subjected to dynamic loads and environmental stresses. The NRL not only helps absorb and distribute these loads more effectively, reducing the risk of cracking, but also provides a barrier against moisture infiltration, enhancing the durability of the pavement base.

The current research attempts to explore the strength development of NRL-modified BA based geopolymer stabilized RCA as a greener material in pavement applications. Geopolymer is formed though the reaction of an aluminosilicate source, such as bottom ash (precursor), with an alkaline activator solution containing sodium hydroxide (NaOH) and solidum silicate (Na_2SiO_3). The alkaline activator solutions were prepared with various Na_2SiO_3:NaOH (G/N) ratios of 1:1, 1:1.5, and 1:2, while the mixtures were modified with NRL at contents of 0.1, 0.2, and 0.3 by weight of the aggregate. The unconfined compressive strength (UCS) test was carried out to determine the strength of the studied mixtures at 7 and 28 days of curing. The strength development was examined through the microstructural and mineralogical analyses using scanning electron microscopy (SEM), energy dispersive x-ray spectroscopy (EDS) and x-ray diffraction (XRD), respectively.

As the outcomes of this study, linking NRL-modification with the stabilization of RCA with bottom ash geopolymer technology represents a newly frontier in pavement engineering. This collaboration could lead to the development of advanced pavement materials that meet the dual demands of sustainability and performance, catering to the infrastructure needs of the future while adhering to the principles of green construction.

1.2 Objectives of the study

This research has been undertaken with the following objectives:

1.2.1 Investigate the strength development of NRL-modified bottom ash based geopolymer stabilized RCA as a sustainable pavement material.

1.2.2 To study the effect of NRL-modification with the stabilization of RCA with bottom ash geopolymer.

1.3 Organization of the Dissertation

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

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

Chapter II presents a literature review related to recycled concrete aggregate, Bottom coal ash, Geopolymer and natural rubber latex. Applications in road construction projects in the past, present, and future trends.

Chapter III presented the study testing procedure, sample preparation, standard of testing, mixed ingredients, and results of unconfined compressive strength with strength development of bottom ash geopolymer stabilized recycled concrete aggregate with various RCA – BA ratio 90:10,80:20,70:30,60:40,50:50 is a factor studied in this research included liquid alkaline activator (L) content, Na_2SiO_3 /NaOH (G/N) is (1/1), (1/1.5), (1/2.0) and curing at room temperature (RT) condition, test UCS at 7 – 28 days. This study has significant impacts on base/subbase layer application for the road construction authority of Thailand by using RCA stabilized with BA geopolymer binder, a sustainable alternative to ordinary PC, in pavement base and subbase course material.

Chapter IV presented the study testing procedure, sample preparation, standard of testing, mixed ingredients, and results of unconfined compressive strength with various Na_2SiO_3:NaOH (G/N) ratios of 1:1, 1:1.5, and 1:2, while the mixtures were modified with NRL at contents of 0.1, 0.2, and 0.3 by weight of the aggregate. After that, the sample was examined with the SEM and Energy Dispersive X-Ray Spectroscopy EDS to analyze the effect of NRL modification with the stabilization of RCA with bottom ash geopolymer. In progress and follow up.

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

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CHAPTER II
LITERATURE REVIEW

2.1 Introduction

The literature on the application of BA and RCA in geopolymer as a subbase layer and pavement base for road building is presented in this chapter. An overview of the specifications for pavement construction and the technical characteristics of Recycled concrete aggregate (RCA) and Bottom (BA) is given first. When RCA and BA are used in the pavement base and subbase application, their engineering qualities—such as gradation, strength, compacted density, moisture content, permeability, and durability—are very valuable.

This chapter also covers the structural characteristics of the mixes of virgin aggregates, BA and RCA, that are utilized as a road structure. Researchers have discovered alternative stabilized techniques for building heavy-load roads as a result of advancements in pavement design, which called for greater quality pavement base structure qualities. This chapter highlights one of the most often utilized methods and procedures: the chemical stabilization of Portland cement (PC) treated granular aggregates.

The trend to replace PC products with a low-carbon chemical stabilized method called geopolymer is then presented, as environmental issues are a major global concern. An overview of geopolymer chemistry uses fly ash applied to applications, and the use of bottom ash-based geopolymer is less than fly ash given in construction material. Included is a mechanical theorem for geopolymer-stabilized recyclable materials based on bottom ash. Furthermore, the broad ideas of the primary environmental issues are covered in this chapter. These issues are extremely important for highway design, development, rehabilitation, construction, and maintenance.

2.2 Specification for pavement construction

Typically, each nation has its own Department of Highways or Department of Rural Roads with full autonomy over highway matters. Nonetheless, Thailand's national road authorities have incorporated international standards, including those of the American Society of Testing Materials (ASTM) and the American Association of State Highway and Transportation Officials (AASHTO), into their specifications. Subbase and

base material requirements have been released by both international standards. For use in the construction of subbase, base, and surface courses, the specification takes on the quality and grading of the following materials sand-clay mixtures gravel stone or slag screenings sand crusher-run coarse aggregate which is made up of gravel, crushed stone, or slag mixed with soil mortar; or any combination of these materials. (Hoy, 2016)

Type of pavement in road construction, there are several different types of pavement used for the construction of roads, highways, airport runways, parking lots, and other paved surfaces. The main types of pavement include flexible pavements Figure 2.1 (a), rigid pavements or semi-rigid pavements Figure 2.1 (b), composite pavements, and interlocking cement concrete block pavement. The choice of pavement type depends on factors such as anticipated traffic loads, environmental conditions, construction costs, and maintenance requirements. Asphalt concrete and jointed plain concrete pavements are the most widely used types for highways and roads. All hard-surfaced pavement types may be broadly divided into two groups stiff and flexible. Bituminous, or asphaltic, surfaces are used to surface flexible pavements. These can take the form of HMA surface courses, which are often utilized on larger volume roads like the Interstate highway network, or pavement surface treatments, such as bituminous surface treatments (BST), which are typically seen on lower volume roads. These pavements are referred to as flexible because the weight of the traffic causes the entire pavement structure to bend or deflect. The majority of the time, a flexible pavement construction is made up of many layers of materials that may bend or bend. Conversely, a PC surface course is made up of stiff pavements. Because PC has a high modulus of elasticity, these pavements are significantly "stiffer" than flexible pavements. Additionally, reinforcing steel, which is often utilized to minimize or eliminate joints, may be used in these pavements.

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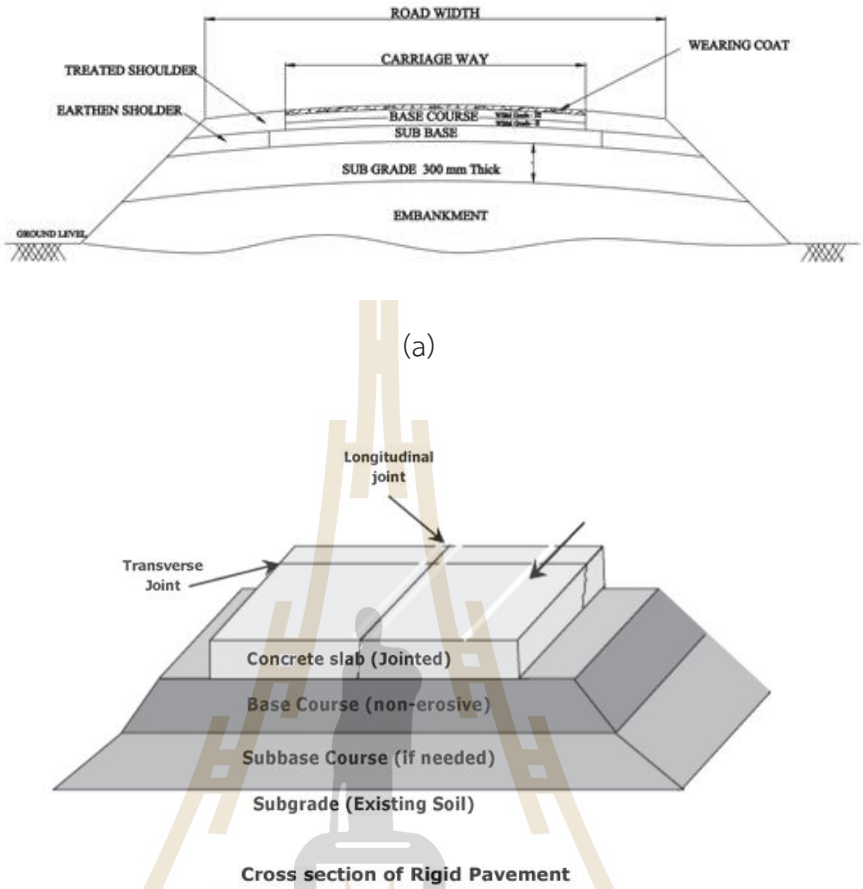

Figure 2.1 Typical pavement construction layers (a) flexible pavement, and (b) concrete pavement (rigid) (not to scale)

2.3 Recycled concrete aggregate (RCA) in construction

Recycling the concrete aggregates left over from specific building procedures can help preserve natural resources and lessen the amount of garbage dumped in nearby landfills (Khan, Wang, & Sarker, 2018). However, a lot of state and federal highway contracts mandate the use of recycled materials in the construction of new roads; the market determines the availability, engineering performance, and financial incentives that drive the rising rate of utilization. In order to build pavement subbases and bases that are more durable at a reasonable cost, it is now imperative to make use of the most recent advancements in alternative cementing methods and accessible RCA. A type of alternative binding material that is well-known is geopolymer binders based on fly ash. These materials belong to a class of low-carbon industrial

byproduct materials. Its application in unbound pavement base and subbase applications has attracted increasing attention in research in the last several years. After much research on this material, it is now well established that using geopolymer technology may significantly cut CO_2 emissions with no negative economic impact. (Gautreau, Zhang, & Wu, 2010; Nisbet, VanGeem, Gajda, & Marceau, 2000) A range of studies have explored the properties and characteristics of recycled concrete aggregate. (Ryu, 2002) found that the aggregate significantly impacts the interfacial property, permeability, and strength of concrete. (Sagoe, Brown, & Taylor, 2002) reported that the differences between fresh and hardened properties of recycled aggregate concrete and natural aggregate concrete are relatively narrow, with some variations in abrasion loss and drying shrinkage. (J.-h. Kim, Sung, Jeon, Lee, & Kim, 2019) focused on the mechanical and durability characteristics of concrete using recycled aggregate, noting improvements in various properties. (Rakshvir & Barai, 2006) highlighted the need to compensate for the greater water absorption of recycled aggregates during mix design and observed a decrease in compressive strength with increasing percentages of recycled concrete aggregates.

The use of recycled concrete aggregates (RCA) in road construction has been extensively studied, with promising results. (Puthussery, Kumar, & Garg, 2017) found that the physical and mechanical properties of RCA were suitable for road construction, with only a slight decrease in tensile strength. (Contrafatto, Cosenza, Barbagallo, & Ognibene, 2018) further supported this, demonstrating that RCA can be used in road sub-base construction and concrete manufacturing, with a higher percentage of recycled aggregates being effective in concrete preparation. However, (Jayakody, Gallage, & Kumar, 2014) noted that the properties of RCA can be inconsistent, with some samples not meeting the minimum requirements for base materials in road construction. (Rakshvir & Barai, 2006) also highlighted the need to compensate for the greater water absorption of recycled aggregates during mix design. These studies collectively suggest that while RCA can be a viable option for road construction, careful consideration of its properties and appropriate mix design are crucial.

The concrete industry has recently become more aware of geopolymers, and several studies have been carried out to examine both their immediate and long-term performance (Concrete, 2005; Davidovits & Sawyer, 1985; Hambling, 2009; Han, Pyzik, & Liu, 2014; Rangan, 2008). According to a 2013 survey, the road base is used for around 68% of recycled concrete aggregate (RCA), with the remaining RCA going toward fresh concrete mixes, asphalt hot mixes, high-value riprap, and low-value items like general fill. (Odion, Khattak, Abader, & Heim, 2019). However, 27% of fly ash is employed in

loose form in structural fills and embankments, and around 50% of fly ash is used in bound form in concrete products (Kravchenko & Ruhl, 2021). Furthermore, a number of research have been published on the use of geopolymers based on alkali-activated fly ash to enhance the mechanical properties of soils. These investigations have demonstrated that the flash content is essential to the geopolymerization process and that the soil mixes' unconfined compressive strength (UCS) rose as the fly ash level increased, peaking at 30% (Cristelo, Glendinning, Miranda, Oliveira, & Silva, 2012; Phummiphan et al., 2018; Zumrawi & Mohammed, 2016).

2.4 The highway construction

Highway construction is an important aspect in infrastructure construction in many developed and developing countries. Highway construction however consumes a large amount of natural quality aggregates, particularly in their pavement base/subbase layers. As a result, the quarries and gravel pits are increasingly exploited as a source of pavement materials, which notably leads to the subsequent devastating of natural environmental resources. The urgent need for new environmentally friendly solutions have made researchers explore new alternative materials that will reduce energy consumption, and greenhouse gas emissions (Hoy, Horpibulsuk, Rachan, Chinkulkijniwat, & Arulrajah, 2016). Highway pavement generally consists of base, subbase, and engineering fill layers, which are typically constructed from suitable materials such as crushed rock and lateritic soil. The government of Thailand's current priority is in the economic expansion of the country over the next decade and has allocated a large budget for the construction of roadway networks across the country.

A number of road infrastructure projects have been implemented to construct transportation systems, particularly in rural areas. Heavy rain during the rainy season frequently causes flooding problems in some regions of Thailand. Hence, road embankments in the country must have an adequate thickness and must also be constructed with durable pavement materials. In general, the subbase/base layer is typically 50–70 cm in thickness, to ensure the road profile is above the flood level. Road construction consumes a vast amount of high-quality materials. The transportation of high-quality imported materials from distant sources increases the road construction cost considerably. Furthermore, transportation of imported materials significantly increases road maintenance costs and the carbon footprint.

The utilization of local resources at the road construction site is thus beneficial from both economic and environmental aspects, which is an approach that is strongly encouraged by the Department of Rural Roads and the Department of Highways,

Thailand (Sukprasert et al., 2021). The scientific and practical methodologies and outcomes from previous research have been reviewed and summarized in this paper in order to make a new illuminating study on cleaner production as well as to assure that waste materials can be mixed with soil as an intuitive practitioner interface technique in pavement applications (Sudla et al., 2018). For each road construction materials, BA was used in highway embankment construction offers an attractive alternative to disposal because substantial economic savings can be attained by the reduction of ash disposal costs and the conservation of natural soils and lands, pavement construction (Gautam, Kalla, Jethoo, Agrawal, & Singh, 2018; López-López, Vega-Zamanillo, Calzada-Pérez, & Taborga-Sedano, 2015; Yoo, Park, & Vo, 2016) and aggregate replacement in concrete pavement production (Arenas, Marrero, Leiva, Solís-Guzmán, & Arenas, 2011; Hannan et al., 2020; Ibrahim, Hamzah, Jamaluddin, Ramadhansyah, & Fadzil, 2015).

As traffic volumes and vehicular axle weights continue to increase with the increasing world population, highway construction and maintenance work have become widespread in all parts of the world (Nwakaire, Yap, Onn, Yuen, & Ibrahim, 2020). As these road construction activities become more frequent, there is an increasing demand for construction materials. There is a global trend to improve sustainability, particularly in the construction industry, due to increased waste generation and consumption of natural materials. Using waste materials for pavement construction has become a viable alternative for preserving natural materials and solving waste disposal problems.

Recycled concrete aggregate (RCA) for example has been used as an alternative unbound material to partially replace crushed rock in pavement applications (Behiry, 2013; Hoy, Tran, et al., 2023; Suddeepong, Hoy, et al., 2022; Tran et al., 2022). The construction of pavements involves a series of layered components such as a subbase, base, and surface course, each with a specific role. The sub-base, which sits directly atop the prepared natural ground level or subgrade, is usually composed of locally sourced materials or stabilized soil. It is designed to evenly distribute the load from the base to the subgrade, effectively safeguarding the impact of aggressive moisture. The base layer above the subbase often consists of crushed aggregate designed to further distribute the load, thereby providing a stable surface for the subsequent pavement layer and protecting the underlying subbase from detrimental environmental effects. The surface course is constructed using high-quality materials like asphalt or concrete, ensuring its ability to resist traffic loads and provide a durable and skid-resistant surface, making it critical for safety and efficiency in transportation.

Based on the type of surface course, the pavement can be classified into flexible pavement (asphalt surface layer) and rigid pavement (concrete surface layer). Because of the rigidity behavior, the load in rigid pavements is distributed over a wide area of the subgrade. This reduces the stress on the subgrade and makes the pavement more tolerant to weaker or less uniformly compacted subgrades when compared with flexible pavement. In addition, rigid pavements are resistant to rutting and weathering and require less maintenance over time (Hrapović, 2023; Nosov, Ushakov, Fotiadi, & Stepush, 2020; Peng, 2022)

2.5 Recycled and reclaimed material in highway construction

There is increasing global interest in green materials for use in green buildings and the use of recycled materials in the construction and rehabilitation in the infrastructure sectors (Hoy, Horpibulsuk, & Arulrajah, 2016). In recent years construction projects have used recycled and reclaimed materials to save costs and focus on global warming. Several researchers have in recent years investigated the usage of recycled waste materials as substitutes for virgin materials in civil infrastructure applications, such as in pavements, footpaths, and embankments. Recycling of concrete aggregates resulting from certain construction processes offers a way to reduce waste disposal loads sent to area landfills and to extend the life of natural resources (Odion et al., 2019). The reuse of these recycled materials in civil engineering infrastructure applications will result in a low-carbon solution, considering that recycled materials have significant carbon savings, compared with virgin quarried materials. C&D materials are increasingly being used in pavement applications, particularly as a base/subbase material. C&D materials that have been evaluated and successfully implemented in recent years in roads, footpaths, and pipe-bedding applications include recycled concrete aggregate (Azam & Cameron, 2013; Poon & Chan, 2006). In many years researchers have been interested in reused of construction materials in applications include recycle concrete aggregate, and Reclaim Asphalt Pavement (Arulrajah, Piratheepan, & Disfani, 2014; Hoyos, Puppala, & Ordonez, 2011; Puppala, Hoyos, & Potturi, 2011; Taha, Al-Harthy, Al-Shamsi, & Al-Zubeidi, 2002) waste rock (Akbulut & Gürer, 2007; Arulrajah, Piratheepan, Ali, & Bo, 2012) and waste glass (Arulrajah, Ali, Disfani, Piratheepan, & Bo, 2013; Disfani, Arulrajah, Bo, & Hankour, 2011; Grubb, Gallagher, Wartman, Liu, & Carnivale III, 2006; Wartman, Grubb, & Nasim, 2004). Waste is generally considered to have no lasting value. A large quantity of municipality solid waste is generated by industrial, human and commercial activities. Recycling is a method of converting various wastes into useful materials that can be reused. Without

a proper recycling process, these wastes are undesirable materials that are disposed of in landfills, which can result in numerous environmental problems. For instance, some waste contains metal or toxic compounds that can contaminate the soil, surface, and groundwater (Sudla et al., 2018).

2.6 Geopolymer stabilization material for highway construction

Soil stabilization has shown to be economical as it provides cheap materials for the construction of low-cost roads. Portland cement stabilization is one of such methods, which has proven to be effective especially in the case of sandy soil due to the ease of pulverization. The primary reaction of cement is with the water in the soil, which leads to the formation of a cementitious material. Cement stabilized road bases using soil as a constituent, provide substantial support to the overlaying pavement layer thereby reducing stresses on subgrade soil. Thus, the use of soil-cement becomes cost-effective in areas that are deficient in aggregate resources. However, the high carbon footprint and cost of using cement for pavement base/subbase stabilization has led to seeking alternative low-carbon stabilization technique like flyash-based geopolymer. Further, the soil-cement causes shrinkage cracks in the base layer, which appear as reflective cracks in hot mixed asphalt (HMA) that are responsible for low ride quality and moisture damage in pavements (Odion et al., 2019). Although, many federal and state highway contracts specify the use of recycled materials in highway construction with increasing rate of usage being influenced by the availability, engineering performance, and financial incentives as determined by the marketplace. Hence, it has become essential to utilize the advanced alternate cementing technologies and available RCA to economically produce more durable pavement subbase and bases. One such alternate binding material is known to be fly ash-based geopoloymer binders. These are class of materials resulting from industrial by-products with a low carbon footprint. Its use in unbound pavement base/subbase applications has generated growing research interest in recent years. This material has been investigated and it is now widely known that the utilization of geopolymer technology could substantially reduce CO_2 with minimum economic detriments (Gautreau et al., 2010; Nisbet et al., 2000).

Bottom ash was ground to a similar particle size as fly ash. Table 2.1 shows the significant chemical composition of coal ash using X-ray fluorescence (XRF). XRD patterns of fly ash and bottom ash displayed in Figure 2.2 show that fly ash contained a higher content of amorphous phase particles compared to the bottom ash. The crystalline phases are predominantly quartz and mullite.

Table 2.1 Chemical composition and physical properties of coal ash. (Chindaprasirt, Jaturapitakkul, Chalee, & Rattanasak, 2009)

Composition (%)	Fly ash	Bottom ash
SiO_2	38.7	38.8
Al_2O_3	20.8	21.3
FeO_3	15.3	12.1
CaO	16.6	16.5
Na2O	1.3	1.0
TiO_2	0.5	0.8
MgO	1.3	1.7
K_2O	2.1	2.5
SO_3	2.6	2.4
LOI	0.8	2.9
Retained on sieve no.325 (% by weight)	32	29

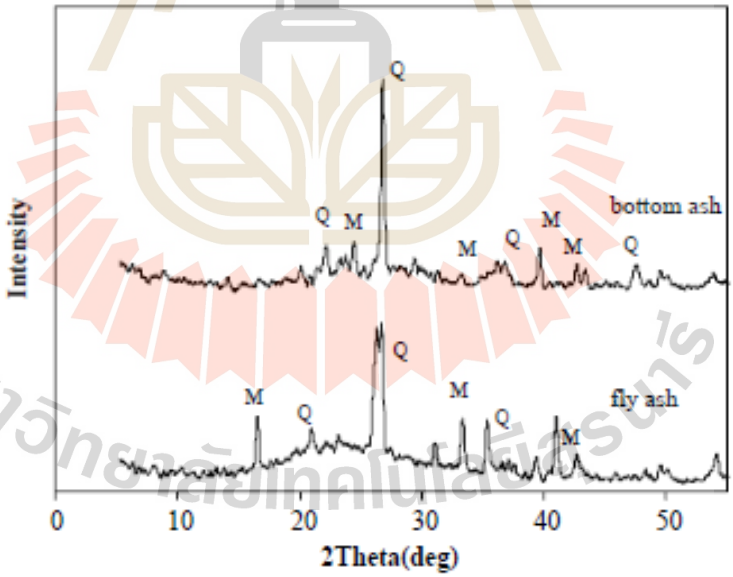

Figure 2.2 XRD patterns of fly ash and bottom ash. Q = quartz, M = mullite. (Chindaprasirt et al., 2009)

Recently, geopolymers have gained prominence attention in the concrete industry, building material, and road construction in pavement base/subbase layer, and several research studies have been conducted to address their short and long-

term performances. Geopolymer is made of alkali-activated aluminosilicate materials such as FA, slag, rice husk ash, and bottom ash. Geopolymers are reported to produce low CO_2 emissions and energy consumption (Palomo, Grutzeck, & Blanco, 1999). These shortcomings have led to an attempt to explore novel low-carbon stabilization methods. Geopolymer is an inorganic aluminosilicate material synthesized by alkaline activation of materials rich in alumina (Al_2O_3) and silica (SiO_2) and is considered a green cementing agent. Geopolymerization involves the chemical reaction of alumino-silicate oxides by alkaline activation, yielding the polycondensation of the material in the three-dimensional silico-aluminate structure (Davidovits, 1991; Zhang, He, & Gambrell, 2010). Three typical structures of geopolymer are: Poly (sialate) type (-SiO-Al-O-), the Poly (sialatesiloxo) type (-Si-O-Al-O-Si-O-) and the Poly (sialate-disiloxo) type (-Si-O-Al-O-Si-O-Si-O-).Geopolymer has in recent years been used to stabilize natural soils to develop green building materials such as masonry products. It was reported that geopolymer based materials possess higher compressive strength and durability against sulfate than cement-based materials (P. Sukmak, De Silva, Horpibulsuk, & Chindaprasirt, 2015; P. Sukmak, Horpibulsuk, & Shen, 2013; P. Sukmak, Horpibulsuk, Shen, Chindaprasirt, & Suksiripattanapong, 2013). Recently, (Suksiripattanapong, Horpibulsuk, Chanprasert, Sukmak, & Arulrajah, 2015) and (Horpibulsuk, Suksiripattanapong, Samingthong, Rachan, & Arulrajah, 2016) successfully stabilized water treatment sludge using fly ash based geopolymer to develop sustainable non-structural and bearing masonry units. It was illustrated that the geopolymer is more effective than PC in stabilizing the water treatment sludge with high alum content. The strength and durability of sludge-geopolymer masonry units are significantly higher than sludge-cement masonry units.

The compressive strength of geopolymer mortars after 48 hours of heat curing at 65°C. When compared to the bottom ash geo polymer, the fly ash geo polymer mortar offers a greater compressive strength. The outcomes also show that geopolymer mortars with relatively low strengths are produced by using a low NaOH concentration of 5 M. Using 5 M NaOH results in a mortar with a moderate strength of 24 MPa for the fly ash geopolymer. Using 10 M and 15 M NaOH results in higher strengths of 35 and 33 MPa. The compressive strengths of more tars for bottom ash are less than those of the fly ash geopolymer, 10, 14, and 18 MPa are the strengths of 5, 10, and 15 M geopolymer mortars, respectively. The thermograph suggests that the degree of polymerization of the bottom ash geo polymer is lower than that of the fly ash polymer. Compared to fly ash, bottom ash would have a lesser dissolution in the NaOH solution. Therefore, a larger concentration of NaOH is needed for the dissolution

of aluminum and silicon dioxide in bentonite ash, additionally. For the production of geopolymers, fly ash, and ground bottom ash are suitable sources. The findings of the compressive strength of geopolymer mortars shown in Figure 2.3 that fly ash exhibits a greater degree of geopolymerization and is more reactive than bottom ash. At 35 MPa, the compressive strength of the fly ash geopolymer mortar is remarkably strong and significantly greater than that of the bottom ash geopolymer mortar, which is only 18 MPa. The NaOH concentration affects a geopolymer's strength as well. For both types of ash, a 10 M NaOH concentration is the ideal one.

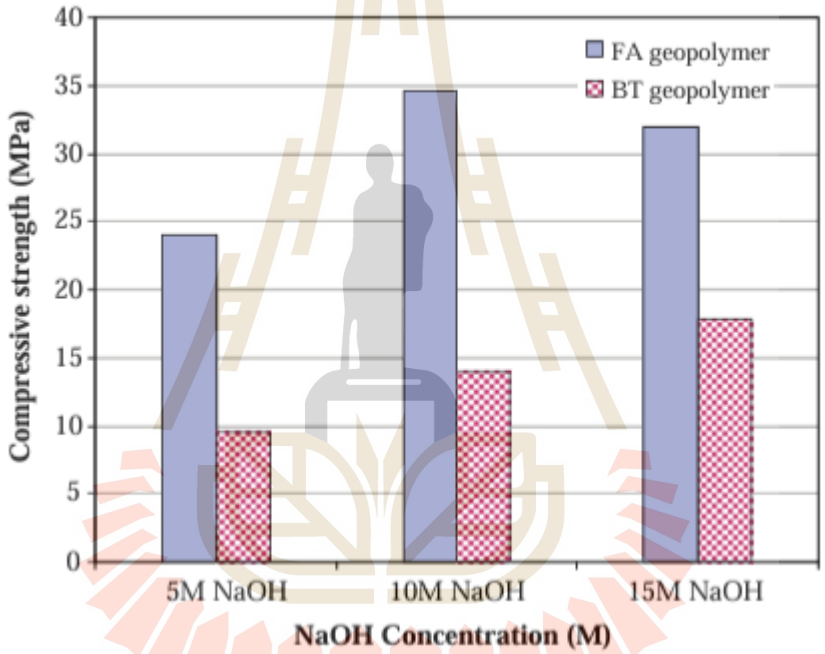

Figure 2.3 Compressive strength of geopolymer mortars between FA and BA (Chindaprasirt et al., 2009)

2.7 Recycle concrete aggregate (RCA)

Globally, it is predicted that 2.59 billion tons of solid garbage would be produced yearly by 2030. This number is anticipated to increase even higher to 3.40 billion tons by 2050. According to estimates from the World Bank, only around 19% of solid waste was recycled or composted worldwide. (Cycling; Kaza, Yao, Bhada-Tata, & Van Woerden, 2018) (Odion et al., 2019) Researching the recycling of concrete aggregates, especially for use in road building, has become a feasible endeavor. The purpose of this study was to determine if recycled concrete aggregate (RCA) combined

with soil, fly ash, and alkali activator may be a viable substitute for soil-cement in applications involving road base or subbase. The final product, called Soil-RCA geopolymer, was created by combining different amounts of fly ash, RCA, sodium hydroxide, and silicate. Using a two-flyash experiment design, the impact of mixing factors on the mechanical characteristics of Soil-RCA geopolymer was examined. For the purpose of sensitivity analysis and ultimate mixture selection, models were also developed to estimate the unconfined compressive strengths depending on mixture characteristics. Based on the investigation and findings, the Soil-RCA geopolymer combination demonstrated good stiffness, strength, and durability. (Al-Mosawe, Albayati, Wang, & Mashaan, 2022) enhanced the characteristics of the pavement roadbed materials by using recycled concrete. The following findings were drawn from the experimental research and modeling for this project. RCA may be utilized in lieu of regular gravel materials at full size to satisfy the material specification requirements for building the pavement subbase layer. Compared to regular gravel, RCA materials have a greater optimal moisture content. The constant proportions for the coarse, fine, and ultrafine materials would be 0.026%, 0.471%, and 0.373%, respectively, if linearity is assumed. The overall bearing capacity and rigidity of the pavement structure will generally be improved when RCA is used in place of regular gravel material for subbase course construction. This effect will be more noticeable when asphalt is used for the pavement top layer. RCA replacement at a 75% coarse replacement, 50% fine replacement, or 100% extra fine replacement was the best usage of replacement to get a higher CBR value. When employing the CC RCA type, the critical tensile strain and maximum compressive strain were reduced by the 100% REF substitution. However, while utilizing the TTB RCA type, the 100% RFA substitution improved these two characteristics. Additionally, the robust modulus's value was optimized by these two suggested substitutions. The pavement structure's design life would be extended if the suggested replacement were to be used, as this would raise the number of permitted load repetitions.

2.8 Bottom ash (BA)

Every year, there is an increase in the consumption of fossil fuels to produce energy. Coal is mainly used to generate steam for industrial operation and electricity generation. Consequently, coal ash is obtained as a waste product that needs to be disposed in an environmentally friendly way. However, because of the large quantity produced, most types of ash, including fly and bottom ash, are disposed of in landfills. This disposal process leads to environmental and other problems (Chindaprasirt et al.,

2009). In Thailand, the annual output of fly ash and bottom ash from large and small power plants totals about 4.0 million tons. Approximately 1.8 million tons of fly ash is used as a pozzolanic material in the concrete industry. Over a million tons of black carbon are produced annually by Thailand's coal-fired power plants during their combustion process. An annual budget of USD 180,000 is allotted by the Electricity Generating Authority of Thailand (EGAT) to dispose of its BA waste in the waste disposal site. In order to assist the government of Thailand's national development program, EGAT looks for the best way to optimize the use of BA in road building. According to its characteristics, BA is a porous aggregate with a rough particle form, low bulk density, and high water absorption. In terms of geotechnical qualities, BA's hydraulic conductivity, shear strength, chemical soundness, and California Bearing Ratio (CBR) are on par with or superior to those of natural aggregates. For this reason, BA is typically employed as a stand-in. (Buritatum et al., 2022b)

The partial replacement of Portland cement with fly ash reduces the heat of hydration and improves the workability and durability of the concrete. However, the level of fly ash replacement is normally restricted to less than 40% of Portland cement (Mehta, 1998). Bottom ash (BA), in contrast, does not possess the same enhanced workability. However, the chemical constituents of these two materials are very similar, with the main difference being particle shape and size. Bottom ash is larger in size and very irregular, containing pores and cavities. Ground to a proper fineness, bottom ash can be used as a pozzolan that produces relatively high-strength concrete (Jaturapitakkul & Cheerarot, 2003). Both bottom ash and fly ash are by-products of the combustion of pulverized coal in power plants. As the temperature in the kiln is higher than the melting point of fly ash, the fly ash melts and forms the bottom ash. Bottom ash generally has a high porous surface and a large particle size, thus resulting in a higher water requirement and lower compressive strength when used in conventional cement concrete. The bottom ash could be grounded to reduce its particle size, thus decreasing the porosity and enhancing the pozzolanic reaction.

The SEM images of BA revealed that the particles were irregular with the agglomeration of spherical particles and some angular and rough particles as shown in Figure 2.4

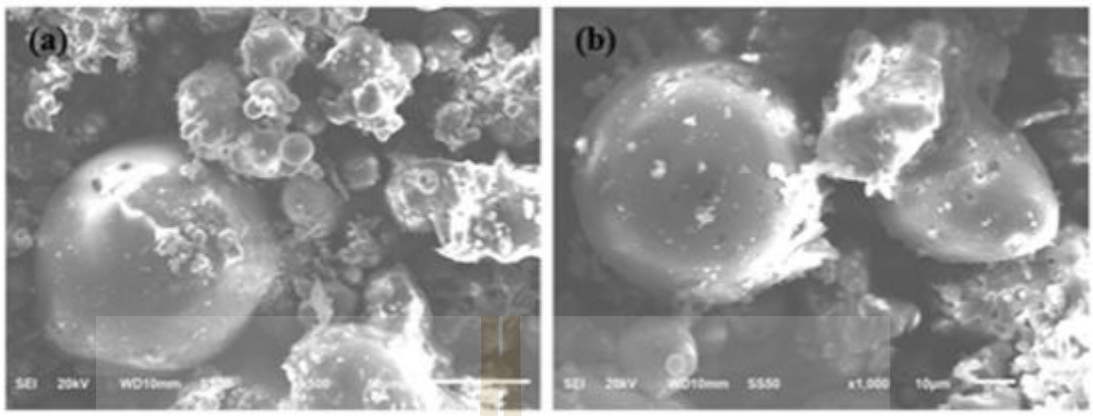

Figure 2.4 SEM image of BA at (a) 500x magnification (b) 1000x magnification. (Kererat, Kroehong, Thaipum, & Chindaprasirt, 2022)

However, the utilization of bottom ash as a cementitious replacement material has not yet been well received due to the need for grinding and the possibility of only the partial replacement of cement. But still, different studies done in this field have laid a foundation for the future utilization of bottom ash in the field of geopolymer paste and concrete production. The utilization would be a big positive step forward rather than treating the bottom ash as waste material (Sathonsaowaphak, Chindaprasirt, & Pimraksa, 2009). Bottom ash (BA) waste from Mae Moh Electric power plant in the north of Thailand is shown in Figure 2.6 The basic properties and particle-size distribution of BA are summarized in Table 2.1 and Figure 2.5, respectively. The particle-size distribution and soundness of BA did not meet the standard to be used as fine aggregate in asphaltwearing course, in accordance with the Thailand Department of Highways standard.

Table 2.2 Basic engineering properties of Bottom ash. (Buritatum et al., 2022a)

Properties	Bottom ash	DH-S 408/1989 Specifications
Soundness (%)	24.3	≤9%
Sand equivalent (%)	53.1	≥50%
Specific gravity	2.53	-

BA contained a high content of fine particles; particles smaller than 4.75 mm are greater than 50%. It is noted that BA particles were coagulated into clusters,

indicating that they react with water. In other words, BA is characterized as a hydrophobic material.

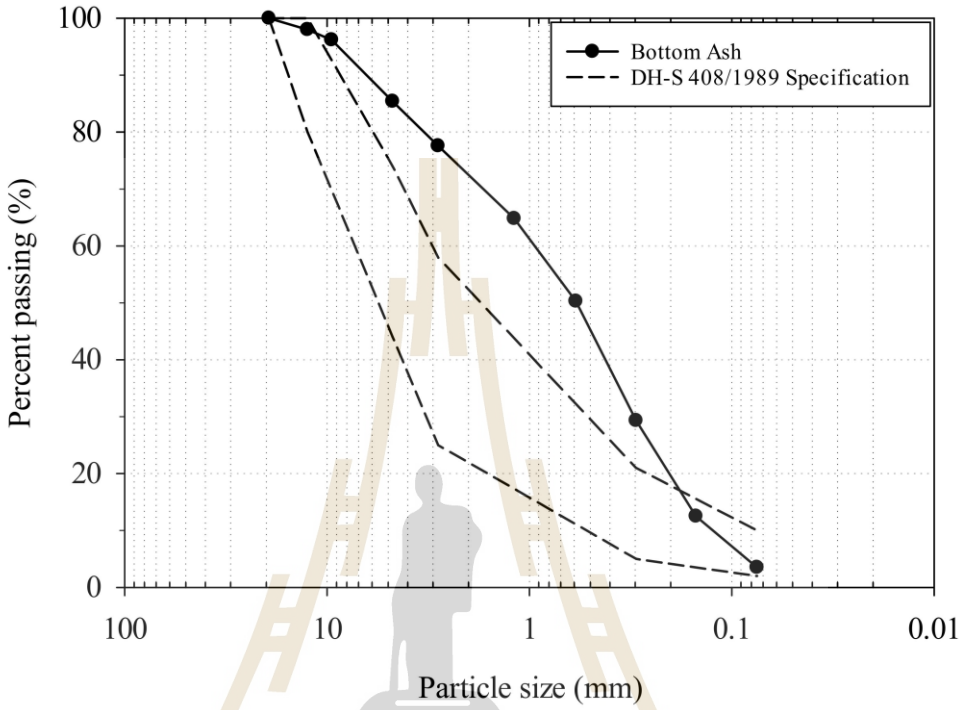

Figure 2.5 Particle size distribution of original BA aggregate. (Buritatum et al., 2022a)



Figure 2.6 Bottom ash waste from Mae Moh Electric power plant (EGAT)

BA can be used in civil engineering works such as aggregate replacement in concrete products, embankment fill, road construction, and reclamation work (H. Kim & Lee, 2015; Torkittikul, Nochaiya, Wongkeo, & Chaipanich, 2017). Previous studies also showed that marginal road materials can be improved by incorporating 10–25% BA. Such mixtures complying to the standards of the Thailand Department of Highways can then be used as a subbase. in Nigeria BA was successfully applied as a compacted material in unbound roads, the use of bottom ash envisaged application should therefore not result in any environmental impact (Abdulahi, 2009).

For each road construction materials BA was used in highway embankment construction offers an attractive alternative to disposal because substantial economic savings can be attained by the reduction of ash disposal costs and the conservation of natural soils and lands, pavement construction (Gautam et al., 2018; López-López et al., 2015; Yoo et al., 2016) and aggregate replacement in concrete pavement production (Arenas et al., 2011; Hannan et al., 2020). That is confirmation that both waste materials (RCA and BA) can used in civil construction, especially in road construction materials from previous research. Almost all previous research has used cement-stabilized waste material is the trend of researchers and scientific to improve mechanical properties and studies to affect microstructure. However the past of cement-stabilized researcher are developed and improved concrete pavements also have several shortcomings, which include; high greenhouse gas emissions, low tensile and flexural strengths, and temperature susceptibility (Mohod & Kadam, 2016).

2.9 Natural rubber latex (NRL)

The BCG Model of economics is the current trend of the world wild, BCG Model is a holistic economic development that will develop the 3D economy simultaneously. The bio-economy system focuses on the use of biological resources to create added value by emphasizing the development of high-value products. Both economies are under the green economy, which is an economic development that focuses not only on economic development. However, it must be developed in tandem with social development and environmental protection in a balanced manner to ensure stability and sustainability at the same time. By transforming Thailand's advantages from biodiversity and culture into competitiveness through innovation to create a growing BCG economy that is globally competitive. Distribute income to communities and reduce inequality. Strong community, eco-friendliness, and sustainable development

The Southeast Asia region is the biggest natural rubber producer in the world. The production of rubber in this region is more than 50% of the total rubber production

worldwide. The top three countries include Thailand, Indonesia, and Vietnam. According to the statistical data in 2019 of the Rubber Authority of Thailand, Thailand had the largest natural rubber export, contributing approximately 38.82% of the world rubber market (Buritatum et al., 2021). (Figure 2.7) The fresh para rubber latex consists of 30–35% of dry natural rubber while the commercial grade has dry rubber content up to 60% (Krishnan, Joseph, & Roy, 2019). Several industries use para rubber because of its high flexibility, excellent insulation, plasticity, waterproofing, and impact resistance (Mark, 2007; G. Sukmak et al., 2020; Wu, Sun, Li, & Zeng, 2017). The NRL contained a dry rubber content of 52% and ammonia content of 0.7%. The rest of the content was water and water-soluble components at 47%. The studied NRL had a pH of 10.4, and its photo is provided in Figure 2,7



Figure 2.7 Natural rubber latex (NRL) (Suddeepong, Buritatum, et al., 2022)

Natural rubber latex (NRL) is a biopolymer from the Hevea brasiliensis tree. The raw state of NRL consists of polymer content (cis-1,4 - Polyisoprene) and water. The solid polymer content consists of approximately 94% rubber hydrocarbon and 6% non-rubber substances, such as phospholipids, and protein. The morphology evidence essentially indicates the rubber particles to be spherical in shape and with a random stuffing arrangement. This particle is typically surrounded by a layer of phospholipids and proteins. The existence of these non-rubber substances causes undesirable attributes, such as premature coagulation. In order to overcome the negative characteristic of NRL, it is usually modified with an additional substance. Ammonia is

an additive substance, which balances the charge between proteins and phospholipids, which results in the stability of the latex particles (Afiq & Azura, 2013; Herculano, de Queiroz, Kinoshita, Oliveira Jr, & Graeff, 2011; Horpibulsuk, Katkan, Sirilerdwattana, & Rachan, 2006; Nawamawat et al., 2011; Norhanifah, Nurulhuda, & Asrul, 2015; Rathnayake, Ismail, Baharin, Darsanasiri, & Rajapakse, 2012; Sakdapipanich, 2007).

In civil construction the application of NRL is used in building and road structures (base/subbase) has been reported by previous research. NRL has the potential to improve the viscosity and elastic recovery of the asphalt binder (Wen, Wang, Zhao, & Sumalee, 2017). However, the price of para rubber is very low due to the oversupply. In Thailand, the government encourages usage of para rubber latex as alternative materials for pavement (Kererat et al., 2022). Road construction is important for developing countries, especially in Thailand, where the grown-up economy is usually a road network for product transportation, in Asian countries, such as Thailand, The Thailand Office of Transport and Traffic Policy and Planning uses NRL in road construction for alternative materials for pavement. A highway pavement is a structure consisting of layers of natural and processed materials above the natural ground level. The pavement structure includes subgrade, base/subbase, and surface layers. A pavement's primary function is to distribute the cyclic loads of vehicles from the top of the pavement to a larger area of the pavement structures without causing any damage to the subgrade. The aim of the pavement structure is to ensure that the transmitted wheel loads are sufficiently reduced so that they do not exceed the capacity of all the pavement layers. In other words, the pavement must be structurally adequate to withstand all stresses and maintain the cracking and deformation within tolerable limits (Hoy, Nhieu, et al., 2023). The basically sound properties of geopolymer could thus be improved with the incorporation of rubber latex. The NRL can improve the properties of geopolymer mortar incorporating NRL, with the setting time, water absorption, abrasion resistance, compressive strength, direct tensile strength, and bending strength. (Chindaprasirt & Ridtirud, 2020). The NRL used to improve indirect tensile resilient modulus (IT Mr), indirect tensile resilient fatigue, dynamic creep, rutting resistance, and skid resistance tests were used to assess the performance of asphalt concrete modified by BA. Its performance and technical characteristics were contrasted with traditional asphalt concrete. The study's findings will support the use of BA as a cleaner paving material, which is an environmentally friendly alternative to coal-fired power plants throughout the globe and EGAT. (Buritatum et al., 2022a)

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CHAPTER III
METHODOLOGY
STRENGTH DEVELOPMENT OF BOTTOM ASH GEOPOLYMER STABILIZED RECYCLED CONCRETE AS A ROAD CONSTRUCTION MATERIAL

3.1 Introduction

The construction industry, particularly road construction, faces significant challenges in sustainability due to its reliance on traditional materials such as natural aggregates and Portland cement. These materials are associated with high CO_2 emissions and depletion of natural resources. As global road infrastructure needs continue to expand, there is an urgent requirement for sustainable solutions that meet performance criteria while minimizing adverse environmental impacts (Giunta, 2023; Hoy et al., 2024; Salehi, Arashpour, Kodikara, & Guppy, 2021; Sha et al., 2021).

Recycled concrete aggregate (RCA) and bottom ash (BA) have emerged as potential eco-friendly alternatives to traditional construction materials (Buritatum et al., 2022). This study uniquely employed 100% waste-derived materials, including RCA and BA, as both aggregate and aluminosilicate precursor, eliminating the need for virgin aggregates This approach directly supports circular economy principles by diverting large quantities of construction demolition waste and coal combustion byproducts from landfills while reducing greenhouse gas emissions, making it a compelling alternative to conventional pavement base materials. RCA, obtained from demolished concrete structures, provides an approach to reduce landfill waste and conserve natural resources (Jurič, Hanžič, Ilić, & Samec, 2006). The incorporation of RCA in new pavement structures contributes to waste reduction in landfills and conserves natural resources by decreasing the demand for virgin aggregate materials. BA, a byproduct of coal combustion, presents another opportunity for waste utilization in construction(Yoon, Lee, & Kim, 2019). However, when used independently, these materials often fail to meet the mechanical strength and durability requirements necessary for road construction (Nanda & Priya, 2024; Poltue et al., 2020; Tiyasangthong et al., 2022).

Geopolymer technology represents a promising approach to address the limitations of RCA and BA (Xiao et al., 2020). Geopolymers are inorganic polymers formed when aluminosilicate materials, such as fly ash or slag, chemically react with alkaline solutions (Davidovits, 2008). This reaction produces a dense, three-dimensional network structure that provides excellent mechanical strength, durability, and resistance to chemical attack (Farooq et al., 2021). The environmental benefits of geopolymer technology are substantial as it utilizes industrial byproducts and reduces CO2 emissions associated with cement production (Hassan, Arif, & Shariq, 2019; Zakka, Lim, & Khun, 2021).

Several studies have demonstrated the effectiveness of geopolymer-stabilized recycled materials in pavement applications. Research has shown that high-calcium fly ash geopolymer can significantly improve the unconfined compressive strength (UCS) of RCA, meeting requirements for both low and high-traffic roads (Phummiphan et al., 2018; Zhang, Provis, Reid, & Wang, 2014). Similarly, studies have demonstrated that fly ash–rice husk ash-based geopolymer can enhance the UCS of RCA as a pavement material (Nuaklong et al., 2019). To achieve desired performance improvements in compressive strength, flexural strength, and elastic modulus, the alkaline activator content in geopolymer-stabilized recycled materials must be optimized (Horpibulsuk et al., 2024; Phoo-ngernkham, Chindaprasirt, Sata, Hanjitsuwan, & Hatanaka, 2014; Poltue et al., 2020). This optimization is necessary due to the formation of additional calcium silicate hydrate (C-S-H) or calcium aluminosilicate hydrate (C-A-S-H) and sodium aluminosilicate hydrate (N-A-S-H) or geopolymer gel in the geopolymer matrix.

While extensive research has been conducted on fly ash-based geopolymers, the potential of bottom ash-based geopolymers in stabilizing RCA remains largely unexplored. Studies indicate that bottom ash-based geopolymers may exhibit lower mechanical strength and durability due to the crystalline content, low amorphous aluminosilicate phase, and coarse particle size, all of which limit dissolution and reduce geopolymerization potential (Chindaprasirt, Jaturapitakkul, Chalee, & Rattanasak, 2009; Sata, Sathonsaowaphak, & Chindaprasirt, 2012). However, these limitations can potentially be addressed through careful optimization of the geopolymerization process, particularly by adjusting the alkaline activator ratio (Xie & Ozbakkaloglu, 2015).

The alkaline activator plays a crucial role in the geopolymerization process, affecting both aluminosilicate precursor dissolution and subsequent geopolymer network formation. By investigating the influence of different alkaline ratios, it may be possible to enhance the reactivity of bottom ash and improve the overall performance of bottom ash-based geopolymers. This approach could lead to the development of more effective stabilization

methods for RCA using bottom ash-based geopolymers, potentially achieving mechanical properties comparable to or surpassing those of fly ash-based systems.

Most research focuses on cement and reinforcement to improve material efficiency for various applications, and there is limited research addressing the importance of complete waste material reuse, particularly waste materials from construction demolition and power plants. Therefore, this research focuses on the effects of various ratios between waste materials (RCA:BA) and different alkaline ratios on bottom ash-based geopolymers to stabilize recycled concrete aggregate, which remains poorly understood.

This research aims to address this research gap by investigating the influence of various RCA:BA ratios and alkaline activators with different Na_2SiO_3:NaOH (G/N) ratios (1:1, 1:1.5, and 1:2 by weight) on the strength and durability of bottom ash-based geopolymer-stabilized RCA. Its performance is compared with the requirements specified by the Department of Highways. Strength development was assessed through comprehensive microstructural and mineralogical analyses, employing scanning electron microscopy (SEM), energy dispersive X-ray spectroscopy (EDS), and X-ray diffraction (XRD) techniques.

This study is based on the hypothesis that an optimal combination of RCA and BA, activated with a suitably high sodium silicate-to-sodium hydroxide ratio, can significantly enhance the mechanical performance and microstructural densification of RCA-BA geopolymer mixtures, achieving strength and durability requirements for high-traffic pavement base applications.

The findings of this research contribute to the development of advanced pavement materials that balance sustainability with performance, addressing future infrastructure needs while adhering to green construction principles. This innovative approach has the potential to advance pavement engineering by offering environmentally friendly solutions without compromising structural integrity.

3.2 Materials and methods

3.2.1 Materials

Two industrial waste streams were selected as raw materials based on their complementary chemical compositions, availability, and potential for geopolymer synthesis: recycled concrete aggregate (RCA) as the primary aggregate component and lignite bottom ash (BA) as the aluminosilicate precursor. The selection criteria prioritized materials with established waste disposal challenges and demonstrated potential for beneficial reuse in construction applications.

3.2.1.1 Recycled concrete aggregate

RCA was obtained from construction demolition projects in Ubon Ratchathani and Sisaket Provinces, Thailand, representing typical concrete waste from regional infrastructure. The material underwent comprehensive characterization to establish baseline properties and suitability for pavement applications.

Particle size distribution analysis (ASTM D422-63) confirmed compliance with the Department of Highways (DOH), Thailand, specifications for pavement base materials (Figure 3.1). The gradation comprised 48.6% gravel (retained on No. 4 sieve), 47.9% sand (passing No. 4, retained on No. 200), and 3.5% fines (passing No. 200 sieve). Under the Unified Soil Classification System, the material was classified as well-graded gravel (GW) with no measurable plasticity.

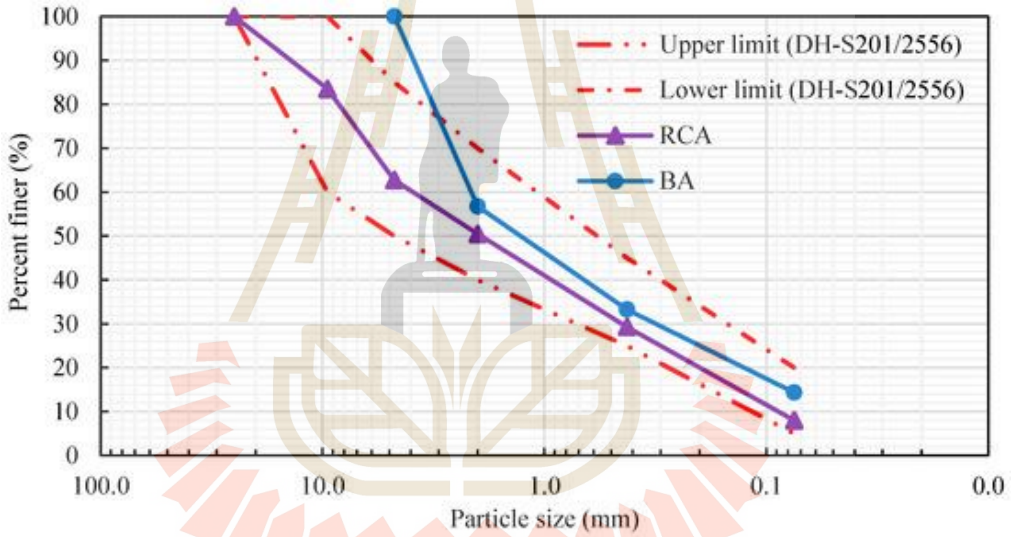
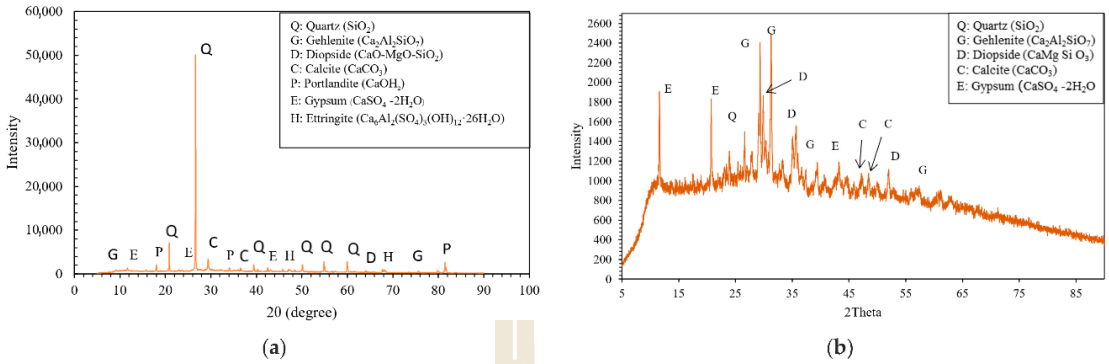


Figure 3.1 Graduation of RCA and BA.

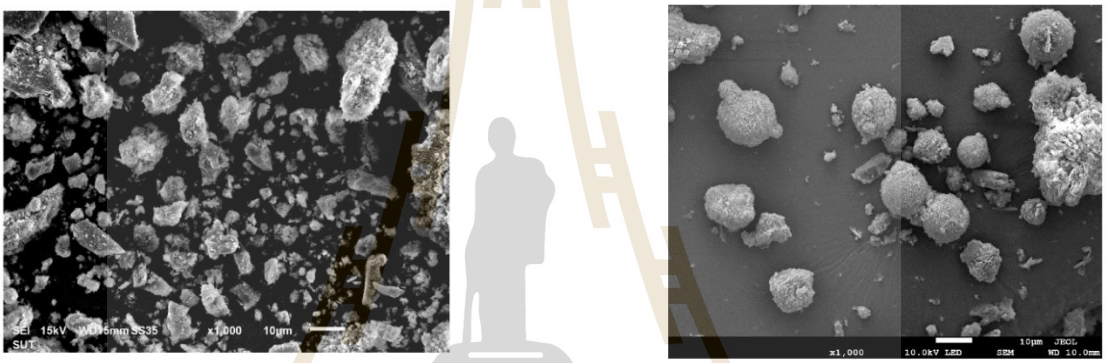
Key mechanical and physical parameters included specific gravity of 2.7, Los Angeles abrasion resistance of 38.1%, flakiness index of 15.6%, and maximum dry density of 18.70 kN/m^3 at an optimum moisture content of 12%. Water absorption values were 6.42% and 7.83% for coarse and fine fractions, respectively, indicating moderate porosity typical of recycled aggregates.

XRD analysis identified predominant crystalline phases including quartz, calcite, and residual cement minerals (Figure 3.2a). SEM examination revealed angular particles with rough surface textures, residual cement paste adherence, and interconnected porosity (Figure 3.3a).



(a) (b)

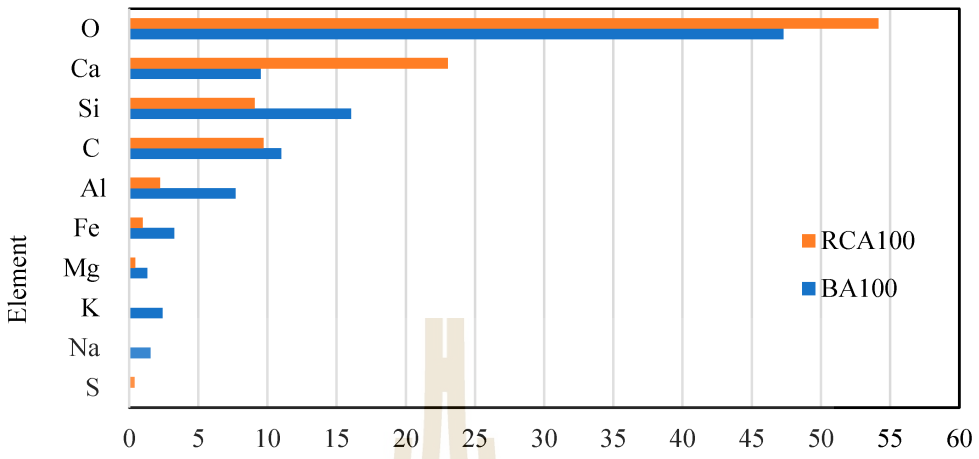
Figure 3.2 XRD patterns of (a) RCA and (b) BA.



(a) (b)

Figure 3.3 SEM images of (a) RCA and (b) BA.

Energy-dispersive X-ray spectroscopy (EDX) analysis was performed using a scanning electron microscope equipped with an EDX detector. Multiple point analyses were conducted on polished sample surfaces to ensure representative elemental composition data. The chemical compositions are presented in Figure 3.4 and demonstrate complementary profiles essential for geopolymer synthesis. RCA exhibited a calcium-rich elemental composition typical of concrete materials, with calcium (Ca) and oxygen (O) as the predominant elements, indicating the presence of unhydrated cement particles and calcium-based compounds such as $Ca(OH)_2$ and $CaCO_3$. Silicon (Si) and carbon (C) were also present in significant proportions, reflecting the silicate phases and carbonate content characteristic of concrete materials. Minor elements included aluminum (Al), iron (Fe), magnesium (Mg), and trace amounts of sulfur (S).



	S	Na	K	Mg	Fe	Al	C	Si	Ca	O
RCA100	0.39	0.00	0.00	0.45	0.97	2.22	9.71	9.07	23.04	54.15
BA100	0.00	1.53	2.40	1.32	3.25	7.69	10.99	16.03	9.50	47.30

Figure 3.4 Chemical compositions RCA and BA obtained from EDX.

3.2.1.2 Bottom ash (BA)

Lignite bottom ash was sourced from Mae Moh power plant (Electricity Generating Authority of Thailand, Changwat Lampang, Thailand), representing the largest lignite-fired facility in Southeast Asia. This material represents approximately 15%–20% of total coal combustion products from the facility.

XRD analysis revealed a predominantly amorphous structure with minor crystalline phases including quartz and feldspathic minerals (Figure 3.2b). EDX analysis confirmed high silica (SiO_2) and alumina (Al_2O_3) contents essential for geopolymer formation, along with elevated alkali contents (Na_2O and K_2O) and minor iron oxide (Fe_2O_3) concentrations.

SEM imaging revealed irregular angular particles with a heterogeneous size distribution and a porous surface structure (Figure 3.2b). The morphology differs significantly from spherical fly ash particles, contributing to different reactivity characteristics in alkaline environments.

The EDX analysis (Figure 3.4) indicated that BA provided essential aluminosilicate components for geopolymer formation, with significantly higher silicon (Si) and aluminum (Al) contents compared to RCA. The BA composition showed an elevated oxygen (O) content, substantial silicon (Si) and aluminum (Al) concentrations, and moderate levels of calcium (Ca), iron (Fe), and trace elements including potassium (K), sodium (Na),

and magnesium (Mg). The higher alkali content (Na and K) in BA contributes to the alkaline environment necessary for geopolymer activation.

The EDX analysis results correlate well with the XRD findings (Figure 3.2), where the high calcium content in RCA corresponds to the calcite and residual cement peaks observed, while the elevated silicon and aluminum contents in BA align with the predominant amorphous content and minor crystalline aluminosilicate phases detected in the diffraction patterns.

This elemental analysis confirms that the combination of calcium-rich RCA and aluminosilicate-rich BA provides an optimal chemical foundation for developing hybrid geopolymer systems with enhanced mechanical properties and sustainability characteristics.

3.2.1.3 Alkaline activators (L)

The preparation of the alkaline activator was a critical step in the geopolymer mix design, requiring careful control of the chemical composition to ensure effective geopolymerization and minimize handling hazards.

In this study, the activator was formulated by blending sodium silicate (Na_2SiO_3) solution with 10 M sodium hydroxide (NaOH) solution. These components were chosen for their effectiveness in dissolving aluminosilicate materials and promoting geopolymerization (Temuujin, Minjigmaa, Lee, Chen-Tan, & Van Riessen, 2011). A binary activator combining Na_2SiO_3 and NaOH was selected to provide (i) silicate species for gel network formation, (ii) a high-pH environment for aluminosilicate dissolution, and (iii) an optimal workability window for field application.

Commercial-grade Na_2SiO_3 (type CR53) was used with the following compositional specifications: 14.5–16.5 wt% Na_2O, 31.5–34.0 wt% SiO_2, H_2O balance, silica modulus (Ms) of 2.0–2.2., density at 20 °C: 1.52 ± 0.02 g/cm^3, and viscosity of 400–600 cP. The NaOH solution was prepared by dissolving analytical-grade NaOH pellets (≥99% purity) in distilled water to achieve a concentration of 10 M (400 g/L). Both solutions were equilibrated for 24 hr at ambient temperature (25 ± 2 °C) to ensure complete dissolution and thermal stabilization prior to mixing.

Three systematically varied compositions were prepared with Na_2SiO_3:NaOH mass ratios (G/N) of 1:1, 1:1.5, and 1:2, corresponding to effective silica moduli of 1.2, 1.0, and 0.8, respectively.

3.2.2 Mix Design and Sample Preparation

A two-factor experimental design was implemented to systematically evaluate Factor A—aggregate blend ratio (5 levels: RCA:BA = 90:10, 80:20, 70:30, 60:40, and 50:50), and Factor B—alkaline activator ratio (3 levels: G/N = 1:1, 1:1.5, and 1:2). Additional

control specimens (RCA100 and BA100 with water only) provided baseline references. The complete factorial design comprised 17 unique compositions with minimum n = 3 replicates per condition (Table 3.1).

The selected RCA:BA ratios were determined based on practical pavement base design considerations; the lower BA content (10%–20%) reflects typical field applications where high aggregate interlock is required for structural stability. In addition, higher BA contents (30%–50%) were included to explore the feasibility of maximizing waste utilization. The 50% replacement level represents the practical upper bound reported in prior research for maintaining acceptable workability and mechanical performance in pavement base materials (Tiyasangthong et al., 2022).

The mix design for this study was systematically developed to evaluate the impact of various Na_2SiO_3:NaOH (G/N) ratios of 1:1, 1:1.5, and 1:2, by weight of the aggregate modification, on the properties of BA-based geopolymer-stabilized RCA (Table 3.1). The design involved creating a series of mixtures with varying contents of alkaline activator ratios and replacement between RCA:BA (90:10, 80:20, 70:30, 60:40, and 50:50) to establish a comprehensive understanding of their individual and combined effects on the geopolymer's performance.

Table 3.1 The mix design of the BA-based geopolymer-stabilized RCA in this study.

Sample ID	Mix Ingredients
90RCA10BA G/N 1:1.0	90%RCA + 10%BA + (1) Na_2SiO_3 + (1) NaOH
90RCA10BA G/N 1:1.5	90%RCA + 10%BA + (1) Na_2SiO_3 + (1.5) NaOH
90RCA10BA G/N 1:2.0	90%RCA + 10%BA + (1) Na_2SiO_3 + (2) NaOH
80RCA20BA G/N 1:1.0	80%RCA + 20%BA + (1) Na_2SiO_3 + (1) NaOH
80RCA20BA G/N 1:1.5	80%RCA + 20%BA + (1) Na_2SiO_3 + (1.5) NaOH
80RCA20BA G/N 1:2.0	80%RCA + 20%BA + (1) Na_2SiO_3 + (2) NaOH
70RCA30BA G/N 1:1.0	70%RCA + 30%BA + (1) Na_2SiO_3 + (1) NaOH
70RCA30BA G/N 1:1.5	70%RCA + 30%BA + (1) Na_2SiO_3 + (1.5) NaOH
70RCA30BA G/N 1:2.0	70%RCA + 30%BA + (1) Na_2SiO_3 + (2) NaOH
60RCA40BA G/N 1:1.0	60%RCA + 40%BA + (1) Na_2SiO_3 + (1) NaOH
60RCA40BA G/N 1:1.5	60%RCA + 40%BA + (1) Na_2SiO_3 + (1.5) NaOH
60RCA40BA G/N 1:2.0	60%RCA + 40%BA + (1) Na_2SiO_3 + (2) NaOH
50RCA50BA G/N 1:1.0	50%RCA + 50%BA + (1) Na_2SiO_3 + (1) NaOH
50RCA50BA G/N 1:1.5	50%RCA + 50%BA + (1) Na_2SiO_3 + (1.5) NaOH
50RCA50BA G/N 1:2.0	50%RCA + 50%BA + (1) Na_2SiO_3 + (2) NaOH

RCA and BA were first dry-mixed for 2 min to achieve uniform distribution. The alkaline activator solution was then gradually added while continuously mixing for 3 min until a homogeneous paste was achieved. The mixtures were immediately transferred to standard Proctor molds (101.6 mm diameter × 116.4 mm height) and compacted under a modified standard Proctor test following ASTM D1557 in five equal layers to determine the maximum dry density (MDD) and optimum liquid content (OLC) for each composition. Specimens were prepared at their respective MDD and OLC conditions for mechanical testing. A ±2% tolerance from the target MDD and OLC was applied as a quality control criterion in line with ASTM D1557 recommendations and standard geotechnical practice. Specimens exceeding this deviation were rejected to ensure consistent density and moisture conditions, thereby minimizing experimental variability and ensuring that observed mechanical property differences were solely due to mix composition and activation ratios.

3.3 Laboratory Experimental Program

The experimental program was systematically designed to comprehensively evaluate the mechanical and microstructural properties of BA-based geopolymer-stabilized RCA. The testing protocol encompassed mechanical performance assessment and detailed microstructural characterization to establish structure–property relationships and validate the effectiveness of the geopolymer stabilization approach.

3.3.1 Unconfined Compressive Strength (UCS)

UCS tests were conducted at 7 and 28 days of curing following ASTM D2166 specifications to evaluate strength development over time. Cylindrical specimens (101.6 mm diameter × 116.4 mm height) were tested using a universal testing machine at a controlled loading rate of 1.0 mm/min to capture both peak strength and post-peak behavior. Load and deformation data were continuously recorded throughout the test until specimen failure, defined as either peak load achievement or 15% axial strain. The UCS values were calculated by dividing the maximum applied load by the original cross-sectional area of the specimen. Testing was performed on a minimum of three specimens per mixture and curing age to ensure statistical reliability, with the results reported as mean values with standard deviation.

3.3.2 Scanning Electron Microscopy (SEM) Analysis

SEM analysis was employed to visualize the microstructure of the geopolymer samples at a high magnification. This analysis provides insights into the microstructure of the BA geopolymer within the matrix, the bonding at the RCA-BA

interface, and the morphology of the geopolymer binder. The SEM examination was conducted on fractured samples post-UCS testing to identify the failure mechanisms and to correlate the mechanical test results with the microstructural characteristics.

3.3.3 X-Ray Diffraction (XRD) Analysis

XRD analysis was utilized to identify the crystalline phases present within the geopolymer matrix and to observe the changes in mineralogy due to the addition of the BA geopolymer and variation in the alkaline activator mixture. The XRD patterns were collected using a diffractometer, with samples being scanned in a 2Theta range, typically between 5° and 80°. The resultant diffractograms were analyzed to determine the presence of specific crystalline compounds and to infer the effectiveness of the geopolymerization process.

3.4 Results and Discussion

3.4.1 UCS Development

3.4.1.1 Strength Performance and Standard Compliance

The UCS results demonstrated significant enhancement achieved through BA-based geopolymer stabilization of RCA for pavement base applications (Figure 3.5). At 7 days of curing, the stabilized mixtures exhibited UCS values ranging from 2.98 to 9.14 MPa, representing substantial improvements over unstabilized controls (UCS of 100% RCA = 0.63 MPa). Strength development continued significantly through 28 days, with UCS values reaching 4.11 to 12.45 MPa, indicating active geopolymerization processes and continued matrix densification.

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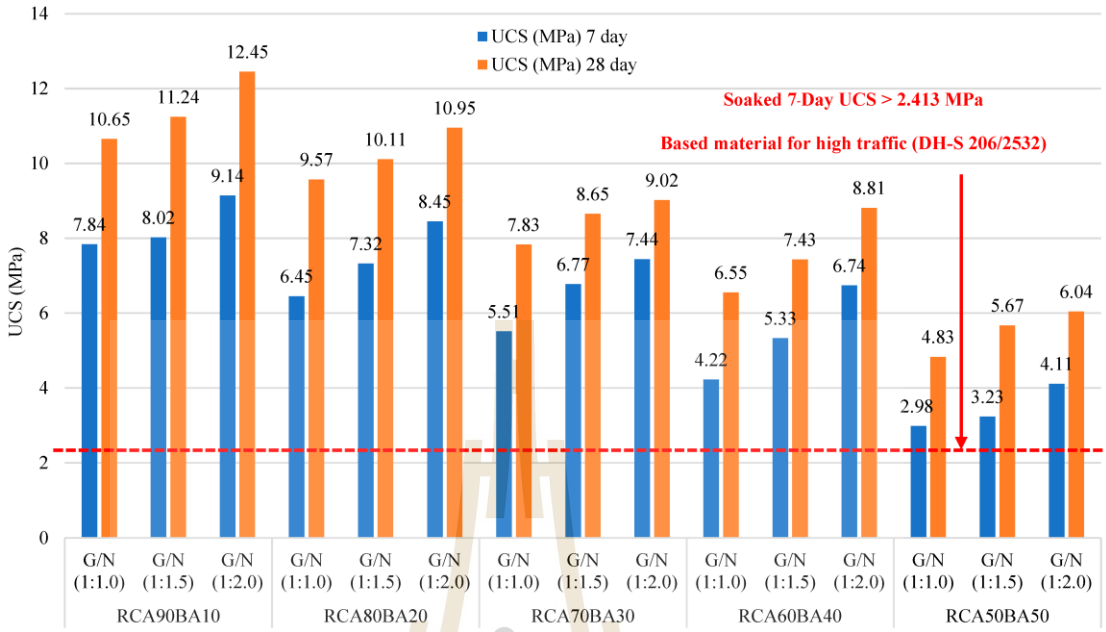


Figure 3.5 UCS of BA-based geopolymer-stabilized RCA samples at 7 and 28 days of ambient curing

Critically, all BA-based geopolymer-stabilized RCA mixtures, irrespective of the G/N ratio (1:1, 1:1.5, and 1:2), significantly exceeded the minimum UCS requirement of 2.413 MPa specified by DOH, Thailand, for high-traffic pavement applications. This compatibility reveals that the developed materials can directly be integrated into existing pavement layer designs without major structural modifications. In addition, this performance demonstrates the potential for these waste-derived materials to replace conventional granular subbase materials in demanding pavement applications. Elevated curing temperatures (40–60°C) might enhance geopolymerization and early strength, but pavement base layers are typically cured under ambient conditions. This study followed field-compatible curing, and the resulting strength confirms its practical suitability without added energy input.

3.4.1.2 Influence of RCA:BA Ratio on Strength Development

The aggregate blend ratio emerged as a critical parameter governing mechanical performance, with RCA90BA10 consistently delivering superior strength characteristics across all alkaline activator conditions. At 28 days, this optimal composition achieved peak UCS values of 10.65, 11.24, and 12.45 MPa for G/N ratios of 1:1, 1:1.5, and 1:2, respectively. The superior performance of RCA90BA10 compared to RCA80BA20 indicated a critical balance between the reactive BA content and aggregate skeleton integrity. At 10% BA, sufficient aluminosilicate is available for gel

formation without disrupting the RCA's strong interlocking framework. However, BA contents exceeding 15%–20% begin to compromise the structural skeleton due to the lower intrinsic strength and higher porosity of BA, which reduces the load transfer efficiency despite increased geopolymer gel formation. This threshold aligns with previous studies on bottom ash geopolymer pavements (Chindaprasirt et al., 2009; Sata et al., 2012).

Progressive increases in the BA content from 20% to 50% resulted in systematic strength reductions, with RCA50BA50 exhibiting the lowest UCS values (4.83–6.04 MPa at 28 days). This declining trend reflects the trade-off between geopolymer binding capacity and structural integrity, where excessive BA replacement reduces the proportion of high-strength aggregate particles while potentially creating a weaker, more porous matrix due to the lower intrinsic strength and higher porosity of bottom ash compared to concrete aggregate.

3.4.1.3 Alkaline Activator Optimization and Geopolymerization Mechanisms

The G/N ratio demonstrated profound influence on strength development, with systematic strength increases observed as the ratio progressed from 1:1 to 1:2. The RCA90BA10 mixture showed remarkable strength enhancement from 10.65 MPa (G/N 1:1) to 12.45 MPa (G/N 1:2) at 28 days, representing a 17% strength increase. Similarly, other mixtures exhibited consistent strength improvements with increasing G/N ratios, with average strength gains of 15%–20% when progressing from G/N 1:1 to G/N 1:2 across all RCA:BA combinations.

This progressive strength enhancement can be attributed to the increased silicate availability in the activating solution, which promotes more extensive geopolymer network formation (Provis & Van Deventer, 2009; Yip, Lukey, Provis, & Van Deventer, 2008). The higher sodium silicate content at G/N 1:2 provides additional silicate species that participate in polycondensation reactions, leading to a more densely cross-linked three-dimensional aluminosilicate network (Duxson, Mallicoat, Lukey, Kriven, & Van Deventer, 2007; Santa, Padoin, Soares, & Riella, 2021). Research by Duxson et al.(Davidovits, 2005) demonstrated that a higher silica modulus in alkaline activators enhances the degree of polymerization in geopolymer systems, which aligns with the observed strength improvements in this study.

The intermediate G/N 1:1.5 ratio consistently produced moderate strength values between the G/N 1:1 and 1:2 extremes, demonstrating a systematic relationship between activator composition and mechanical performance. This graduated response indicates optimal control over geopolymer network development through activator formulation. The studies by Palomo et al.(Sivasakthi &

Jeyalakshmi, 2021) and Provis and van Deventer (Kim, Dang, & Do, 2016) showed that the SiO_2/Na_2O ratio in alkaline activators directly influences gel formation kinetics and final strength development, supporting the trends observed in this research.

The enhanced performance at higher G/N ratios also reflects the improved dissolution of aluminosilicate species from the bottom ash, as confirmed by Fernández-Jiménez and Palomo (Singh & Subramaniam, 2017), who reported that an increased silicate concentration accelerates the dissolution–precipitation mechanism essential for geopolymer formation. Additionally, a higher silicate content promotes the formation of more stable and cross-linked gel structures, as demonstrated by Lahoti et al.(Lahoti, Wong, Yang, & Tan, 2018) in their investigation of fly ash-based geopolymers.

This systematic strength enhancement with an increasing G/N ratio provides clear guidance for mixture optimization and demonstrates the potential for tailoring mechanical properties through alkaline activator design. The consistent improvement across all RCA:BA combinations confirmed the universal applicability of this optimization approach for BA-based geopolymer systems.

3.4.1.4 Toughness Properties of BA-Based Geopolymer-Stabilized RCA

Toughness indicates a material's ability to absorb energy and resist breaking under stress. The modulus of toughness quantifies this capacity, guiding material selection for durable and impact-resistant applications (Moazami, Yusoff, Muniandy, & Hamid, 2013). Materials with a high modulus of toughness can absorb more energy before breaking, enhancing their durability and reliability. This makes the modulus of toughness a key factor in selecting materials across various industries and applications (Tran et al., 2022).

The influence of the G/N ratio on toughness exhibited distinct patterns that varied with the RCA:BA composition and curing age (Figure 6). For the optimal RCA90BA10 mixture, a G/N ratio of 1:2 achieved the highest toughness values at both curing ages (105.67 N·m at 7 days and 107.89 N·m at 28 days), followed by a G/N ratio of 1:1.5 (97.21 N·m at 7 days and 105.55 N·m at 28 days), while a G/N ratio of 1:1 showed the lowest performance (88.39 N·m at 7 days and 98.67 N·m at 28 days). This systematic increase in toughness with higher G/N ratios demonstrates that enhanced silicate availability promotes superior energy absorption characteristics (Cristelo, Glendinning, Fernandes, & Pinto, 2012; Hanjitsuwan et al., 2014).

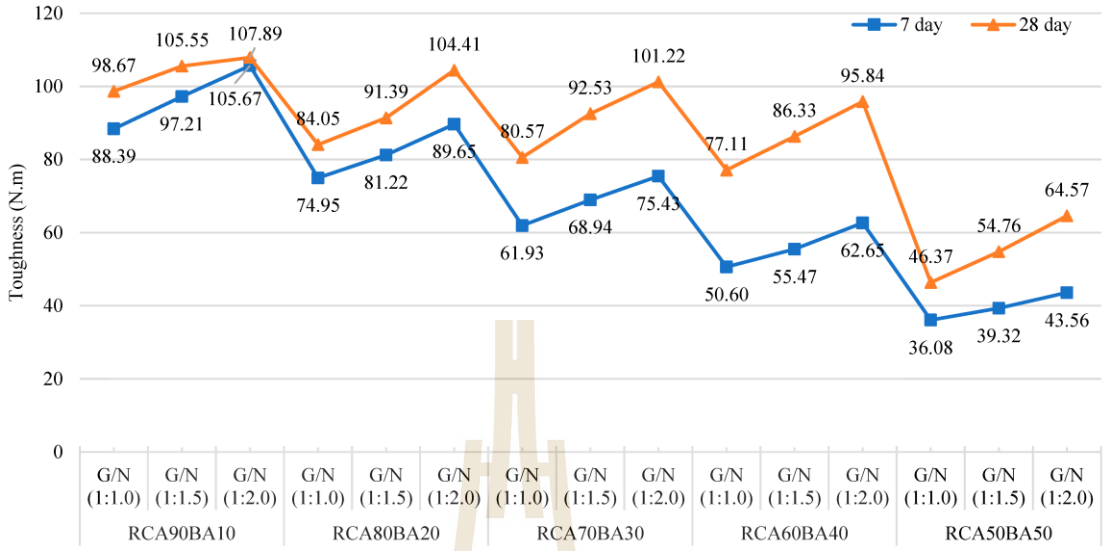


Figure 3.6 Toughness of BA-based geopolymer-stabilized RCA samples.

A particularly significant observation emerges for mixtures with a higher BA content (RCA70BA30, RCA60BA40, and RCA50BA50), where the effect of the G/N ratio becomes more pronounced with an extended curing time. For RCA70BA30, the mixture with a G/N ratio of 1:2 showed remarkable toughness development from 75.43 N·m at 7 days to 101.22 N·m at 28 days (34% increase), while toughness development with a G/N ratio of 1:1 only improved from 61.93 N·m to 80.57 N·m (30% increase). Similarly, RCA60BA40 with a G/N ratio of 1:2 demonstrated substantial improvement from 62.65 N·m to 95.84 N·m (53% increase) compared to more modest gains at lower G/N ratios.

This trend is most pronounced in the RCA50BA50 mixture, where a G/N ratio of 1:2 showed significant toughness enhancement from 43.56 N·m at 7 days to 64.57 N·m at 28 days (48% increase), while G/N ratios of 1:1 and 1:1.5 exhibited much smaller improvements (20% and 39% increases, respectively). This pattern indicates that a higher silicate content becomes increasingly critical for long-term toughness development as the BA content increases.

The enhanced long-term toughness development at higher G/N ratios in mixtures with a high BA content can be attributed to continued geopolymerization processes that benefit from the additional silicate availability. The higher silicate content provides more opportunity for ongoing polycondensation reactions, leading to progressive matrix densification and improved energy absorption capacity over time (Peter Duxson et al., 2007; Khale & Chaudhary, 2007). This effect is

particularly important in BA-rich mixtures where the initially weaker matrix requires an extended reaction time to achieve optimal performance characteristics.

This time-dependent G/N effect demonstrates that the benefits of a higher silicate content extend beyond immediate strength gains to include progressive toughness enhancement, making the G/N ratio of 1:2 the optimal choice for both immediate and long-term performance in BA-based geopolymer-stabilized RCA systems, especially for mixtures with a higher BA content.

It is noteworthy that toughness and strength trends deviate slightly at higher BA contents (>40%). While UCS decreases due to the lower intrinsic strength and higher porosity of BA, the same porous and heterogeneous matrix promotes energy dissipation by enabling microcrack deflection and progressive crack bridging within the geopolymer gel. This mechanism increases the material's energy absorption capacity despite its reduced peak load-bearing capacity, a phenomenon similarly observed in other waste-based geopolymer systems (Cristelo et al., 2012; Khale & Chaudhary, 2007).

3.4.2 Microstructural Analysis

Scanning electron microscopy analysis provides comprehensive insights into the microstructural development mechanisms governing the performance of BA-based geopolymer-stabilized RCA systems. The systematic examination of specimens with varying RCA:BA ratios and alkaline activator compositions reveals fundamental structure–property relationships that establish the scientific basis for mechanical performance optimization.

3.4.2.1 Microstructural Development in Systems with a Low Bottom Ash Content

The microstructural characteristics of RCA90BA10 specimens demonstrated a clear correlation between alkaline activator composition and geopolymer network development. Figure 3.7a presents the formulation with a G/N ratio of 1:1, which exhibited incomplete geopolymerization characterized by heterogeneous matrix formation and extensive unreacted bottom ash particles. The microstructure revealed limited gel formation with discontinuous binding phases, resulting in a porous structure with weak interfacial bonding between aggregate and binder components. This incomplete activation aligned with the established geopolymerization principles described by Provis and van Deventer, where an insufficient alkaline concentration restricted aluminosilicate dissolution and subsequent network formation.

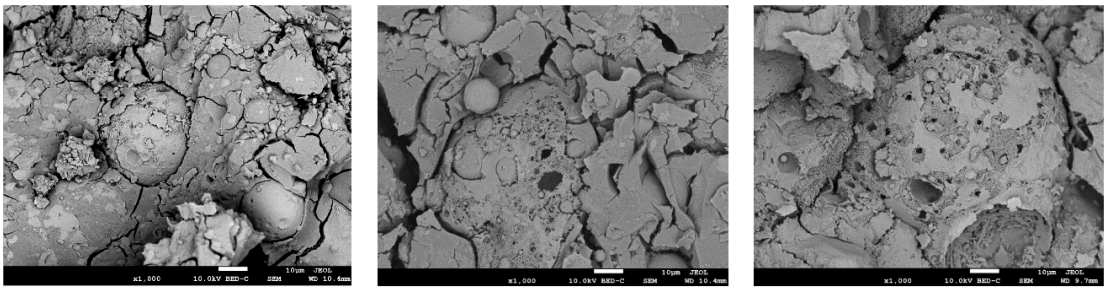


Figure 3.7 SEM images of RCA90BA10: (a) G/N ratio of 1:1, (b) G/N ratio of 1:1.5, and (c) G/N ratio of 1:2 at 28 days of curing.

The formulation with a G/N ratio of 1:1.5 shown in Figure 3.7b demonstrated significant microstructural advancement with enhanced geopolymer gel formation and improved matrix cohesion. The increased alkaline activator content promotes more complete dissolution of aluminosilicate precursors, resulting in abundant formation of calcium silicate hydrate (C-S-H) and sodium aluminosilicate hydrate (N-A-S-H) gel phases. The microstructure exhibits reduced porosity and more continuous binding networks, indicating improved activation efficiency consistent with the findings reported by Duxson et al. (PSWM Duxson et al., 2007) regarding optimal activator composition effects on matrix development.

Figure 3.7c presents the formulation with a G/N ratio of 1:2, which achieved the most advanced microstructural development characterized by extensive geopolymer gel formation and optimal matrix densification. The higher sodium silicate content promoted complete dissolution of bottom ash particles and facilitated the formation of well-integrated three-dimensional geopolymer networks. The microstructure demonstrated superior particle encapsulation and binding, creating a dense composite material with enhanced load transfer characteristics. This microstructural optimization validated the mechanical performance results and supported the geopolymerization mechanisms described by Fernández-Jiménez and Palomo (Kovalchuk, Fernández-Jiménez, & Palomo, 2007).

3.4.2.2 Microstructural Development in Systems with a High Bottom Ash Content

The examination of RCA60BA40 specimens revealed the challenges and optimization requirements associated with increased bottom ash utilization. Figure 3.8a demonstrates that the formulation with a G/N ratio of 1:1 produced inadequate microstructural development when applied to systems with a

higher bottom ash content. The SEM analysis revealed extensive microcracking, incomplete geopolymerization, and poor matrix cohesion, indicating that the activator concentration was insufficient for the elevated aluminosilicate content. This observation aligns with the research by Chindaprasirt et al.(Chindaprasirt et al., 2009), who established that bottom ash-based systems require enhanced activation to overcome inherent reactivity limitations.

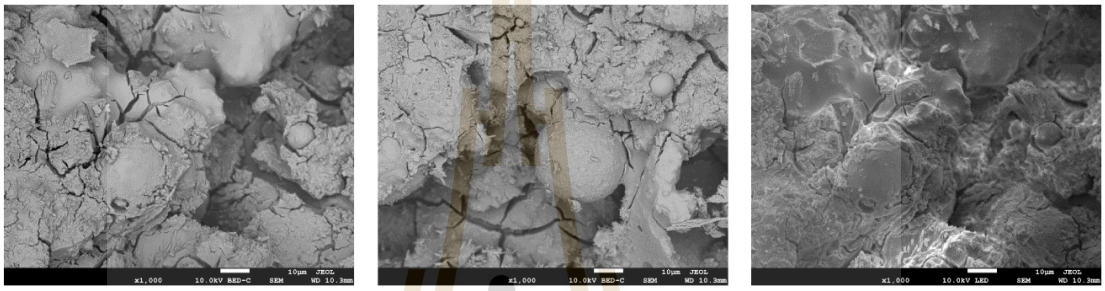


Figure 3.8 SEM images of RCA60BA40: (a) G/N ratio of 1:1, (b) G/N ratio of 1:1.5, and (c) G/N ratio of 1:2 at 28 days of curing.

The formulation with a G/N ratio of 1:1.5 shown in Figure 3.8b exhibited marked microstructural improvement with enhanced gel formation and reduced porosity compared to the lower activator ratio. The increased alkaline content promoted better dissolution of the higher bottom ash content, resulting in more extensive geopolymer network development. However, the microstructure still exhibited some limitations in terms of complete matrix integration, suggesting that further optimization remains beneficial for systems with a high bottom ash content.

Figure 3.8c presents the formulation with a G/N ratio of 1:2 applied to RCA60BA40, which demonstrated successful activation of the system with a high bottom ash content. The microstructure exhibited well-developed geopolymer networks with effective particle binding and matrix densification. The higher sodium silicate content provided sufficient alkaline activation to promote complete geopolymerization despite the increased aluminosilicate demand, resulting in microstructural characteristics comparable to systems with a lower bottom ash content. This finding validated the optimization approach described by Xu et al. (Xu & Van Deventer, 2000), who demonstrated that enhanced silicate availability becomes essential for systems with a high aluminosilicate content.

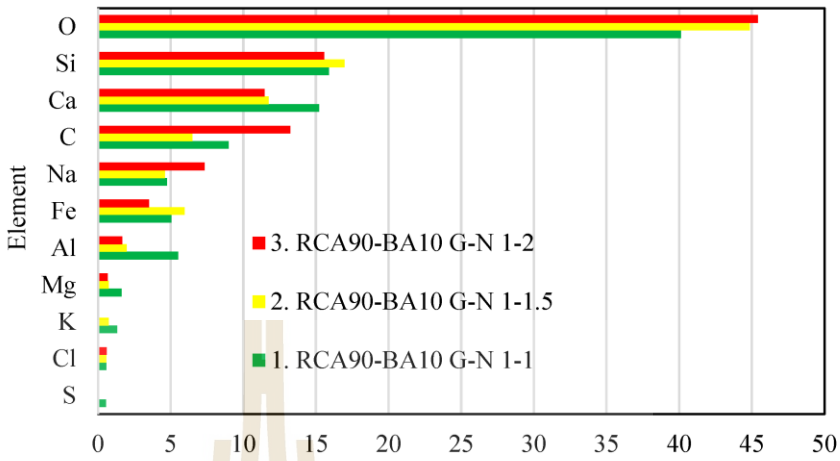
The SEM analysis indicated that the porous BA surface promotes extensive geopolymer gel coating and interfacial bonding, forming a continuous and relatively ductile gel network. This morphology enables microcrack bridging and deflection, forcing cracks to follow tortuous paths and dissipating more energy before failure. Although these BA-rich systems exhibit lower peak compressive strength due to reduced aggregate skeleton rigidity, the interconnected gel network facilitates gradual stress transfer post-peak, thereby improving energy absorption and post-failure ductility.

The microstructural evidence demonstrated that optimal geopolymer formation requires balanced dissolution of aluminosilicate precursors and adequate silicate availability for network formation. The formulation with a G/N ratio of 1:2 consistently produced superior microstructural characteristics across both bottom ash content levels, indicating that this activator composition provided optimal conditions for geopolymerization in waste-derived systems. The research by Singh and Subramaniam (Liu et al., 2022) supported these findings, demonstrating similar optimization requirements for alkali-activated systems with varying precursor compositions.

3.4.3 EDX Analysis

EDX analysis provides a quantitative assessment of elemental distributions within the geopolymer matrices and establishes critical relationships between chemical composition and mechanical performance. The systematic evaluation of the RCA90BA10 and RCA60BA40 systems across varying alkaline activator ratios revealed fundamental insights into geopolymerization chemistry and optimization principles for waste-derived construction materials.

The EDX analysis of RCA90BA10 specimens demonstrates systematic chemical composition changes that correlate directly with the observed mechanical performance improvements. Figure 9 reveals that oxygen constitutes the predominant element across all formulations, comprising approximately 45%–48% by weight, which reflects the extensive oxide formation essential for geopolymer network development. This high oxygen content indicates the successful formation of silicate and aluminate networks that constitute the structural backbone of the geopolymer matrix, consistent with the fundamental geopolymer chemistry principles established by Davidovits (Davidovits, 2005, 2008).



	S	Cl	K	Mg	Al	Fe	Na	C	Ca	Si	O
3. RCA90-BA10 G-N 1-2		0.60		0.68	1.68	3.51	7.34	13.24	11.48	15.57	45.41
2. RCA90-BA10 G-N 1-1.5		0.57	0.74	0.75	1.97	5.97	4.62	6.50	11.75	16.95	44.85
1. RCA90-BA10 G-N 1-1	0.56	0.57	1.32	1.63	5.51	5.05	4.74	8.99	15.22	15.90	40.12

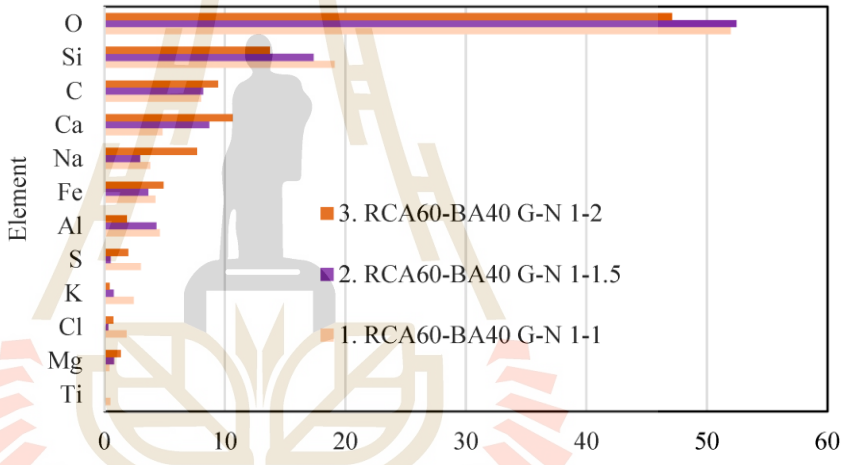
Figure 3.9 Chemical compositions of RCA90BA10 formulations at various G/N ratios.

The silicon content exhibited progressive increase with advancing G/N ratios, rising from approximately 12% in the formulation with a G/N ratio of 1:1 to 15% in that with a G/N ratio of 1:2. This enhancement is attributed to the increased availability of dissolved silicate species in higher G/N ratios, which promoted gel formation and improved strength development. The research by Fernández-Jiménez and Palomo (Kovalchuk et al., 2007) demonstrated that elevated silicate availability promotes more extensive polycondensation reactions, which explains the superior mechanical performance observed in formulations with a G/N ratio of 1:2. The concurrent increase in sodium content from 4% to 6% reflects the enhanced alkaline environment necessary for optimal aluminosilicate dissolution and subsequent geopolymer gel formation.

The calcium content demonstrated interesting variation across the G/N series, decreasing from approximately 11% in the formulation with a G/N ratio of 1:1 to 9% in that with a G/N ratio of 1:2. This trend indicates that calcium-based phases, primarily calcium silicate hydrate formations, become relatively less prominent as sodium aluminosilicate hydrate gel formation increased with enhanced silicate availability. The study by Yip et al (Yip et al., 2008). confirmed that balanced activator compositions promote synergistic formation of both calcium-based and sodium-based

gel phases, optimizing the hybrid binding characteristics observed in the superior performing formulations.

The EDX examination of RCA60BA40 specimens revealed distinct chemical composition patterns that reflect the challenges and optimization requirements associated with increased bottom ash utilization. Figure 3.10 demonstrates that the oxygen content remains consistently high across all formulations, indicating successful oxide network formation despite the elevated aluminosilicate content. However, the overall distribution of other elements exhibited different patterns compared to the RCA90BA10 system, highlighting the compositional adjustments required for optimal performance in formulations with a high bottom ash content.



	Ti	Mg	Cl	K	S	Al	Fe	Na	Ca	C	Si	O
3. RCA60-BA40 G-N 1-2		1.36	0.74	0.44	2.00	1.87	4.90	7.70	10.65	9.44	13.73	47.10
2. RCA60-BA40 G-N 1-1.5		0.82	0.34	0.77	0.52	4.33	3.66	2.97	8.71	8.19	17.37	52.47
1. RCA60-BA40 G-N 1-1	0.49	0.42	1.86	2.44	3.04	4.61	4.25	3.82	4.84	8.04	19.13	51.97

Figure 3.10 Chemical compositions of RCA60BA40 formulations at various G/N ratios.

The silicon content in RCA60BA40 systems indicated less pronounced variation across G/N ratios compared to RCA90BA10, ranging from approximately 13% to 16%. This more moderate increase implies that the higher aluminosilicate content from increased bottom ash provides additional reactive sites that consume the available silicate species more effectively. The research by Singh and Subramaniam (Singh & Subramaniam, 2017) established that systems with an elevated aluminosilicate content required enhanced silicate availability to achieve optimal Si/Al

ratios for geopolymer formation, which explained the mechanical performance improvements observed with higher G/N ratios in these formulations.

The sodium content progression in RCA60BA40 systems exhibited similar trends to RCA90BA10 but with slightly higher absolute values, reflecting the increased alkaline demand for activating the higher bottom ash content. The aluminum content showed moderate increases across the G/N series, consistent with the enhanced dissolution of aluminosilicate species from the bottom ash under more aggressive alkaline conditions. The study by Lahoti et al (Lahoti et al., 2018). demonstrated that optimal geopolymer formation required balanced dissolution of both silicate and aluminate species, which was achieved through careful activator optimization.

The Si/Al ratio analysis presented in Figure 3.11 provides critical insights into the geopolymerization optimization principles governing these waste-derived systems. The RCA90BA10 formulations demonstrated that the progressive Si/Al ratio increased from approximately 2.9 with a G/N ratio of 1:1 to 9.3 with a G/N ratio of 1:2, indicating enhanced silicate availability relative to the aluminate content. The research by Lahoti et al. established that Si/Al ratios in the range of 1.5 to 4.0 promote optimal geopolymer network formation, suggesting that the formulations with G/N ratios of 1:1 and 1:1.5 achieve more balanced stoichiometry for geopolymerization compared to the system with a G/N ratio of 1:2.

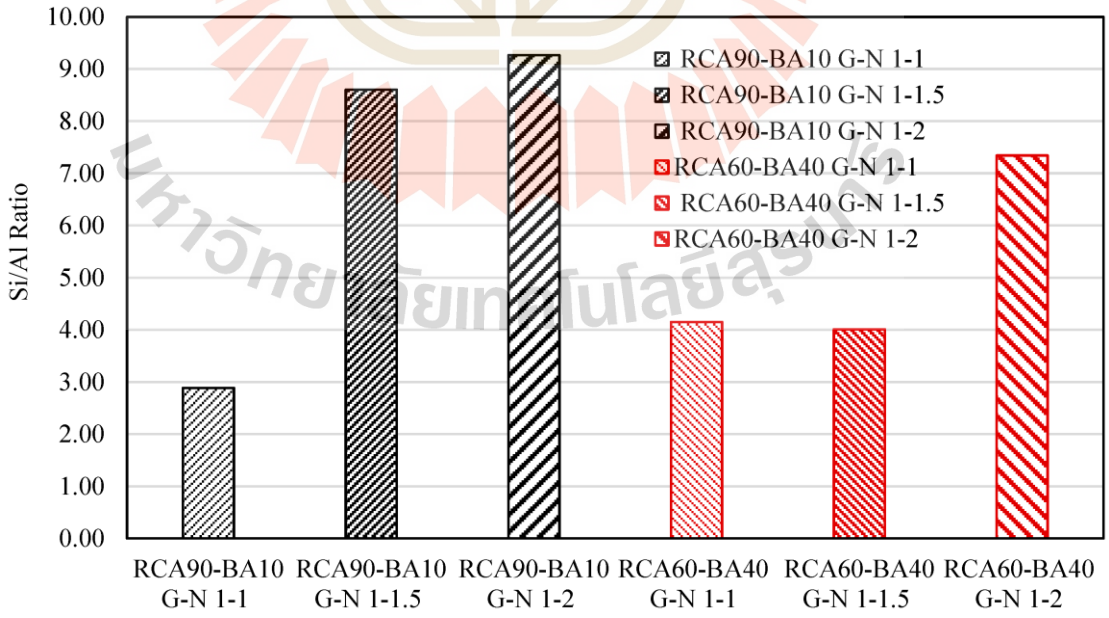


Figure 3.11 Si/Al ratios of RCA90BA10 and RCA60BA40 with various G/N ratios.

However, the mechanical performance results indicate that the formulation with the G/N ratio of 1:2 achieved superior strength characteristics despite the elevated Si/Al ratio. This apparent contradiction can be explained by the formation of hybrid gel systems that incorporate both sodium aluminosilicate hydrate and calcium silicate hydrate phases, as described by Cristelo et al. (Cristelo et al., 2012). The excess silicate availability in formulations with a G/N ratio of 1:2 promoted enhanced formation of calcium silicate hydrate phases that complement the primary geopolymer network, resulting in superior mechanical performance through synergistic binding mechanisms.

The RCA60BA40 systems exhibited lower Si/Al ratios across all G/N formulations, ranging from approximately 4.2 to 7.4, which reflected the higher aluminosilicate content from increased bottom ash utilization. These ratios remain within ranges that promote effective geopolymer formation while requiring higher activator concentrations to achieve optimal performance. The study by Liu et al. (Liu et al., 2022) confirmed that Si/Al ratios between 2.0 and 8.0 can produce effective geopolymer systems when properly activated, validating the mechanical performance improvements observed in optimized RCA60BA40 formulations.

3.4.4 XRD Analysis

The XRD analysis revealed systematic mineralogical transformations that directly correlate with the superior mechanical performance of RCA90BA10 formulations compared to RCA60BA40 systems. The diffraction patterns demonstrated clear evidence of geopolymerization progression and established the crystalline–amorphous phase relationships governing these waste-derived systems.

The XRD patterns in Figure 12 identified four primary crystalline phases across all formulations: quartz (SiO_2), calcite ($CaCO_3$), gehlenite ($Ca_2Al_2SiO_7$), and diopside ($CaO\text{-}MgO\text{-}SiO_2$). Quartz exhibited the most prominent peaks at 21°, 27°, and 50° 2θ, remaining stable throughout geopolymerization and serving as an inert aggregate framework. Calcite phases, originating from carbonated cement in the RCA, displayed characteristic peaks at 23°, 29°, and 36° 2θ and contributed to hybrid binding mechanisms through both physical and chemical interactions. The calcium-bearing phases (gehlenite and diopside) show evidence of partial dissolution, particularly in formulations with a higher G/N ratio, indicating their participation in secondary geopolymerization reactions (Cristelo et al., 2012; Kumar & Revathi, 2020).

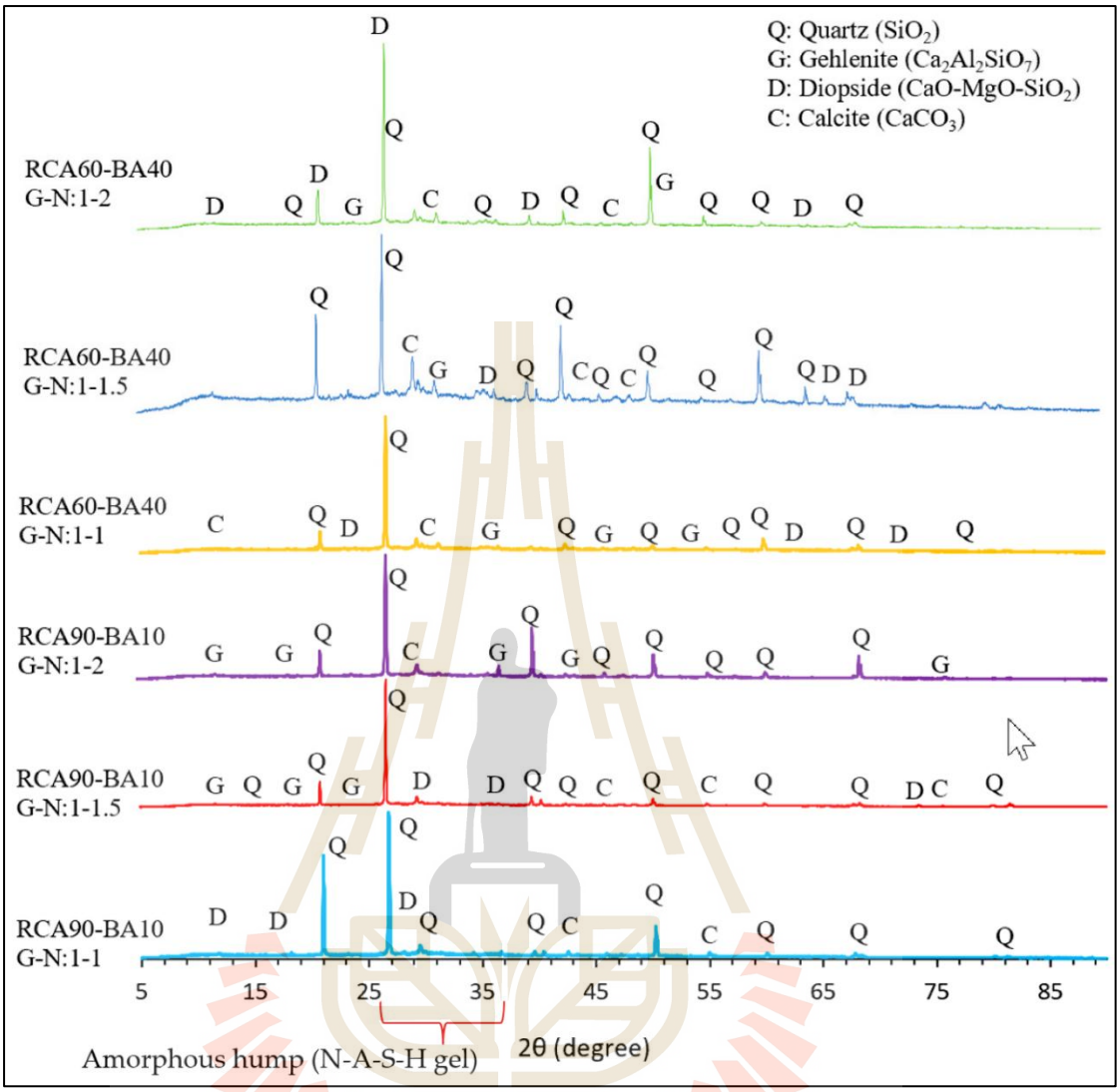


Figure 3.12 XRD patterns of RCA90BA10 and RCA60BA40 with various G/N ratios.

The most significant mineralogical indicator of successful geopolymerization appeared as a broad diffraction hump between 20° and 35° 2θ, representing amorphous sodium aluminosilicate hydrate gel formation. The RCA90BA10 series demonstrated optimal amorphous content development with progressive enhancement from a G/N ratio of 1:1 to 1:2, directly correlating with the superior UCS values achieved by these formulations. The RCA90BA10 composition with a G/N ratio of 1:2 exhibited the most pronounced and well-defined amorphous hump, corresponding to its exceptional compressive strength of 12.45 MPa at 28 days (El Alouani et al., 2024; Sinha, Kumar, & Kumar, 2014).

The comparison between the RCA90BA10 and RCA60BA40 systems revealed fundamental differences in mineralogical development that explain the superior performance of formulations with a lower bottom ash content. While RCA60BA40 compositions show evidence of amorphous gel formation, the patterns indicated less efficient geopolymerization compared to RCA90BA10 systems. The higher bottom ash content in RCA60BA40 formulations created challenges in achieving complete activation, resulting in more persistent crystalline phases and less extensive amorphous network development.

The RCA90BA10 formulations demonstrated a more refined amorphous content with sharper, more defined humps between 20° and 35° 2θ, indicating superior gel quality and network connectivity. This enhanced amorphous content directly correlated with the higher UCS values achieved by RCA90BA10 formulations across all G/N ratios. The research by Bobirică et al. (Bobirică et al., 2020) confirmed that an optimal bottom ash content enables more effective geopolymerization, supporting the observed performance superiority of the 10% bottom ash replacement level.

The correlation between amorphous content quality and mechanical strength established clear optimization principles for waste-derived geopolymer systems. The findings demonstrate that a controlled bottom ash content combined with appropriate alkaline activation enables superior mineralogical development and exceptional performance characteristics suitable for demanding pavement applications.

Compared to fly ash (FA)-based geopolymers, BA-based systems exhibit distinct differences in material characteristics and performance. FA consists of fine, spherical particles with high amorphous SiO_2 and Al_2O_3 contents, which enhance reactivity and promote extensive gel formation, resulting in higher UCS. It was seen that its UCS exceeded 15 MPa at 7 days under similar curing conditions (Tiyasangthong et al., 2022). Consequently, an increasing FA content generally leads to higher UCS due to the progressive development of C-S-H and N-A-S-H gels. In contrast, BA comprises coarser, angular, and more porous particles with higher crystalline quartz and calcite contents, which limit its reactivity. Increasing the BA content beyond 20% reduces UCS as the weaker BA particles and their higher crystalline fraction compromise the aggregate skeleton's load-bearing capacity despite additional gel formation. However, the BA-based geopolymer-stabilized RCA demonstrated adequate structural performance, meeting pavement base strength requirements even at 50% BA replacement, while offering enhanced toughness and significant sustainability benefits through the utilization of 100% waste-derived materials.

Utilizing 1 ton of RCA in place of natural aggregate can reduce landfill waste by approximately 0.8 tons and save up to 20–25 kg of CO_2 compared to virgin aggregate processing (Limbachiya, Meddah, & Ouchagour, 2012). Moreover, using BA in place of cement or virgin binders can further reduce CO_2 emissions by 150–200 kg of CO_2 per ton of cement avoided (Nakararoj et al., 2022). Therefore, the use of 100% waste-derived RCA and BA in this study potentially contributed to a reduction of over 200 kg of CO_2 emissions and diverted over 1.5 tons of industrial waste from the landfills per ton of stabilized base material produced.

3.5 Conclusions

This research successfully demonstrated the viability of BA-based geopolymer stabilized RCA as a high-performance, sustainable pavement subbase material utilizing 100% waste-derived components.

The formulation of RCA90BA10 with a G/N ratio of 1:2 achieved exceptional performance, reaching 9.14 MPa UCS at 7 days and exceeding the Department of Highways, Thailand, requirement of 2.413 MPa. All studied mixtures surpassed minimum specifications regardless of the alkaline activator ratio, demonstrating the robustness of the geopolymer stabilization approach. Toughness evaluation confirmed superior energy absorption capacity of 107.89 N·m for the optimal composition, indicating excellent durability for pavement applications.

Microstructural characterization revealed that higher G/N ratios promoted extensive sodium aluminosilicate hydrate and calcium silicate hydrate gel formation, creating dense matrices that directly correlated with mechanical performance. XRD analysis confirmed successful geopolymerization through pronounced amorphous gel development between 20° and 35° 2θ. The research established that RCA90BA10 achieved optimal balance between reactive aluminosilicate content and structural aggregate framework, while higher bottom ash contents beyond 10% resulted in systematic strength reduction.

The environmental benefits are substantial, with this technology diverting construction demolition waste and power plant byproducts from landfills while reducing greenhouse gas emissions compared to conventional cement-stabilized materials. The superior performance characteristics achieved through waste utilization provide compelling evidence for policy makers and industry practitioners to adopt geopolymer technology for sustainable infrastructure development.

This research advances sustainable construction materials technology by demonstrating that waste-derived geopolymer systems can exceed conventional

material performance while addressing critical environmental challenges, providing a viable pathway for next-generation pavement materials that balance structural requirements with environmental responsibility.

While this study demonstrates the mechanical suitability of BA-based geopolymer-stabilized RCA for pavement base applications, further durability validation is essential for real-world deployment. Future research should include freeze–thaw resistance, wet–dry cycling, water absorption, sulfate attack, and acid resistance testing to simulate environmental exposure conditions. In addition, future studies could apply ML models (e.g., ANN and RF) to predict strength and durability based on BA properties, mix ratios, and curing conditions, aiding in efficient design and quality control (Ramadan, Kassem, Elkordi, & Joumblat, 2025). Given the inherent porosity of BA and the alkaline nature of geopolymer matrices, these assessments will provide critical insights into the long-term integrity, dimensional stability, and chemical durability of the developed material in both temperate and tropical field conditions. Furthermore, the variability of BA from different power plants, driven by differences in fuel and combustion conditions, may influence its reactivity and strength development. To ensure consistent performance, source-specific characterization and mix design adjustments are recommended. Developing classification guidelines for BA could support broader and more reliable application in geopolymer stabilization.

The performance of RCA-BA geopolymer mixes can be influenced by the variability of RCA sources. Factors such as the original concrete strength, residual cement content, and particle porosity affect both mechanical properties and alkali activation potential. Stronger or less-weathered RCA may contribute to improved bonding and strength through continued hydration or secondary reactions, potentially shifting the optimal RCA:BA or G/N ratios. Therefore, mix designs should be tailored to specific RCA sources for consistent field performance.

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CHAPTER IV
METHODOLOGY
PERFORMANCE OF NATURAL RUBBER LATEX MODIFIED BOTTOM ASH-BASED GEOPOLYMER STABILIZED RECYCLED CONCRETE AGGREGATE AS A PAVEMENT SUBBASE MATERIAL

4.1 Introduction

Recently, geopolymers have gained prominence attention in the concrete industry, building material, road construction in pavement base/subbase layer, and several research studies have been conducted to address their short and long-term performances. Geopolymer is made of alkali-activated aluminosilicate materials such as FA, slag, rice husk ash, and bottom ash. Geopolymers are reported to produce low CO_2 emissions and energy consumption (Palomo, Grutzeck, & Blanco, 1999). These shortcomings have led to an attempt to explore novel low carbon stabilization methods. Geopolymer is an inorganic aluminosilicate material synthesized by alkaline activation of materials rich in alumina (Al_2O_3) and silica (SiO_2) and is considered as a green cementing agent. Geopolymerization involves the chemical reaction of alumino-silicate oxides by alkaline activation, yielding the polycondensation of the material in the three-dimensional silico-aluminate structure (Davidovits, 1991; Zhang, He, & Gambrell, 2010). Three typical structures of geopolymer are: Poly (sialate) type (-SiO-Al-O-), the Poly (sialatesiloxo) type (-Si-O-Al-O-Si-O-), and the Poly (sialate-disiloxo) type (-Si-O-Al-O-Si-O-Si-O-). Geopolymer has in recent years been used to stabilize natural soils to develop green building materials such as masonry products. It was reported that geopolymer based materials possess higher compressive strength and durability against sulfate than cement based materials (Sukmak, De Silva, Horpibulsuk, & Chindaprasirt, 2015; Sukmak, Horpibulsuk, & Shen, 2013; Sukmak, Horpibulsuk, Shen, Chindaprasirt, & Suksiripattanapong, 2013). Recently, (Suksiripattanapong, Horpibulsuk, Chanprasert, Sukmak, & Arulrajah, 2015) and (Horpibulsuk, Suksiripattanapong, Samingthong, Rachan, & Arulrajah, 2016) successfully stabilized water treatment sludge using fly ash based geopolymer to develop sustainable non-structural and bearing masonry units. It was illustrated that the geopolymer is more effective than PC in stabilizing the water treatment sludge with high alum content. The strength and

durability of sludge-geopolymer masonry units is significantly higher than sludge-cement masonry units.

Highway construction is an important aspect in infrastructure construction in many developed and developing countries. Highway construction however consumes a large amount of natural quality aggregates, particularly in their pavement base/subbase layers. As a result, the quarries and gravel pits are increasingly exploited as a source of pavement materials, which notably leads to subsequent devastating of natural environmental resources. The urgent need for new environmentally friendly solutions have made researchers explore new alternative materials that will reduce energy consumption, and greenhouse gas emissions (Hoy, Horpibulsuk, Rachan, Chinkulkijniwat, & Arulrajah, 2016). Highway pavement generally consists of base, subbase, and engineering fill layers, which are typically constructed from suitable materials such as crushed rock and lateritic soil. The government of Thailand's current priority is in the economic expansion of the country over the next decade and has allocated a large budget for the construction of roadway networks across the country. A number of road infrastructure projects have been implemented to construct transportation systems, particularly in rural areas. Heavy rain during the rainy season frequently causes flooding problems in some regions of Thailand. Hence, road embankments in the country must have an adequate thickness and must also be constructed with durable pavement materials. In general, the subbase/base layer is typically 50–70 cm in thickness, to ensure the road profile is above the flood level. Road construction consumes a vast amount of high-quality materials. The transportation of high-quality imported materials from distant sources increases the road construction cost considerably. Furthermore, transportation of imported materials significantly increases road maintenance costs and the carbon footprint. The utilization of local resources at the road construction site is thus beneficial from both economic and environmental aspects, which is an approach that is strongly encouraged by the Department of Rural Roads and the Department of Highways, Thailand (Sukprasert et al., 2021). The scientific and practical methodologies and outcomes from previous research have been reviewed and summarized in this paper in order to make a new illuminating study on cleaner production as well as to assure that waste materials can be mixed with soil as an intuitive practitioner interface technique in pavement applications (Sudla et al., 2018). For each road construction materials BA was used in highway embankment construction offers an attractive alternative to disposal because substantial economic savings can be attained by the reduction of ash disposal costs and the conservation of natural soils and lands, pavement construction (Gautam, Kalla,

Jethoo, Agrawal, & Singh, 2018; López-López, Vega-Zamanillo, Calzada-Pérez, & Taborga-Sedano, 2015; Yoo, Park, & Vo, 2016) and aggregate replacement in concrete pavement production (Arenas, Marrero, Leiva, Solís-Guzmán, & Arenas, 2011; Hannan et al., 2020; Ibrahim, Hamzah, Jamaluddin, Ramadhansyah, & Fadzil, 2015).

Within the context of sustainable material innovation, the integration of NRL modified bottom ash in geopolymer stabilization of RCA opens new avenues for high-performance base materials. The inclusion of NRL in the bottom ash geopolymer matrix introduces unique properties to the pavement base material. NRL, known for its elasticity and water resistance, imparts flexibility and resilience to the geopolymer-stabilized RCA. This modification is particularly beneficial for pavement applications, where materials are subjected to dynamic loads and environmental stresses. The NRL not only helps to absorb and distribute these loads more effectively, reducing the risk of cracking, but also provides a barrier against moisture infiltration, enhancing the durability of the pavement base.

Geopolymer is formed though the reaction of an aluminosilicate source, such as bottom ash (precursor), with an alkaline activator solution containing sodium hydroxide (NaOH) and solidum silicate (Na_2SiO_3). The alkaline activator solutions were prepared with various Na_2SiO_3:NaOH (G/N) ratios of 1:1, 1:1.5, and 1:2, while the mixtures were modified with NRL at contents of 0.1, 0.2, and 0.3 by weight of the aggregate. The unconfined compressive strength (UCS) test was carried out to determine the strength of the studied mixtures at 7 and 28 days of curing. The strength development was examined through the microstructural and mineralogical analyses using scanning electron microscopy (SEM), energy dispersive x-ray spectroscopy (EDS), and x-ray diffraction (XRD), respectively.

4.2 Materials and methods

4.2.1 Recycle Concrete Aggregate (RCA)

Recycled concrete aggregate (RCA) and bottom ash (BA) were used as waste materials in this research. RCA was collected from construction projects in Ubonratchatani and Sisaket Provinces, Thailand. The RCA had low moisture content (less than 0.3 wt%). Particle size distribution of air-dried RCA was determined by sieve analysis per ASTM-D422-63 (Testing & Materials, 2002). Figure 4.1 shows that the grading curve of RCA met specifications for pavement base material designated by the Department of Highways (DOH), Thailand. RCA had 48.6% gravel, 47.9% sand, and 3.5% fines (passing No. 200 sieve) and no plasticity. Based on the unified soil classification system (USCS) (ASTM-D2487-17, 2017), RCA was classified as well-graded gravel (GW).

The specific gravity of RCA was found to be 2.7. RCA had Los Angeles abrasion and flakiness index values of 38.1 and 15.6, respectively. The maximum dry unit weight was 18.70 kN/m^3 at an optimum moisture content of 12% based on a modified Proctor compaction test. Coarse and fine RCA water absorption was 6.42% and 7.83%, respectively.

The gradation of RCA was investigated by dry sieve analysis ASTM D422- 63. The grain size distribution curve of RCA complied with the grading limits for subgrade material Type D as shown in Figure 4.1 From the sieve analysis (% that passes through No. 200 sieve) and consistency limits (no plasticity), the RCA was classified as GP-SW according to the Unified Soil Classification System ASTM D2487. This is the group of poorly graded gravel to well-graded sand.

4.2.2 Bottom ash (BA)

Lignite bottom ash (BA) was sourced from the Mae Moh mine, the largest lignite power plant in northern Thailand, operated by the Electricity Generating Authority of Thailand (EGAT). BA particles were irregularly shaped with agglomerations, pores, and angular, rough surfaces, as observed by scanning electron microscopy (SEM) analysis Figure 4.1 and Table 3.1 summarizes the chemical composition of BA detected by X-ray fluorescent (XRF) analysis. The predominant component in the BA comprises the highest percentage of silicon dioxide (59.50%), which is a key ingredient that contributes to the pozzolanic activity of the ash. Followed by aluminum oxide (25.7%), which plays a crucial role in the geopolymerization process, reacting with the silicon dioxide and alkaline activator to form the geopolymer matrix. Constituting a low percentage (2.92%) of the ash, calcium oxide is known to affect the setting time and strength development in geopolymer.

Table 4.1 Chemical compositions of bottom ash.

Component (%)	Value
Silicon dioxide (SiO_2)	59.50
Aluminum oxide (Al_2O_3)	25.70
Iron oxide (Fe_2O_3)	6.07
Calcium oxide (CaO)	2.92
Magnesium oxide (MgO)	0.80
Potassium oxide (K_2O)	1.56

Lignite bottom ash came from the Mae Moh power station in the north of Thailand, This is the largest lignite power plant and is operated by the Electricity Generating Authority of Thailand (EGAT) used in this research, fresh bottom ash as shown in Figure 4.2 The as-received BA particles were relatively large and very irregular showing agglomeration of some spherical particles and other fragments with observable pores as shown in Figure 4.3(a). The particle shape and the size distribution were examined by scanning electron microscopy (SEM), and the chemical composition was determined by energy dispersive spectroscopy (EDS), and shown in Figure 4.3(b) respectively. The SEM images revealed that the particles were irregular with agglomeration of spherical particles and some angular and rough particles. The size distribution was similar to that of sand

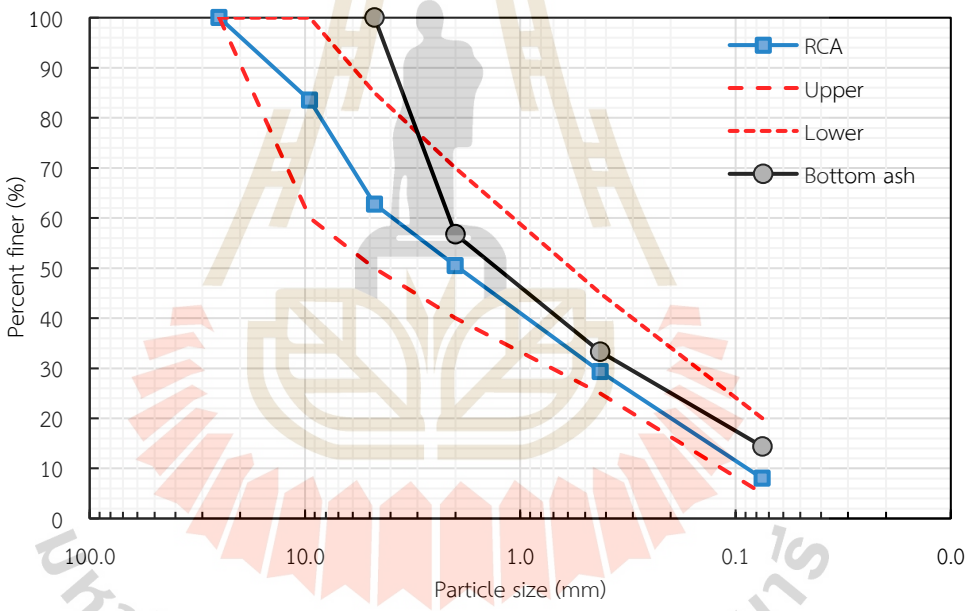


Figure 4.1 Grain size distribution of RCA and Bottom ash.

The gradation of BA was investigated by dry sieve analysis (ASTM D422- 63) (ASTM, 2007). The grain size distribution curve of BA complied with the grading limits for subgrade material Type D as per DH-S 205–1989 as shown in Figure 4.1 From the sieve analysis (% that passes through No. 200 sieve) and consistency limits (no plasticity), the BA was classified as SW-SM according to the Unified Soil Classification System (ASTM D2487) (ASTM, 2007). This is the group of well-graded sand with silty fines.

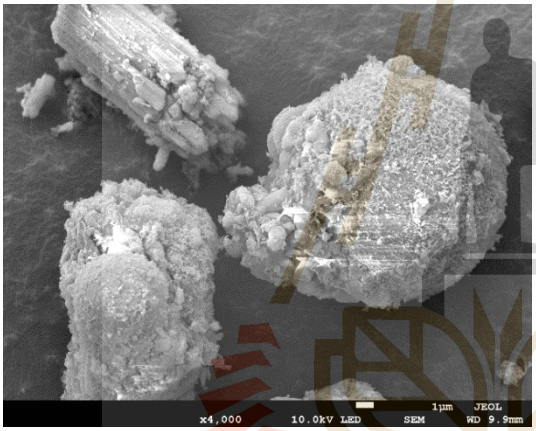


(a) Mea Moh power plant Thailand

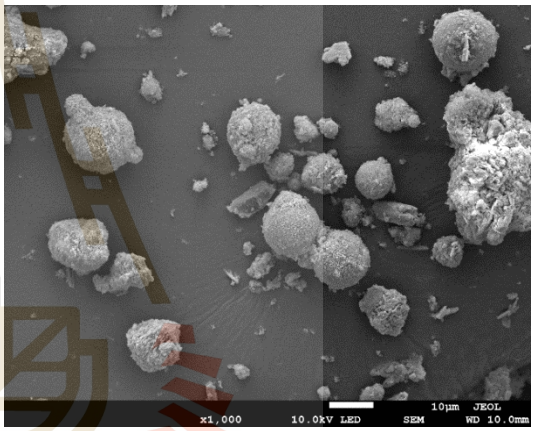


(b) Ground bottom ash

Figure 4.2 Fresh Bottom ash at Mea Moh power plant, Thailand.



(a) As-received bottom ash



(b) ground bottom ash

Figure 4.3 SEM of as-received bottom ash and ground bottom ash (a) As-received bottom ash and (b) ground bottom ash.

Figure 4.4 illustrates the X-ray diffraction (XRD) pattern of BA. The peak intensities, denoted by their counts, show the relative abundance of the minerals, with gehlenite and diopside being the most prominent. The diversity of crystalline phases indicates that the BA can provide a key role when used as a precursor in geopolymer production, contributing to the mechanical properties.

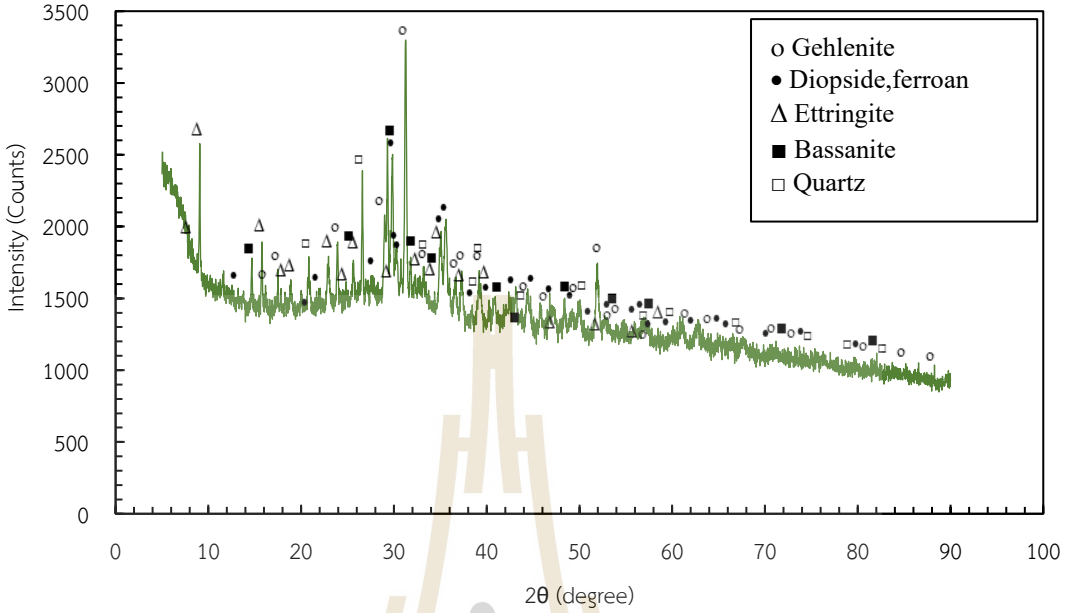


Figure 4.4 XRD pattern of bottom ash.

4.2.3 Natural rubber latex (NRL)

The natural rubber latex (NRL) used in this study was of a low ammonia concentrated latex type, conforming to the ISO 2004-1988 standard. The NRL was used as an additive to enhance the properties of BA-based geopolymer stabilized RCA. NRL was treated with deproteinization agent to remove allergenic proteins, improve latex stability, enhance compatibility with other components, and ultimately contribute to better mechanical properties in the final product. The NRL in this study was in a liquid form, containing both solid and liquid constituents. The total slid content of NRL accounted for 33.06% of its weight, comprising primarily of dry rubber (30.8%), sludge (2.46%), and a minimal coagulum content (0.024%). The specific gravity and pH of the NRL were 0.96 and 8, respectively.

4.2.4 Alkaline activator

The formulation of the alkaline activator was a critical step in the geopolymer preparation process. It required careful consideration of the chemical composition to ensure effective geopolymerization while minimizing potential hazards. In this study, an alkaline activator was formulated by blending sodium silicate (Na_2SiO_3) solution with 5M sodium hydroxide (NaOH) solution. The selected Na_2SiO_3 was Type CR53, which contained about 14.5-16.5 wt% Na_2O (sodium oxide) and 31.5-34 wt% SiO_2 (silicon dioxide), providing an optimal balance of silica and sodium necessary for the

geopolymerization process. The selection of a 5M NaOH solution was particularly informed by considerations regarding human safety and handling hazards. Previous study (Chindaprasirt, Jaturapitakkul, Chalee, & Rattanasak, 2009) have indicated that higher concentrations of NaOH can pose increased risks due to its highly caustic nature. Hence, the 5M concentration was deemed effective in initiating the dissolution of aluminosilicate materials while maintaining a safer profile for practical use.

4.2.5 Mix design and sample preparation

The mix design for this study was systematically developed to evaluate the impact of NRL modification on the properties of BA-based geopolymer stabilized RCA (Table 2). The design involved creating a series of mixtures with varying NRL content and alkaline activator ratios to establish a comprehensive understanding of their individual and combined effects on the geopolymer's performance.

The control mix, designated as RCA70BA30, consisted of 70% RCA and 30% BA by weight, mixed solely with water without any alkaline activator or NRL. This baseline mixture was intended to assess the fundamental properties of the RCA-BA blend.

A series of NRL-modified mixtures were prepared with a constant Na_2SiO_3/NaOH (G/N) ratio of 1, while the NRL content was varied at 0.1%, 0.2%, and 0.3% by weight of aggregate (sample IDs: GN1/1NRL0.1, GN1/1NRL0.2, and GN1/1NRL0.3). Additional mixtures were designed with increased Na_2SiO_3/NaOH (G/N) ratios of 1.5 to 2, with corresponding NRL contents of 0.1%, 0.2%, and 0.3%, respectively (Sample IDs: GN1/1.5NRL0.1, GN1/1.5NRL0.2, GN1/1.5NRL0.3, and GN1/2NRL0.1, GN1/2NRL0.2, GN1/2NRL0.3).

The RCA and BA were first dry-mixed to achieve a uniform distribution. The alkaline activator solution was then gradually added to the dry mixture and mixed until a homogenous mixture was obtained. Then, NRL was added to the mixture in the predetermined percentage, ensuring thorough blending for even distribution within the mixture. The resulting mixtures were cast into the cylindrical mold with 101.6 mm in diameter and 116.4 mm in height. Each mixture was compacted under a modified Proctor compaction effort to determine its maximum dry density (MDD) and optimum liquid content (OLC). The sample was then prepared at MDD and OLC of each studied mixture for unconfined compressive strength test. Samples were covered with plastic sheeting to prevent moisture loss and cured at room temperature for 24 hours before demolding. After demolding, the samples were further cured at room temperature (25 ± 2°) until the testing ages at 7 and 28 days.

4.3 Mix design and sample preparation

The mix design for this study was systematically developed to evaluate the impact of NRL modification on the properties of BA-based geopolymer stabilized RCA (Table 4.2). The design involved creating a series of mixtures with varying NRL content and alkaline activator ratios to establish a comprehensive understanding of their individual and combined effects on the geopolymer's performance.

Table 4.2 The mix design of NRL-modified BA-based geopolymer stabilized RCA

Sample ID	Mixture ingredient	Alkaline Activator	NRL (%)
		$NaOH/Na_2SiO_3$ (G/N) ratio	By weight of aggregate
70RCA30BA	70RCA + 30BA + water (Control)	-	-
G/N1:1NRL0.1	70RCA + 30BA + (1) NaOH + (1) Na_2SiO_3 + NRL (0.1)	1	0.1
G/N1:1NRL0.2	70RCA + 30BA + (1) NaOH + (1) Na_2SiO_3 + NRL (0.2)	1	0.2
G/N1:1NRL0.3	70RCA + 30BA + (1) NaOH + (1) Na_2SiO_3 + NRL (0.3)	1	0.3
G/N1:1.5NRL0.1	70RCA + 30BA + (1) NaOH + (1.5) Na_2SiO_3 + NRL (0.1)	1.5	0.1
G/N1:1.5NRL0.2	70RCA + 30BA + (1) NaOH + (1.5) Na_2SiO_3 + NRL (0.2)	1.5	0.2
G/N1:1.5NRL0.3	70RCA + 30BA + (1) NaOH + (1.5) Na_2SiO_3 + NRL (0.3)	1.5	0.3
G/N1:2NRL0.1	70RCA + 30BA + (1) NaOH + (2) Na_2SiO_3 + NRL (0.1)	2	0.1
G/N1:2NRL0.2	70RCA + 30BA + (1) NaOH + (2) Na_2SiO_3 + NRL (0.2)	2	0.2
G/N1:2NRL0.3	70RCA + 30BA + (1) NaOH + (2) Na_2SiO_3 + NRL (0.3)	2	0.3

The control mix, designated as RCA70BA30, consisted of 70% RCA and 30% BA by weight, mixed solely with water without any alkaline activator or NRL. This baseline mixture was intended to assess the fundamental properties of the RCA-BA blend.

A series of NRL-modified mixtures were prepared with a constant Na_2SiO_3/NaOH (G/N) ratio of 1, while the NRL content was varied at 0.1%, 0.2%, and 0.3% by weight of aggregate (sample IDs: GN1/1NRL0.1, GN1/1NRL0.2, and GN1/1NRL0.3). Additional mixtures were designed with increased Na_2SiO_3/NaOH (G/N) ratios of 1.5 to 2, with corresponding NRL contents of 0.1%, 0.2%, and 0.3%, respectively (Sample IDs: GN1/1.5NRL0.1, GN1/1.5NRL0.2, GN1/1.5NRL0.3, and GN1/2NRL0.1, GN1/2NRL0.2, GN1/2NRL0.3).

The RCA and BA were first dry-mixed to achieve a uniform distribution. The alkaline activator solution was then gradually added to the dry mixture and mixed until a homogenous mixture was obtained. Then, NRL was added to the mixture in the predetermined percentage, ensuring thorough blending for even distribution within the mixture. The resulting mixtures were cast into the cylindrical mold with 101.6 mm in diameter and 116.4 mm in height. Each mixture was compacted under a modified Proctor compaction effort to determine its maximum dry density (MDD) and optimum liquid content (OLC). The sample was then prepared at MDD and OLC of each studied mixture for unconfined compressive strength test. Samples were covered with plastic sheeting to prevent moisture loss and cured at room temperature for 24 hours before demolding. After demolding, the samples were further cured at a room temperature (25±2°C) until the testing ages at 7 and 28 days.

4.3.1 Laboratory Experimental Program

The experimental program was meticulously designed to evaluate the mechanical and microstructural properties of NRL-modified BA-based geopolymer stabilized RCA. The program consisted of two main testing categories: mechanical tests and microstructural analysis.

4.3.2 Modified compaction test

Sample were prepared in accordance with the modified Proctor compaction test according to the ASTM D1557 (ASTM, 2012) (ASTM-D1557-12, 2012; ASTM, 2012), ensuring optimal compaction and consistent density across all samples. The compaction procedure was instrumental in simulating field compaction conditions and providing samples that represent the maximum dry density (MDD) and optimal liquid content (OLC).

4.3.3 Unconfined compressive strength

Following curing at 7 and 28 days, the samples were subjected to an unconfined compressive strength (UCS) test. The UCS test was conducted in compliance with ASTM D2166 (ASTM-D2166-06, 2006), providing a measure of the material's strength when subjected to axial loading conditions. The test was performed

at a rate of 1mm/min to track the strength development of the geopolymer over time. The peak load at failure was recorded, and the compressive strength was calculated to assess the NRL's contribution to the overall structural integrity of the geopolymer matrix.

4.3.4 Scanning Electron Microscopy (SEM) analysis

Scanning electron microscopy (SEM) analysis was employed to visualize the microstructure of the geopolymer samples at a high magnification. This analysis provides insights into the distribution of NRL within the matrix, the bonding at the RCA-BA interface, and the morphology of the geopolymer binder. The SEM examination was conducted on fractured of samples post-UCS testing to identify the failure mechanisms and to correlate the mechanical test results with the microstructural characteristics.

4.3.5 X-Ray Diffraction (XRD) analysis

X-ray diffraction (XRD) analysis was utilized to identify the crystalline phases present within the geopolymer matrix and to observe the changes in mineralogy due to the addition of NRL and variation in the alkaline activator mixture. The XRD patterns were collected using a diffractometer, with samples being scanned in a 2Theta range typically between 5° and 80°. The resultant diffractograms were analyzed to determine the presence of specific crystalline compounds and to infer the geopolymerization process's effectiveness.

4.4 Results and Discussion

4.4.1 Unconfined compressive strength development

The unconfined compressive strength (UCS) results, as shown in Figure 4.5, demonstrate the influence of NRL content and alkaline activator ratio on the strength development of BA-based geopolymer stabilized RCA mixtures at 7 and 28 days of curing.

At 7 days, the UCS values of the NRL-modified mixtures ranged from 1.30 to 4.05 MPa, while the control mix (RCA70BA30 blend) exhibited a UCS of 0.63 MPa. The highest UCS was achieved by the mixture with 0.1% NRL and a G/N ratio of 1:1, followed by the mixtures with 0.2% and 0.3% NRL at the same G/N ratio. This trend suggests that a lower NRL content and a balanced G/N ratio contribute to better early-age strength development.

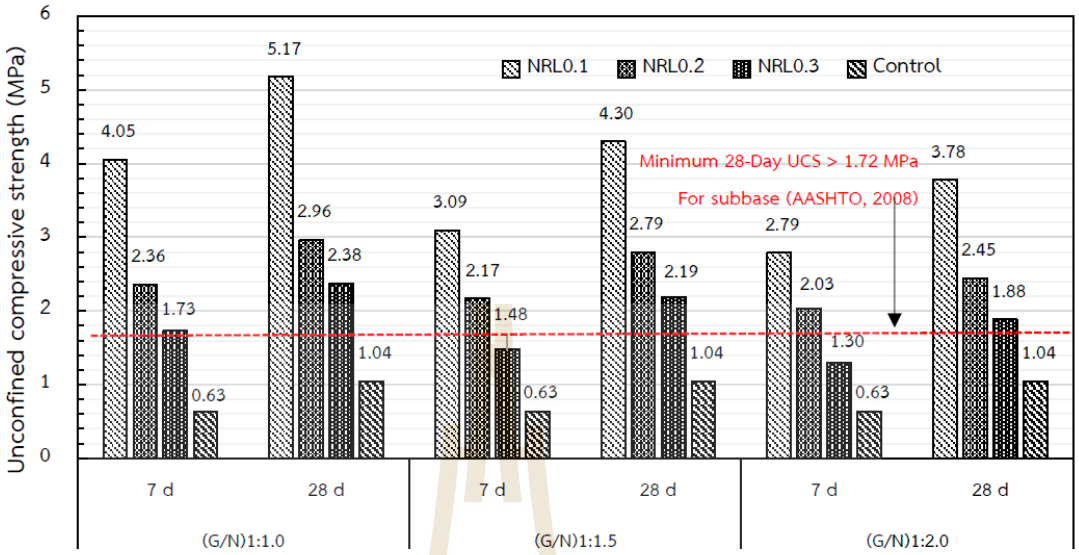


Figure 4.5 UCS of NRL-modified BA-based geopolymer stabilized RCA samples.

After 28 days of curing, the UCS values of the NRL-modified mixtures increased significantly, ranging from 1.88 to 5.17 MPa, while the control mix reached 1.04 MPa. The mixture with 0.1% NRL and a G/N ratio of 1:1 continued to exhibit the highest UCS, indicating its optimal composition for strength development. The mixtures with higher G/N ratios (1:1.5 and 1:2) showed relatively lower UCS values compared to those with a G/N ratio of 1:1 This implies that an excessive amount of sodium silicate in the alkaline activator may hinder the strength gain. This may be due to the optimal silica to alumina ratio, which is critical in forming a strong geopolymer network. However, as the silica content increased in the activator solution (G/N ratio of 1:1.5 and 1:20), the UCS values tended to decrease. This decrease could be attributed to an excess of silica leading to a less reactive system where the silica is not effectively utilized, resulting in a weaker matrix.

The American Association of State Highway and Transportation Officials (AASTHO) provides guidance on the minimum strength requirements for pavement layers in their mechanics-empirical pavement design guide (MEPDG), which indicates that the minimum 28-day UCS requirement for a subbase material is 1.72 MPa (AASHTO, 2008). This strength criterion ensures that the subbase layer possesses sufficient bearing capacity and stability to support the upper pavement layers and distribute the traffic loads effectively to underlying layers.

Figure 4.5 evident that all the NRL-modified BA-based geopolymer stabilized RCA mixtures, irrespective of the G/N ratio (1:1, 1:1/5, and 1:2) or NRL content (0.1%, 0.2, and 0.3%), surpass the minimum requirement of 1.72 MPa specified by AASHTO (2008) for subbase materials. It is noteworthy that even the control mixture (RCA70BA30 blend without geopolymer or NRL modification) achieves a 28-day UCS of 1.0 MPa, which is lower than the minimum requirement of 1.72 MPa for subbase materials. This indicates the significant enhancement in strength and performance brought about by the NRL-modified BA-based geopolymer stabilization of the RCA.

The synergistic effect of the alkaline activator ratio (G/N) and NRL content on the strength development of BA-based geopolymer stabilized RCA mixture is evident from the UCS results. The combination of a lower G/N ratio and an optimal NRL content leads to a remarkable improvement in the mechanical properties of the stabilized mixtures. The lower G/N ratio of 1:1 ensures a sufficient concentration of sodium hydroxide, which is essential for the dissolution of the aluminosilicate precursors and the formation of a stable geopolymer gel. Simultaneously, the presence of NRL at an optimum content of 0.1% or 0.2% improves the adhesion between the RCA particles and the geopolymer matrix, resulting in a more compact and resilient structure. This synergistic effect is particularly evident when comparing the UCS values of the mixtures with different G/N ratios and NRL contents. The mixture with 0.1% NRL at a G/N ratio of 1:1 achieved the highest UCS of 4.05 MPa at 7 days and 5.17 MPa at 28 days, surpassing the minimum requirements for both low-volume and high-volume traffic pavements. In contrast, mixtures with higher G/N ratios or excessive NRL contents showed relatively lower UCS values, indicating the importance of optimizing both parameters simultaneously.

The synergy between the G/N ratio and NRL content not only enhances the strength development but also contributes to the overall performance and durability of the stabilized mixtures. The optimized combination of these two factors results in a geopolymer matrix with improved bonding, flexibility, and resistance to cracking, which are crucial for the long-term performance of pavement base materials.

These results highlight the effectiveness of NRL modification in enhancing the strength properties of BA-based geopolymer stabilized RCA mixtures. The incorporation of NRL improves the bonding between the RCA and the geopolymer matrix, leading to better load transfer and high compressive strength. The optimal NRL content and G/N ratio identified in this study, particularly the mixture with 0.1% NRL at a G/N ratio of 1:1, demonstrate the potential for developing high-performance and

sustainable pavement base materials that can meet the strength requirements for both low-volume and high-volume traffic pavements.

4.4.2 Microstructural Analysis

The scanning electron microscopy (SEM) analysis provides valuable insights into the microstructural characteristics of the NRL-modified BA-based geopolymer stabilized RCA mixtures. The SEM images illustrate the influence of the G/N ratio and NRL content on the morphology, bonding, and formation of geopolymer products within the matrix.

4.4.3 Effect of G/N ratio on microstructural property

The effect of the G/N ratio on the microstructure is illustrated in Figure 4.6, which presents the SEM images of the control mixture (RCA70BA30) and NRL-modified BA-based geopolymer mixtures with varying G/N ratios (1:1, 1:1.5, and 1:2) at a constant NRL content of 0.1%. The control mixture (Figure 4.6a) exhibits a relatively porous and heterogeneous microstructure, with visible voids and weak bonding between the RCA and BA particles, which corresponds with its lower UCS values as shown in Figure 4.5. In contrast, the NRL-modified BA-based geopolymer mixture with a G/N ratio of 1:1 (Figure 4.6b) shows a more compact and denser microstructure, with enhanced bonding between the RCA particles and the matrix. This improvement in microstructural properties can be attributed to the balanced composition of the alkaline activator (G/N), which facilitates effective geopolymerization and the formation of stable geopolymer products, such as calcium aluminosilicate hydrate (C-A-S-H) and sodium aluminosilicate hydrate (N-A-S-H) gels (Provis & Van Deventer, 2009; Yip, Lukey, Provis, & Van Deventer, 2008).(Santa, Padoin, Soares, and Riella (2021) indicated that the geopolymerization of the BA-based geopolymer involves the dissolution of the aluminosilicate material such as BA in an alkaline activator solution, followed by the polycondensation of the leached Al and Si species to form the geopolymer gels. The presence of these gels is critical for the strength development and durability of the geopolymer matrix (Davidovits, 2005; Peter Duxson et al., 2007; Duxson, Mallicoat, Lukey, Kriven, & Van Deventer, 2007). The NRL films can be observed as thin, bridging structures that enhance the interfacial bonding between the RCA particles and the geopolymer gel products.

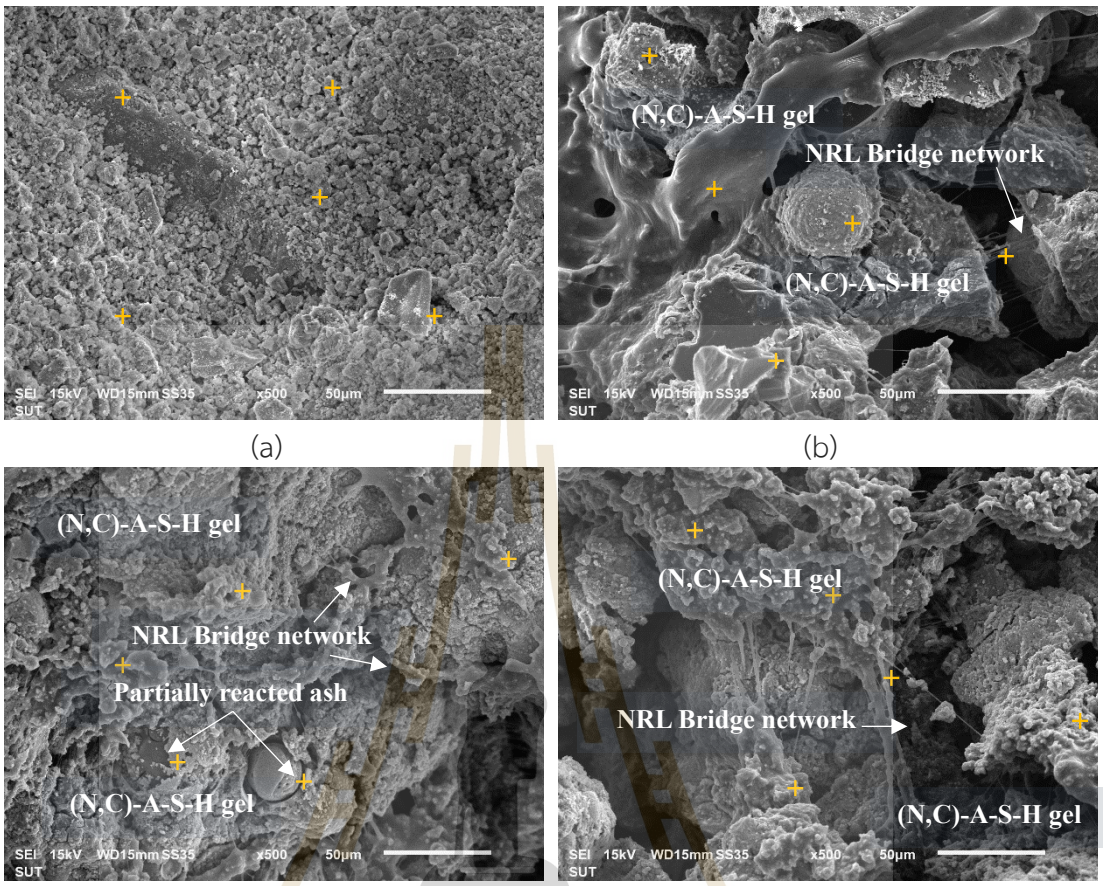


Figure 4.6 SEM-EDX analysis of NRL-modified BA-based geopolymer stabilized RCA samples: a) RCA70BA30 (Control), b) G/N1:1.0NRL0.1, c) G/N1:1.5NRL0.1, and d) G/N1:2.0NRL0.1.

As the G/N ratio increases to 1:1.5 (Figure 4.6c) and 1:2 (Figure 4.6d), the NRL films are still present, acting as bridging structures, but the overall microstructure is notably change compared to the mixture with a G/N ratio of 1:1. It is found that an overly high silica content can lead to the formation of a silica-rich gel layer on the surface of the BA and RCA particles, hindering the further dissolution of aluminosilicate species and resulting in an incomplete geopolymerization reaction. In other word, the excess soluble silica provided by the sodium silicate (Na_2SiO_3) contributes to the formation of a more silica-rich gel, known as poly(sialate-siloxo) or PSS gel (Bhagath Singh & Subramaniam, 2017; Kim, Dang, & Do, 2016; M, R, & P, 2021). It can form a barrier layer on the surface of the unreacted particle, lead to weaken the overall strength and integrity of the geopolymer matrix.

The EDX analysis presented in Table 4.3 provides insights into the elemental composition of the NRL-modified BA-based geopolymer stabilized RCA mixtures. The major elements analyzed include carbon (C), oxygen (O), iron (Fe), sodium (Na), calcium (Ca), aluminum (Al), and silicon (Si). Several research reported that Si/Al ratio is a crucial parameter influencing the geopolymerization process and the properties of the resulting geopolymer (Davidovits, 2005; Peter Duxson et al., 2007; PSWM Duxson et al., 2007). The control mixture, consisting of 70%RCA and 30%BA without any geopolymer or NRL, serves as a baseline for comparison. The EDX analysis reveals that the control mixture has a high Si/Al ratio of 17.6, indicating a predominance of silicon-rich compounds in the blend. The presence of calcium (1.83%) suggests the potential formation of calcium-containing phases, such as calcium silicate hydrate (C-S-H) in the mixture.

Table 4.3 EDX analysis of NRL-modified BA-based geopolymer stabilized RCA mixtures.

Sample IDs	Major elements analyzed (all results in weight%)							Si/Al ratio
	C	O	Fe	Na	Ca	Al	Si	
70RCA30BA (control)	9.57	51.82	1.07	4.87	1.83	1.75	30.74	17.6
G/N1:1.0NRL0.1	37.90	31.15	1.05	2.54	6.69	3.03	17.62	5.80
G/N1:1.5NRL0.1	39.28	32.67	1.33	2.63	6.75	2.38	16.79	7.10
G/N1:2.0NRL0.1	38.94	33.34	1.45	2.79	6.81	1.88	15.72	8.40

The incorporation of the NRL and BA-based geopolymer in the RCA mixture leads to significant changes in the elemental composition of G/N1:1NRL0.1 mixture compared to the control mixture. The Si/Al ratio decreases from 17.6 in the control mixtures to 5.80 in the G/N1:1NRL0.1 mixture. This decrease can be attributed to the dissolution of aluminum-rich compounds from the BA during the geopolymer process, resulting in a lower Si/Al in the geopolymer gel. In addition, the G/N1:1NRL0.1 mixture exhibits a higher calcium content (6.69%) compared to the control mixture. The increase in calcium content can be attributed to the formation of calcium aluminosilicate hydrate (C-A-S-H) gel alongside the sodium aluminosilicate hydrate (N-A-S-H) gel in the geopolymer matrix.

As the G/N ratio increases from 1:1 to 1:1.5, and 1:2, the Si/Al ratio in the stabilized mixtures also increases from 5.80 to 7.10 and 8.40, respectively. This

increase in the Si/Al ratio can be attributed to the higher amount of soluble silica provided by the increased Na_2SiO_3 content in the alkaline activator solution.

The optimized combination of NRL content and G/N ratio in the NRL-modified mixtures, particularly the mixture with 0.1% NRL and a G/N ratio of 1:1, capitalizes on the beneficial effects of a lower Si/Al ratio and the presence of calcium. This synergistic effect contributes to the enhanced mechanical properties and microstructural characteristics of the NRL-modified BA-based geopolymer stabilized RCA mixtures.

4.4.4 Effect of NRL on microstructural property

Figure 4.7 presents the SEM images of NRL-modified mixtures with varying NRL contents (0.1%, 0.2%, and 0.3%) at a constant G/N ratio of 1:1. The mixture with 0.1% NRL (Figure 4.7a) exhibits a dense and homogeneous microstructure, with a well-developed geopolymer gel network. The NRL films form thin, continuous bridging structures that enhance the interface bonding between the RCA particles and geopolymer matrix.

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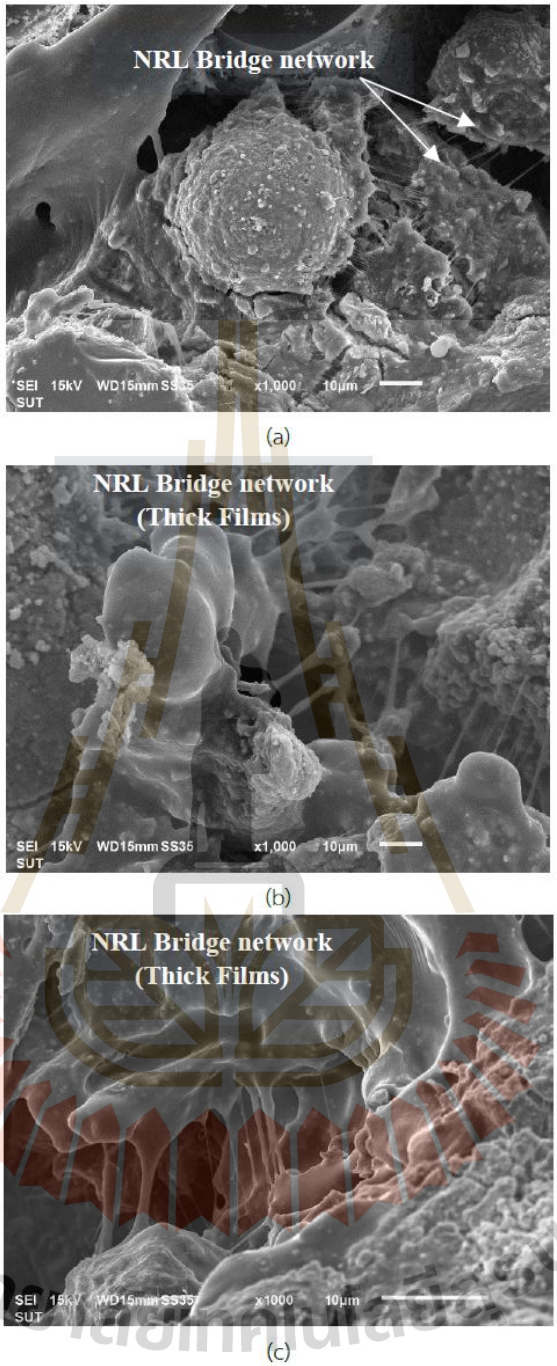

Figure 4.7 SEM images of NRL-modified BA-based geopolymer stabilized RCA samples: G/N1:1.0NRL0.1, b) G/N1:1.0NRL0.2, and c) G/N1:1.0NRL0.3

The physical interaction is related to the mechanical interlocking of the NRL film with the rough and porous surface of the matrix. The NRL film penetrates into the surface irregularities and pores of the RCA particles, creating a physical anchor that enhances the bond strength between the particles and the matrix. This implies that

the synergistic characteristic between the NRL films and geopolymer gels can lead to enhance the strength development of BA-based geopolymer stabilized RCA.

As the NRL content increases to 0.2% (Figure 4.7b) and 0.3% (Figure 4.7c), the microstructure remains relatively compact and homogeneous, but the NRL films become thicker and more prominent. The thicker NRL films may contribute to a slightly more ductile behavior of the geopolymer matrix. However, the excessive thickness of the NLR films at higher content may lead to a decrease in dissolution of aluminosilicate-rich BA during the geopolymer process and resulted in sluggish strength development. The findings indicate an intricate interplay between the G/N ratio, NRL content, and the resulting UCS. The microstructural observations from the SEM-EDX analysis corroborate the findings from the UCS results, where the mixture with 0.1% NRL and a G/N ratio of 1:1 exhibited the highest strength development. The dense and homogeneous microstructure, the presence of well-developed (N,C)-A-S-H gels, and the effective bridging mechanism provided by the thin NRL films contribute to the superior mechanical performance of this mixture.

4.4.5 XRD analysis

The XRD analysis provides valuable information on the mineralogical composition and the formation of geopolymer reaction products in the NRL-modified BA-based geopolymer stabilized RCA mixtures. To investigate the influence of NRL content and G/N ratios on the polymerization process and the resulting geopolymer products, the XRD patterns of NRL-modified samples with varying G/N ratios and NRL contents were examined and compared with the control sample (RCA70BA30).

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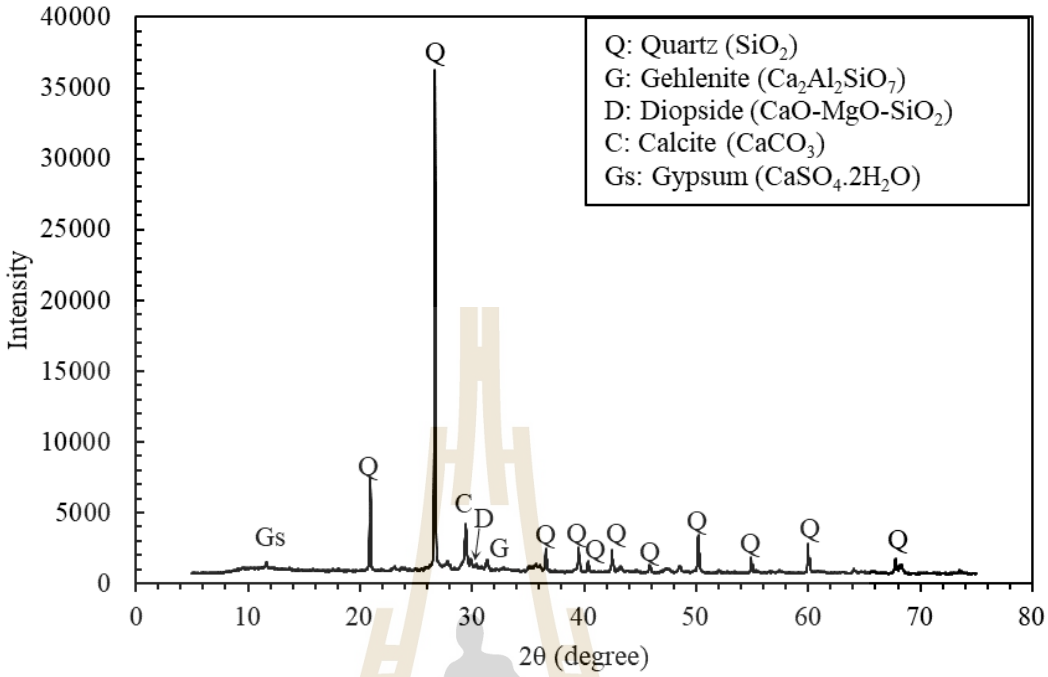

Figure 4.8 XRD patterns of RCA70BA30 (Control sample).

Figure 4.8 illustrates the XRD patterns of the control sample, which consists of 70%RCA and 30% BA without any geopolymer or NRL modification. The XRD pattern exhibits sharp peaks corresponding to the crystalline phases present in the RCA and BA, such as quartz (SiO_2), calcite ($CaCO_3$), and hematite (Fe_2O_3). The absence of broad humps in broad humps in the XRD pattern indicates the lack of amorphous geopolymer gel formation in the control sample.

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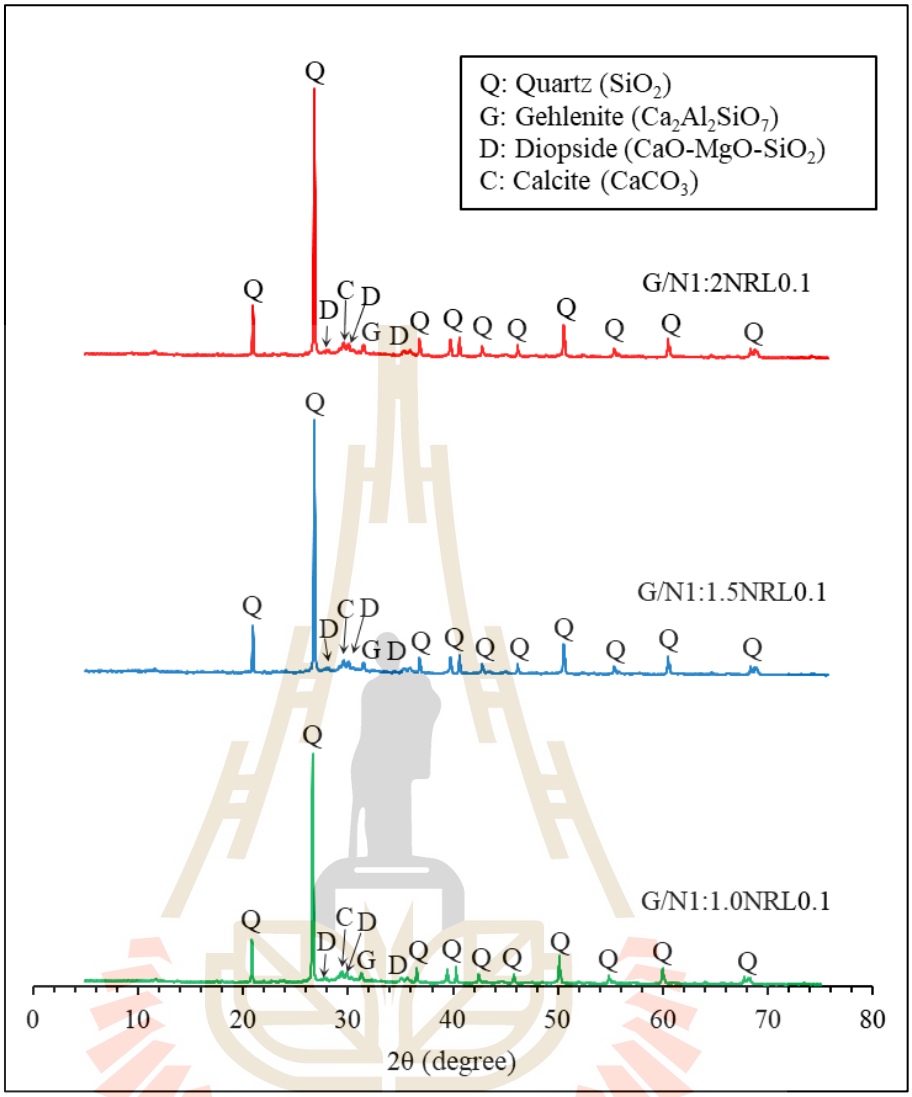

Figure 4.9 XRD patterns of NRL-modified BA-based geopolymer stabilized RCA samples.

Figure 4.9 demonstrates the XRD patterns of the NRL-modified BA-based geopolymer stabilized RCA samples with varying G/N ratios (1:1, 1:1.5, and 1:2) at a constant NRL content of 0.1%. the XRD patterns of the NRL-modified samples exhibit a notable reduction in the intensity of the crystalline peaks compared to the control sample. This reduction in peak intensity suggests the dissolution of the crystalline phases and the formation of amorphous geopolymer gel products (El Alouani et al., 2024; Sinha, Kumar, & Kumar, 2014). In addition, the XRD patterns show a gradually increase in the background hump between 20° and 40° 2θ, indicating the formation of amorphous geopolymer gel (Bobirică et al., 2020). The broad hump is more pronounced in the sample with a G/N ratio of 1:1, implying a higher degree of geopolymerization and the formation of a more extensive amorphous geopolymer network.

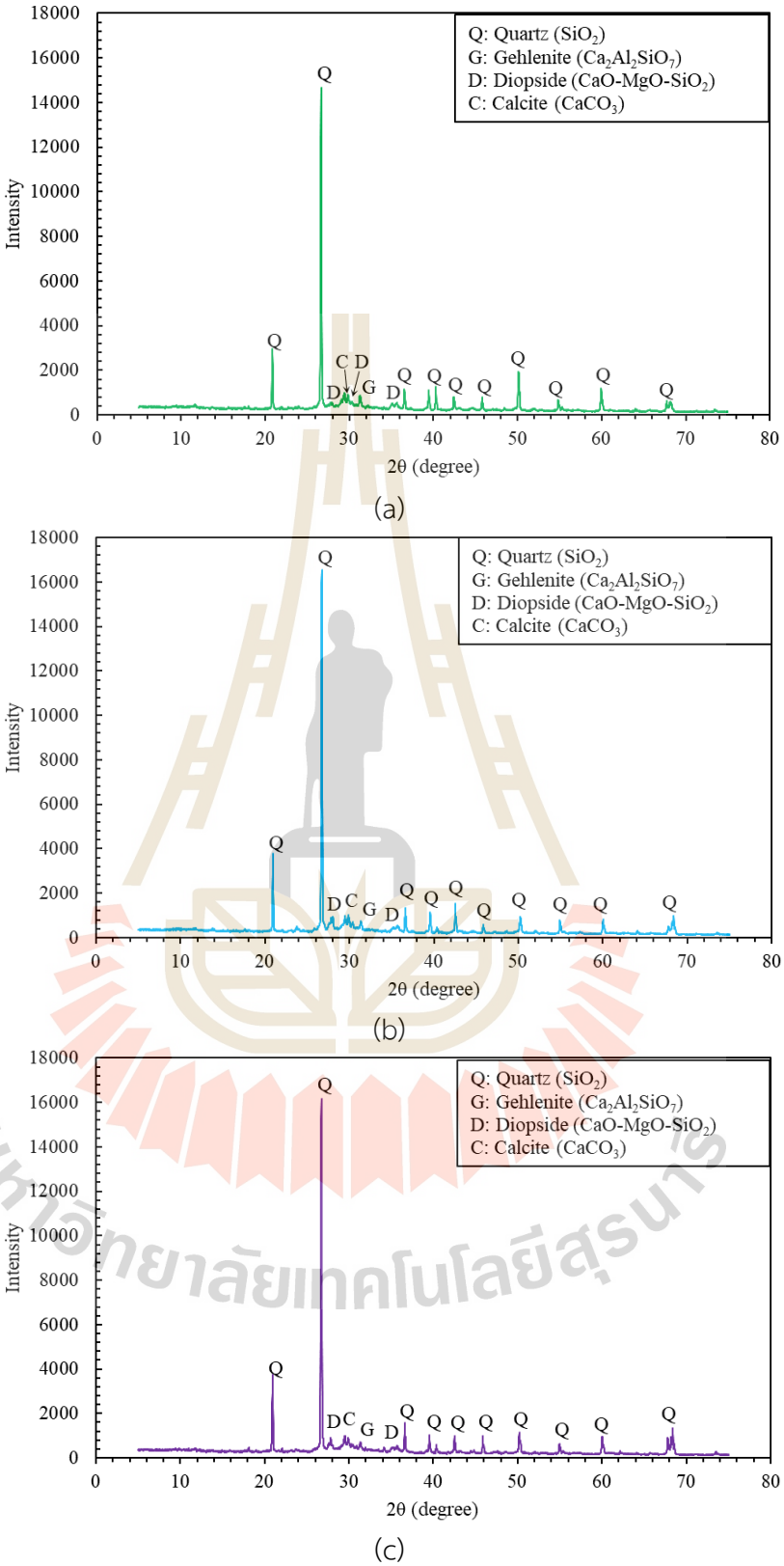

Figure 4.10 XRD patterns of NRL-modified BA-based geopolymer stabilized RCA samples: a) G/N1:1.0NRL0.1, b) G/N1:1.0NRL0.2, c) G/N1:1.0NRL0.3

Figure 4.10 presents the XRD patterns of the NRL-modified BA-based geopolymer stabilized RCA samples with varying NRL contents (0.1%, 0.2%, and 0.3%) at a constant G/N ratio of 1:1. The XRD patterns of the NLR-modified samples a show a significant reduction in the intensity of the crystalline peaks compared to the control sample, indicating the dissolution of the crystalline phases and the formation of amorphous geopolymer gel (Kumar & Revathi, 2020). The sample with 0.1% NRL shows the lowest intensity of the crystalline peaks and most pronounced broad hump, indicating the optimal NRL content for promoting geopolymerization and the formation of amorphous geopolymer gel products. Furthermore, as the NRL content increase from 0.1% to 0.3%, the XRD patterns reveal the presence of residual crystalline phases, such as quartz and calcite, which have not been completely dissolved during the geopolymerization process. As a result, a slow strength development was gain.

The XRD analysis supports the findings from the microstructural characterization by SEM analysis and the mechanical testing that G/N ratio and NRL content play a significant role in the geopolymerization process. If was found that the sample containing 0.1% NRL and a G/N ratio of 1:1 exhibiting the most pronounced geopolymerization and amorphous geopolymer gel formation. This finding highlights the effectiveness of the NRL-modified BA-based geopolymer in stabilizing RCA and producing a sustainable and high-performance pavement base material.

4.5 Conclusion

The present study instigated the performance of natural rubber latex (NRL) modified bottom ash (BA)-based geopolymer stabilized recycled concrete aggregate (RCA) as a sustainable pavement base material. The influence factors studies, including NRL content (0.1%, 0.2%, and 0.3% by weight of aggregate) and alkaline activator ratios ($NaOH:Na_2SiO_3$ (G/N) = 1:1, 1:1.5, and 1:2) on the strength development of the mixture. The main findings of the research are as follows:

1) The incorporation of NRL and the optimization of the alkaline activator ratio significantly enhanced the unconfined compressive strength (UCS) of the stabilized RCA mixtures. All the NRL-modified BA-based geopolymer stabilized RCA mixtures, irrespective of the G/N ratio (1:1, 1:1/5, and 1:2) or NRL content (0.1%, 0.2, and 0.3%), surpass the minimum requirement of 1.72 MPa for subbase materials. The mixture containing 0.1% NRL and a G/N ratio of 1:1 achieved the highest UCS values of 4.05 MPa and 5.17 MPa at 7 and 28 days, respectively. However, the UCS values of all stabilized RCA mixture decreased with increasing G/N ratios and/or NRL ratios.

2) The microstructure analyses, including SEM, EDX, and XRD, revealed the formation of a dense and homogeneous geopolymer matrix in the NRL-modified mixtures. The NRL films acted as bridging structures that enhanced the bonding between RCA particles and the matrix, contributing to the improved mechanical properties.

3) The alkaline activator ratio and NRL content played a crucial role in the geopolymerization process and the strength development of the stabilized mixtures. The XRD analysis confirmed the dissolution of crystalline phase and the formation of amorphous geopolymer gel in the NRL-modified mixtures, with the mixture containing 0.1% NRL and a NaOH:Na_2SiO_3 ratio of 1:1 exhibiting the most pronounced geopolymerization.

4) A balanced NaOH:Na_2SiO_3 ratio of 1:1 promoted the formation of a stable geopolymer gel, while higher ratios led to a silica-rich gel that hindered further geopolymerization and strength gain. Meanwhile, excessive amounts of NRL led to a reduction in strength compared to the mixture with 0.1% NRL. This suggests that there is an optimal NRL content beyond which the strength development is hindered, possibly due to the formation of thicker NRL films that may interfere with the geopolymerization process.

The findings of this study demonstrate the potential of NRL-modified bottom ash-based geopolymer stabilized RCA as an eco-friendly and high-performance alternative to conventional pavement base materials, provided that the NRL content is optimized. The utilization of waste materials, such as RCA and bottom ash, coupled with the innovative use of NRL as a modifier, contributes to the development of sustainable pavement solutions.

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CHAPTER V
CONCLUSIONS AND RECOMMENDATIONS

5.1 Summarization

Very recent decades, the rapid expansion of infrastructure in Thailand and other developing nations has created an increasing demand for natural aggregates in highway and pavement construction. This demand has accelerated the exploitation of quarries and gravel pits, leading to significant environmental degradation and depletion of finite natural resources. Simultaneously, the global imperative to mitigate climate change and reduce greenhouse gas emissions has intensified the pursuit of more sustainable construction practices. Within the field of pavement engineering, the use of recycled construction and demolition waste materials, such as Recycled Concrete Aggregate (RCA), along with industrial byproducts like bottom ash (BA), has gained attention as a potential substitute for conventional aggregates. Nevertheless, these materials in their untreated state often exhibit insufficient strength and durability to ensure long-term road performance. Traditional stabilization using Portland cement can enhance their engineering properties but contributes substantially to CO_2 emissions, thereby aggravating environmental concerns.

To overcome these limitations, geopolymer technology has been introduced as an environmentally friendly alternative binder. By utilizing industrial byproducts, this approach reduces reliance on virgin aggregates while lowering the carbon footprint of pavement materials. Furthermore, the integration of Natural Rubber Latex (NRL) into BA-based geopolymer stabilized RCA has demonstrated added benefits, including enhanced flexibility, water resistance, and resilience to environmental stresses.

Accordingly, this study investigated the strength, durability, and microstructural behavior of BA–geopolymer stabilized RCA with and without NRL modification, with the overarching objective of developing a sustainable and high-performance pavement subbase material. This chapter presents a synthesis of the principal findings, formulates the overall conclusions, and provides recommendations for future research and practical applications.

The findings of this research, as presented in Chapters III and IV, confirm the potential of bottom ash (BA)–based geopolymer stabilized recycled concrete aggregate (RCA), with and without natural rubber latex (NRL) modification, as a sustainable

pavement subbase material. The laboratory investigations demonstrated that BA–geopolymer stabilized RCA mixtures developed substantial improvements in unconfined compressive strength compared with untreated RCA. Among the studied formulations, the RCA90BA10 mixture with a G/N ratio of 1:2 provided the most outstanding performance, achieving compressive strengths that exceeded the Department of Highways (DOH, Thailand) minimum requirement of 2.413 MPa for base courses. Microstructural examinations through SEM, XRD, and EDX confirmed the successful formation of sodium aluminosilicate hydrate (N–A–S–H) and calcium-based gels, which contributed to a denser matrix, improved bonding, and enhanced long-term stability.

The incorporation of NRL into BA–geopolymer stabilized RCA further enhanced the engineering properties of the mixtures. At an optimum dosage of 0.1% NRL with a G/N ratio of 1:1, the 28-day unconfined compressive strength reached 5.17 MPa, significantly surpassing the American Association of State Highway and Transportation Officials (AASHTO, 2008) requirement of 1.72 MPa for subbase layers. The microstructural analysis revealed that NRL acted as a bridging agent between RCA and BA particles, effectively reducing porosity and mitigating the propagation of micro-cracks, while also providing additional flexibility and water resistance to the stabilized system. However, excessive silica content in the activator reduced the extent of geopolymerization, indicating that balance in mix design remains essential for maximizing performance.

In terms of durability, the results showed that all NRL-modified BA–geopolymer mixtures exceeded strength requirements for both low- and high-volume traffic conditions. The synergistic effect of appropriate alkaline activator ratios and controlled NRL contents contributed to superior resilience against dynamic loading and environmental stresses, ensuring the reliability of the material for practical pavement applications.

Overall, the study demonstrates that the utilization of RCA and BA, two abundant waste-derived materials, can be successfully converted into high-performance pavement subbase materials through geopolymer technology. When combined with NRL, the system not only enhances mechanical and durability properties but also contributes to broader environmental benefits by reducing the consumption of virgin aggregates, minimizing landfill disposal, and lowering CO_2 emissions. These outcomes strongly align with Thailand's national objectives of promoting sustainable construction practices and reducing the environmental footprint of road infrastructure.

5.2 Recommendation for future work

The experimental results and analyses conducted in this research, several recommendations are proposed for future studies and practical applications of BA–geopolymer stabilized RCA with and without NRL modification:

Field Applications in the large-scale field trials should be conducted to validate laboratory findings under actual traffic loading and diverse climatic conditions. Monitoring long-term performance will provide critical insights into the feasibility of adopting this material in national road networks.

Durability studies in further research should focus on the resistance of BA–geopolymer RCA to long-term environmental exposures such as freeze–thaw cycles, sulfate and acid attack, and prolonged water immersion. These studies are essential to ensure long-term durability and reliability in tropical and flood-prone regions of Thailand.

Optimization of mix design investigations should explore the effects of varying classes of bottom ash, different RCA sources, and alternative activator concentrations to optimize the mix design for regional material availability. Additionally, hybrid binders combining geopolymer and supplementary additives could be evaluated for enhanced performance.

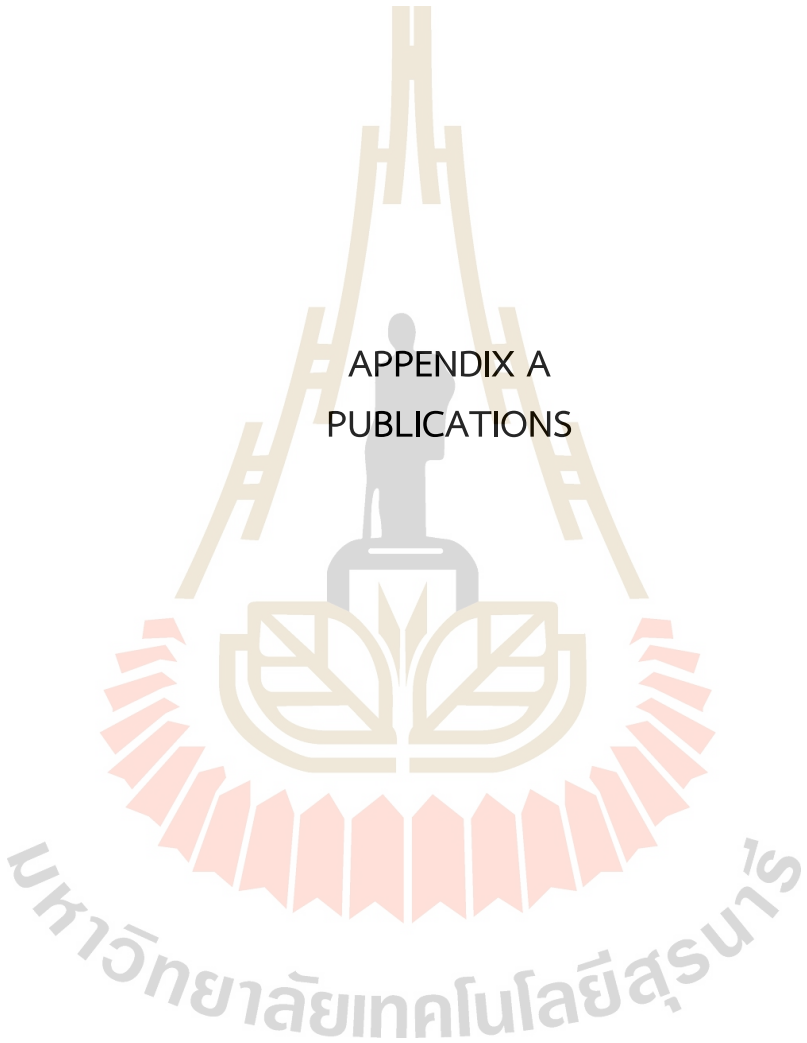
NRL modification enhancement future work should examine the synergistic effects of NRL with other natural or synthetic polymers, fibers, or nano-materials. This could further improve crack resistance, flexibility, and moisture tolerance of the stabilized mixtures.

Life-cycle and cost-benefit analysis, a comprehensive life-cycle assessment (LCA) and cost–benefit evaluation should be undertaken to compare BA–geopolymer RCA with conventional cement-stabilized materials. This would provide quantitative evidence of its environmental and economic advantages.

Standardization and policy integration technical guidelines and specifications should be developed for BA–geopolymer stabilized RCA in both subbase and base course applications. Collaboration with the Department of Highways (DOH) and the Department of Rural Roads (DRR) is recommended to integrate these materials into official road construction standards.

Scaling toward sustainable infrastructure policymakers and engineers are encouraged to incorporate geopolymer technology and NRL-modified waste-based materials into Thailand's broader sustainability roadmap. This will contribute to reducing dependence on natural aggregates, minimizing landfill disposal, and lowering CO_2 emissions from road construction.

APPENDIX A
PUBLICATIONS



LIST OF PUBLICATIONS

INTERNATIONAL JOURNAL PAPERS

Hoy, M., Traiyasut, C., Horpibulsuk, S., Chinkulkijniwat, A., Suddeepong, A., Buritatum, A., Yaowarat, T., Julvorawong, M., & Savetviwat, T. (2025). Strength Development of Bottom Ash-Based Geopolymer-Stabilized Recycled Concrete Aggregate as a Pavement Base Material. Coatings, 15(8), 935. https://doi.org/10.3390/coatings15080935

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Strength Development of Bottom Ash-Based Geopolymer-Stabilized Recycled Concrete Aggregate as a Pavement Base Material

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Abstract

This study investigated a 100% waste-derived material system, using bottom ash (BA) and recycled concrete aggregate (RCA) for sustainable pavement base applications. This innovative approach diverts both construction and power plant waste from landfills while replacing conventional natural aggregates and cement-based binders. Five RCA:BA replacement ratios (90:10 to 50:50) were evaluated with three Na_2SiO_3:NaOH alkaline activator ratios (1:1, 1:1.5, and 1:2) through unconfined compressive strength (UCS) testing, scanning electron microscopy, energy dispersive X-ray spectroscopy (SEM-EDX), and X-ray diffraction (XRD) analysis. The RCA90BA10 composition with a G/N ratio of 1:2 achieved exceptional performance, reaching 9.14 MPa UCS at 7 days while exceeding the Department of Highways, Thailand, requirement of 2.413 MPa. All geopolymer-stabilized mixtures substantially surpassed minimum specifications, validating the technology for high-traffic pavement applications. Toughness evaluation confirmed superior energy absorption capacity of 107.89 N·m for the optimal formulation. Microstructural characterization revealed that higher G/N ratios promoted extensive sodium aluminosilicate hydrate and calcium silicate hydrate gel formation, creating dense, well-integrated matrices. XRD patterns confirmed successful geopolymerization through pronounced amorphous gel development between 20° and 35° 2θ, correlating directly with mechanical performance improvements. The RCA90BA10 formulation demonstrated optimal balance between reactive aluminosilicate content and structural aggregate framework. This technology offers significant environmental benefits by diverting construction and power plant waste from landfills while achieving mechanical properties superior to conventional materials, providing a scalable solution for sustainable infrastructure development.

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Academic Editor: Qiao Dong

Received: 4 July 2025
Revised: 6 August 2025
Accepted: 7 August 2025
Published: 11 August 2025

Citation: Hoy, M.; Traiyasut, C.; Horpibulsuk, S.; Chinkulkijniwat, A.; Suddeepong, A.; Buritatum, A.; Yaowarat, T.; Julvorawong, M.; Savetviwat, T. Strength Development of Bottom Ash-Based Geopolymer-Stabilized Recycled Concrete Aggregate as a Pavement Base Material. *Coatings* **2025**, *15*, 935. https://doi.org/10.3390/coatings15080935

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Keywords: recycle concrete aggregate; bottom ash; geopolymer; microstructure; unconfined compressive strength; pavement base material

1. Introduction

The construction industry, particularly road construction, faces significant challenges in sustainability due to its reliance on traditional materials such as natural aggregates and Portland cement. These materials are associated with high CO_2 emissions and depletion of natural resources. As global road infrastructure needs continue to expand, there is an urgent requirement for sustainable solutions that meet performance criteria while minimizing adverse environmental impacts [1–4].

Recycled concrete aggregate (RCA) and bottom ash (BA) have emerged as potential eco-friendly alternatives to traditional construction materials [5]. This study uniquely employed 100% waste-derived materials, including RCA and BA, as both aggregate and aluminosilicate precursor, eliminating the need for virgin aggregates This approach directly supports circular economy principles by diverting large quantities of construction demolition waste and coal combustion byproducts from landfills while reducing greenhouse gas emissions, making it a compelling alternative to conventional pavement base materials. RCA, obtained from demolished concrete structures, provides an approach to reduce landfill waste and conserve natural resources [6]. The incorporation of RCA in new pavement structures contributes to waste reduction in landfills and conserves natural resources by decreasing the demand for virgin aggregate materials. BA, a byproduct of coal combustion, presents another opportunity for waste utilization in construction [7]. However, when used independently, these materials often fail to meet the mechanical strength and durability requirements necessary for road construction [8–10].

Geopolymer technology represents a promising approach to address the limitations of RCA and BA [11]. Geopolymers are inorganic polymers formed when aluminosilicate materials, such as fly ash or slag, chemically react with alkaline solutions [12]. This reaction produces a dense, three-dimensional network structure that provides excellent mechanical strength, durability, and resistance to chemical attack [13]. The environmental benefits of geopolymer technology are substantial as it utilizes industrial byproducts and reduces CO_2 emissions associated with cement production [14,15].

Several studies have demonstrated the effectiveness of geopolymer-stabilized recycled materials in pavement applications. Research has shown that high-calcium fly ash geopolymer can significantly improve the unconfined compressive strength (UCS) of RCA, meeting requirements for both low and high-traffic roads [16,17]. Similarly, studies have demonstrated that fly ash–rice husk ash-based geopolymer can enhance the UCS of RCA as a pavement material [18]. To achieve desired performance improvements in compressive strength, flexural strength, and elastic modulus, the alkaline activator content in geopolymer-stabilized recycled materials must be optimized [9,19,20]. This optimization is necessary due to the formation of additional calcium silicate hydrate (C-S-H) or calcium aluminosilicate hydrate (C-A-S-H) and sodium aluminosilicate hydrate (N-A-S-H) or geopolymer gel in the geopolymer matrix.

While extensive research has been conducted on fly ash-based geopolymers, the potential of bottom ash-based geopolymers in stabilizing RCA remains largely unexplored. Studies indicate that bottom ash-based geopolymers may exhibit lower mechanical strength and durability due to the crystalline content, low amorphous aluminosilicate phase, and coarse particle size, all of which limit dissolution and reduce geopolymerization potential [21,22].

However, these limitations can potentially be addressed through careful optimization of the geopolymerization process, particularly by adjusting the alkaline activator ratio [23].

The alkaline activator plays a crucial role in the geopolymerization process, affecting both aluminosilicate precursor dissolution and subsequent geopolymer network formation. By investigating the influence of different alkaline ratios, it may be possible to enhance the reactivity of bottom ash and improve the overall performance of bottom ash-based geopolymers. This approach could lead to the development of more effective stabilization methods for RCA using bottom ash-based geopolymers, potentially achieving mechanical properties comparable to or surpassing those of fly ash-based systems.

Most research focuses on cement and reinforcement to improve material efficiency for various applications, and there is limited research addressing the importance of complete waste material reuse, particularly waste materials from construction demolition and power plants. Therefore, this research focuses on the effects of various ratios between waste materials (RCA:BA) and different alkaline ratios on bottom ash-based geopolymers to stabilize recycled concrete aggregate, which remains poorly understood.

This research aims to address this research gap by investigating the influence of various RCA:BA ratios and alkaline activators with different Na_2SiO_3:NaOH (G/N) ratios (1:1, 1:1.5, and 1:2 by weight) on the strength and durability of bottom ash-based geopolymer-stabilized RCA. Its performance is compared with the requirements specified by the Department of Highways. Strength development was assessed through comprehensive microstructural and mineralogical analyses, employing scanning electron microscopy (SEM), energy dispersive X-ray spectroscopy (EDS), and X-ray diffraction (XRD) techniques.

This study is based on the hypothesis that an optimal combination of RCA and BA, activated with a suitably high sodium silicate-to-sodium hydroxide ratio, can significantly enhance the mechanical performance and microstructural densification of RCA-BA geopolymer mixtures, achieving strength and durability requirements for high-traffic pavement base applications.

The findings of this research contribute to the development of advanced pavement materials that balance sustainability with performance, addressing future infrastructure needs while adhering to green construction principles. This innovative approach has the potential to advance pavement engineering by offering environmentally friendly solutions without compromising structural integrity.

2. Materials and Methods

2.1. Materials

Two industrial waste streams were selected as raw materials based on their complementary chemical compositions, availability, and potential for geopolymer synthesis: recycled concrete aggregate (RCA) as the primary aggregate component and lignite bottom ash (BA) as the aluminosilicate precursor. The selection criteria prioritized materials with established waste disposal challenges and demonstrated potential for beneficial reuse in construction applications.

RCA was obtained from construction demolition projects in Ubon Ratchathani and Sisaket Provinces, Thailand, representing typical concrete waste from regional infrastructure. The material underwent comprehensive characterization to establish baseline properties and suitability for pavement applications.

Particle size distribution analysis (ASTM D422-63) confirmed compliance with the Department of Highways (DOH), Thailand, specifications for pavement base materials (Figure 1). The gradation comprised 48.6% gravel (retained on No. 4 sieve), 47.9% sand (passing No. 4, retained on No. 200), and 3.5% fines (passing No. 200 sieve). Under the

Unified Soil Classification System, the material was classified as well-graded gravel (GW) with no measurable plasticity.

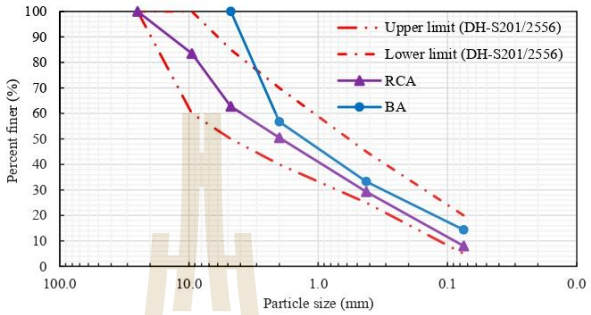


Figure 1. Graduation of RCA and BA.

Key mechanical and physical parameters included specific gravity of 2.7, Los Angeles abrasion resistance of 38.1%, flakiness index of 15.6%, and maximum dry density of 18.70 kN/m^3 at an optimum moisture content of 12%. Water absorption values were 6.42% and 7.83% for coarse and fine fractions, respectively, indicating moderate porosity typical of recycled aggregates.

XRD analysis identified predominant crystalline phases including quartz, calcite, and residual cement minerals (Figure 2a). SEM examination revealed angular particles with rough surface textures, residual cement paste adherence, and interconnected porosity (Figure 3a).

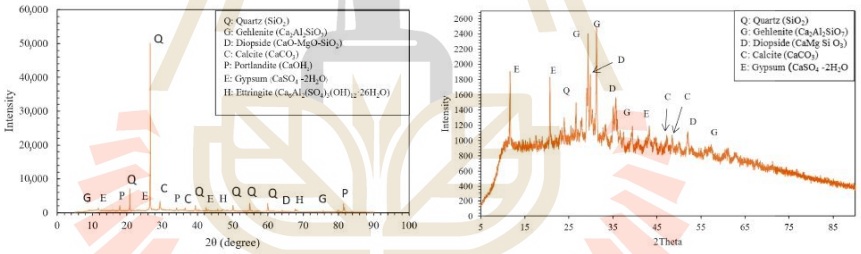


Figure 2. XRD patterns of (**a**) RCA and (**b**) BA.

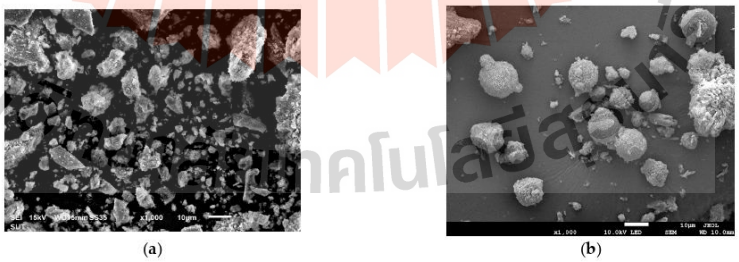
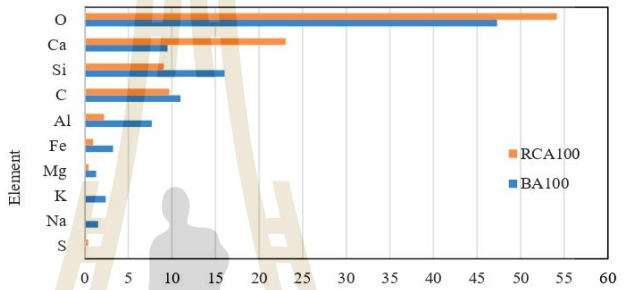


Figure 3. SEM images of (**a**) RCA and (**b**) BA.

Energy-dispersive X-ray spectroscopy (EDX) analysis was performed using a scanning electron microscope equipped with an EDX detector. Multiple point analyses were conducted on polished sample surfaces to ensure representative elemental composition data. The chemical compositions are presented in Figure 4 and demonstrate complementary profiles essential for geopolymer synthesis. RCA exhibited a calcium-rich elemental composition typical of concrete materials, with calcium (Ca) and oxygen (O) as the predominant elements, indicating the presence of unhydrated cement particles and calcium-based compounds such as $Ca(OH)_2$ and $CaCO_3$. Silicon (Si) and carbon (C) were also present in significant proportions, reflecting the silicate phases and carbonate content characteristic of concrete materials. Minor elements included aluminum (Al), iron (Fe), magnesium (Mg), and trace amounts of sulfur (S).



	S	Na	K	Mg	Fe	Al	C	Si	Ca	O
RCA100	0.39	0.00	0.00	0.45	0.97	2.22	9.71	9.07	23.04	54.15
BA100	0.00	1.53	2.40	1.32	3.25	7.69	10.99	16.03	9.50	47.30

Figure 4. Chemical compositions RCA and BA obtained from EDX.

Lignite bottom ash was sourced from Mae Moh power plant (Electricity Generating Authority of Thailand, Changwat Lampang, Thailand), representing the largest lignite-fired facility in Southeast Asia. This material represents approximately 15%–20% of total coal combustion products from the facility.

XRD analysis revealed a predominantly amorphous structure with minor crystalline phases including quartz and feldspathic minerals (Figure 2b). EDX analysis confirmed high silica (SiO_2) and alumina (Al_2O_3) contents essential for geopolymer formation, along with elevated alkali contents (Na_2O and K_2O) and minor iron oxide (Fe_2O_3) concentrations.

SEM imaging revealed irregular angular particles with a heterogeneous size distribution and a porous surface structure (Figure 3b). The morphology differs significantly from spherical fly ash particles, contributing to different reactivity characteristics in alkaline environments.

The EDX analysis (Figure 4) indicated that BA provided essential aluminosilicate components for geopolymer formation, with significantly higher silicon (Si) and aluminum (Al) contents compared to RCA. The BA composition showed an elevated oxygen (O) content, substantial silicon (Si) and aluminum (Al) concentrations, and moderate levels of calcium (Ca), iron (Fe), and trace elements including potassium (K), sodium (Na), and magnesium (Mg). The higher alkali content (Na and K) in BA contributes to the alkaline environment necessary for geopolymer activation.

The EDX analysis results correlate well with the XRD findings (Figure 2), where the high calcium content in RCA corresponds to the calcite and residual cement peaks observed, while the elevated silicon and aluminum contents in BA align with the predominant amorphous content and minor crystalline aluminosilicate phases detected in the diffraction patterns.

This elemental analysis confirms that the combination of calcium-rich RCA and aluminosilicate-rich BA provides an optimal chemical foundation for developing hybrid geopolymer systems with enhanced mechanical properties and sustainability characteristics.

2.2. Alkaline Activator

The preparation of the alkaline activator was a critical step in the geopolymer mix design, requiring careful control of the chemical composition to ensure effective geopolymerization and minimize handling hazards.

In this study, the activator was formulated by blending sodium silicate (Na_2SiO_3) solution with 10 M sodium hydroxide (NaOH) solution. These components were chosen for their effectiveness in dissolving aluminosilicate materials and promoting geopolymerization [24]. A binary activator combining Na_2SiO_3 and NaOH was selected to provide (i) silicate species for gel network formation, (ii) a high-pH environment for aluminosilicate dissolution, and (iii) an optimal workability window for field application.

Commercial-grade Na_2SiO_3 (type CR53) was used with the following compositional specifications: 14.5–16.5 wt% Na_2O, 31.5–34.0 wt% SiO_2, H_2O balance, silica modulus (Ms) of 2.0–2.2., density at 20 °C: 1.52 ± 0.02 g/cm^3, and viscosity of 400–600 cP. The NaOH solution was prepared by dissolving analytical-grade NaOH pellets (≥99% purity) in distilled water to achieve a concentration of 10 M (400 g/L). Both solutions were equilibrated for 24 h at ambient temperature (25 ± 2 °C) to ensure complete dissolution and thermal stabilization prior to mixing.

Three systematically varied compositions were prepared with Na_2SiO_3:NaOH mass ratios (G/N) of 1:1, 1:1.5, and 1:2, corresponding to effective silica moduli of 1.2, 1.0, and 0.8, respectively.

2.3. Mix Design and Sample Preparation

A two-factor experimental design was implemented to systematically evaluate Factor A—aggregate blend ratio (5 levels: RCA:BA = 90:10, 80:20, 70:30, 60:40, and 50:50), and Factor B—alkaline activator ratio (3 levels: G/N = 1:1, 1:1.5, and 1:2). Additional control specimens (RCA100 and BA100 with water only) provided baseline references. The complete factorial design comprised 17 unique compositions with minimum $n = 3$ replicates per condition (Table 1).

Table 1. The mix design of the BA-based geopolymer-stabilized RCA in this study.

Sample ID	Mix Ingredients
90RCA10BA G/N 1:1.0	90%RCA + 10%BA + (1) Na_2SiO_3 + (1) NaOH
90RCA10BA G/N 1:1.5	90%RCA + 10%BA + (1) Na_2SiO_3 + (1.5) NaOH
90RCA10BA G/N 1:2.0	90%RCA + 10%BA + (1) Na_2SiO_3 + (2) NaOH
80RCA20BA G/N 1:1.0	80%RCA + 20%BA + (1) Na_2SiO_3 + (1) NaOH
80RCA20BA G/N 1:1.5	80%RCA + 20%BA + (1) Na_2SiO_3 + (1.5) NaOH
80RCA20BA G/N 1:2.0	80%RCA + 20%BA + (1) Na_2SiO_3 + (2) NaOH
70RCA30BA G/N 1:1.0	70%RCA + 30%BA + (1) Na_2SiO_3 + (1) NaOH
70RCA30BA G/N 1:1.5	70%RCA + 30%BA + (1) Na_2SiO_3 + (1.5) NaOH
70RCA30BA G/N 1:2.0	70%RCA + 30%BA + (1) Na_2SiO_3 + (2) NaOH
60RCA40BA G/N 1:1.0	60%RCA + 40%BA + (1) Na_2SiO_3 + (1) NaOH
60RCA40BA G/N 1:1.5	60%RCA + 40%BA + (1) Na_2SiO_3 + (1.5) NaOH
60RCA40BA G/N 1:2.0	60%RCA + 40%BA + (1) Na_2SiO_3 + (2) NaOH
50RCA50BA G/N 1:1.0	50%RCA + 50%BA + (1) Na_2SiO_3 + (1) NaOH
50RCA50BA G/N 1:1.5	50%RCA + 50%BA + (1) Na_2SiO_3 + (1.5) NaOH
50RCA50BA G/N 1:2.0	50%RCA + 50%BA + (1) Na_2SiO_3 + (2) NaOH

The selected RCA:BA ratios were determined based on practical pavement base design considerations; the lower BA content (10%–20%) reflects typical field applications where high aggregate interlock is required for structural stability. In addition, higher BA contents (30%–50%) were included to explore the feasibility of maximizing waste utilization. The 50% replacement level represents the practical upper bound reported in prior research for maintaining acceptable workability and mechanical performance in pavement base materials [8].

The mix design for this study was systematically developed to evaluate the impact of various Na_2SiO_3:NaOH (G/N) ratios of 1:1, 1:1.5, and 1:2, by weight of the aggregate modification, on the properties of BA-based geopolymer-stabilized RCA (Table 1). The design involved creating a series of mixtures with varying contents of alkaline activator ratios and replacement between RCA:BA (90:10, 80:20, 70:30, 60:40, and 50:50) to establish a comprehensive understanding of their individual and combined effects on the geopolymer's performance.

RCA and BA were first dry-mixed for 2 min to achieve uniform distribution. The alkaline activator solution was then gradually added while continuously mixing for 3 min until a homogeneous paste was achieved. The mixtures were immediately transferred to standard Proctor molds (101.6 mm diameter × 116.4 mm height) and compacted under a modified standard Proctor test following ASTM D1557 in five equal layers to determine the maximum dry density (MDD) and optimum liquid content (OLC) for each composition. Specimens were prepared at their respective MDD and OLC conditions for mechanical testing. A ±2% tolerance from the target MDD and OLC was applied as a quality control criterion in line with ASTM D1557 recommendations and standard geotechnical practice. Specimens exceeding this deviation were rejected to ensure consistent density and moisture conditions, thereby minimizing experimental variability and ensuring that observed mechanical property differences were solely due to mix composition and activation ratios.

3. Laboratory Experimental Program

The experimental program was systematically designed to comprehensively evaluate the mechanical and microstructural properties of BA-based geopolymer-stabilized RCA. The testing protocol encompassed mechanical performance assessment and detailed microstructural characterization to establish structure–property relationships and validate the effectiveness of the geopolymer stabilization approach.

3.1. Unconfined Compressive Strength (UCS)

UCS tests were conducted at 7 and 28 days of curing following ASTM D2166 specifications to evaluate strength development over time. Cylindrical specimens (101.6 mm diameter × 116.4 mm height) were tested using a universal testing machine at a controlled loading rate of 1.0 mm/min to capture both peak strength and post-peak behavior. Load and deformation data were continuously recorded throughout the test until specimen failure, defined as either peak load achievement or 15% axial strain. The UCS values were calculated by dividing the maximum applied load by the original cross-sectional area of the specimen. Testing was performed on a minimum of three specimens per mixture and curing age to ensure statistical reliability, with the results reported as mean values with standard deviation.

3.2. Scanning Electron Microscopy (SEM) Analysis

SEM analysis was employed to visualize the microstructure of the geopolymer samples at a high magnification. This analysis provides insights into the microstructure of the BA geopolymer within the matrix, the bonding at the RCA-BA interface, and the morphology

of the geopolymer binder. The SEM examination was conducted on fractured samples post-UCS testing to identify the failure mechanisms and to correlate the mechanical test results with the microstructural characteristics.

3.3. X-Ray Diffraction (XRD) Analysis

XRD analysis was utilized to identify the crystalline phases present within the geopolymer matrix and to observe the changes in mineralogy due to the addition of the BA geopolymer and variation in the alkaline activator mixture. The XRD patterns were collected using a diffractometer, with samples being scanned in a 2Theta range, typically between 5° and 80°. The resultant diffractograms were analyzed to determine the presence of specific crystalline compounds and to infer the effectiveness of the geopolymerization process.

4. Results and Discussion

4.1. UCS Development

4.1.1. Strength Performance and Standard Compliance

The UCS results demonstrated significant enhancement achieved through BA-based geopolymer stabilization of RCA for pavement base applications (Figure 5). At 7 days of curing, the stabilized mixtures exhibited UCS values ranging from 2.98 to 9.14 MPa, representing substantial improvements over unstabilized controls (UCS of 100% RCA = 0.63 MPa). Strength development continued significantly through 28 days, with UCS values reaching 4.11 to 12.45 MPa, indicating active geopolymerization processes and continued matrix densification.

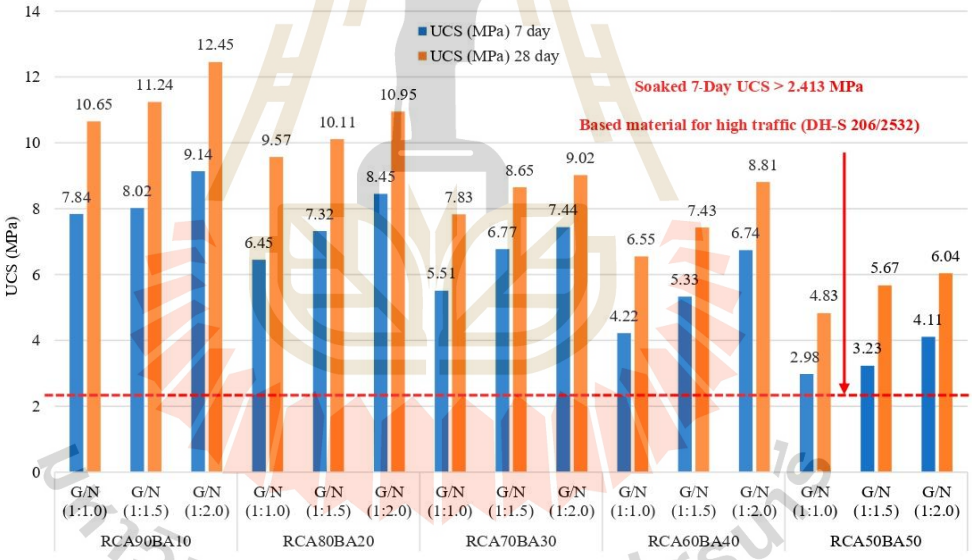


Figure 5. UCS of BA-based geopolymer-stabilized RCA samples at 7 and 28 days of ambient curing.

Critically, all BA-based geopolymer-stabilized RCA mixtures, irrespective of the G/N ratio (1:1, 1:1.5, and 1:2), significantly exceeded the minimum UCS requirement of 2.413 MPa specified by DOH, Thailand, for high-traffic pavement applications. This compatibility reveals that the developed materials can directly be integrated into existing pavement layer designs without major structural modifications. In addition, this performance demon-

strates the potential for these waste-derived materials to replace conventional granular subbase materials in demanding pavement applications. Elevated curing temperatures (40–60 °C) might enhance geopolymerization and early strength, but pavement base layers are typically cured under ambient conditions. This study followed field-compatible curing, and the resulting strength confirms its practical suitability without added energy input.

4.1.2. Influence of RCA:BA Ratio on Strength Development

The aggregate blend ratio emerged as a critical parameter governing mechanical performance, with RCA90BA10 consistently delivering superior strength characteristics across all alkaline activator conditions. At 28 days, this optimal composition achieved peak UCS values of 10.65, 11.24, and 12.45 MPa for G/N ratios of 1:1, 1:1.5, and 1:2, respectively. The superior performance of RCA90BA10 compared to RCA80BA20 indicated a critical balance between the reactive BA content and aggregate skeleton integrity. At 10% BA, sufficient aluminosilicate is available for gel formation without disrupting the RCA's strong interlocking framework. However, BA contents exceeding 15%–20% begin to compromise the structural skeleton due to the lower intrinsic strength and higher porosity of BA, which reduces the load transfer efficiency despite increased geopolymer gel formation. This threshold aligns with previous studies on bottom ash geopolymer pavements [21,22].

Progressive increases in the BA content from 20% to 50% resulted in systematic strength reductions, with RCA50BA50 exhibiting the lowest UCS values (4.83–6.04 MPa at 28 days). This declining trend reflects the trade-off between geopolymer binding capacity and structural integrity, where excessive BA replacement reduces the proportion of high-strength aggregate particles while potentially creating a weaker, more porous matrix due to the lower intrinsic strength and higher porosity of bottom ash compared to concrete aggregate.

4.1.3. Alkaline Activator Optimization and Geopolymerization Mechanisms

The G/N ratio demonstrated profound influence on strength development, with systematic strength increases observed as the ratio progressed from 1:1 to 1:2. The RCA90BA10 mixture showed remarkable strength enhancement from 10.65 MPa (G/N 1:1) to 12.45 MPa (G/N 1:2) at 28 days, representing a 17% strength increase. Similarly, other mixtures exhibited consistent strength improvements with increasing G/N ratios, with average strength gains of 15%–20% when progressing from G/N 1:1 to G/N 1:2 across all RCA:BA combinations.

This progressive strength enhancement can be attributed to the increased silicate availability in the activating solution, which promotes more extensive geopolymer network formation [25,26]. The higher sodium silicate content at G/N 1:2 provides additional silicate species that participate in polycondensation reactions, leading to a more densely cross-linked three-dimensional aluminosilicate network [27,28]. Research by Duxson et al. [29] demonstrated that a higher silica modulus in alkaline activators enhances the degree of polymerization in geopolymer systems, which aligns with the observed strength improvements in this study.

The intermediate G/N 1:1.5 ratio consistently produced moderate strength values between the G/N 1:1 and 1:2 extremes, demonstrating a systematic relationship between activator composition and mechanical performance. This graduated response indicates optimal control over geopolymer network development through activator formulation. The studies by Palomo et al. [30] and Provis and van Deventer [31] showed that the SiO_2/Na_2O ratio in alkaline activators directly influences gel formation kinetics and final strength development, supporting the trends observed in this research.

The enhanced performance at higher G/N ratios also reflects the improved dissolution of aluminosilicate species from the bottom ash, as confirmed by Fernández-Jiménez and Palomo [32], who reported that an increased silicate concentration accelerates the

dissolution–precipitation mechanism essential for geopolymer formation. Additionally, a higher silicate content promotes the formation of more stable and cross-linked gel structures, as demonstrated by Lahoti et al. [33] in their investigation of fly ash-based geopolymers.

This systematic strength enhancement with an increasing G/N ratio provides clear guidance for mixture optimization and demonstrates the potential for tailoring mechanical properties through alkaline activator design. The consistent improvement across all RCA:BA combinations confirmed the universal applicability of this optimization approach for BA-based geopolymer systems.

4.1.4. Toughness Properties of BA-Based Geopolymer-Stabilized RCA

Toughness indicates a material's ability to absorb energy and resist breaking under stress. The modulus of toughness quantifies this capacity, guiding material selection for durable and impact-resistant applications [34]. Materials with a high modulus of toughness can absorb more energy before breaking, enhancing their durability and reliability. This makes the modulus of toughness a key factor in selecting materials across various industries and applications [35].

The influence of the G/N ratio on toughness exhibited distinct patterns that varied with the RCA:BA composition and curing age (Figure 6). For the optimal RCA90BA10 mixture, a G/N ratio of 1:2 achieved the highest toughness values at both curing ages (105.67 N·m at 7 days and 107.89 N·m at 28 days), followed by a G/N ratio of 1:1.5 (97.21 N·m at 7 days and 105.55 N·m at 28 days), while a G/N ratio of 1:1 showed the lowest performance (88.39 N·m at 7 days and 98.67 N·m at 28 days). This systematic increase in toughness with higher G/N ratios demonstrates that enhanced silicate availability promotes superior energy absorption characteristics [36,37].

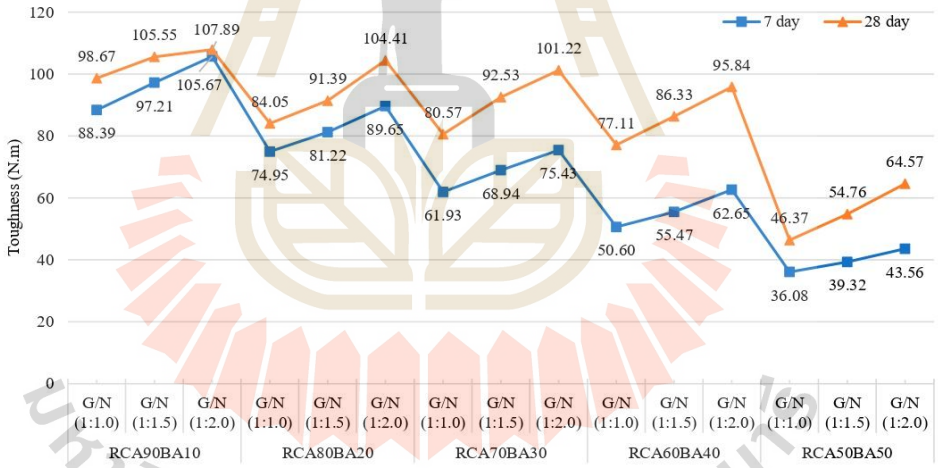


Figure 6. Toughness of BA-based geopolymer-stabilized RCA samples.

A particularly significant observation emerges for mixtures with a higher BA content (RCA70BA30, RCA60BA40, and RCA50BA50), where the effect of the G/N ratio becomes more pronounced with an extended curing time. For RCA70BA30, the mixture with a G/N ratio of 1:2 showed remarkable toughness development from 75.43 N·m at 7 days to 101.22 N·m at 28 days (34% increase), while toughness development with a G/N ratio of 1:1 only improved from 61.93 N·m to 80.57 N·m (30% increase). Similarly, RCA60BA40 with a

G/N ratio of 1:2 demonstrated substantial improvement from 62.65 N·m to 95.84 N·m (53% increase) compared to more modest gains at lower G/N ratios.

This trend is most pronounced in the RCA50BA50 mixture, where a G/N ratio of 1:2 showed significant toughness enhancement from 43.56 N·m at 7 days to 64.57 N·m at 28 days (48% increase), while G/N ratios of 1:1 and 1:1.5 exhibited much smaller improvements (20% and 39% increases, respectively). This pattern indicates that a higher silicate content becomes increasingly critical for long-term toughness development as the BA content increases.

The enhanced long-term toughness development at higher G/N ratios in mixtures with a high BA content can be attributed to continued geopolymerization processes that benefit from the additional silicate availability. The higher silicate content provides more opportunity for ongoing polycondensation reactions, leading to progressive matrix densification and improved energy absorption capacity over time [38,39]. This effect is particularly important in BA-rich mixtures where the initially weaker matrix requires an extended reaction time to achieve optimal performance characteristics.

This time-dependent G/N effect demonstrates that the benefits of a higher silicate content extend beyond immediate strength gains to include progressive toughness enhancement, making the G/N ratio of 1:2 the optimal choice for both immediate and long-term performance in BA-based geopolymer-stabilized RCA systems, especially for mixtures with a higher BA content.

It is noteworthy that toughness and strength trends deviate slightly at higher BA contents (>40%). While UCS decreases due to the lower intrinsic strength and higher porosity of BA, the same porous and heterogeneous matrix promotes energy dissipation by enabling microcrack deflection and progressive crack bridging within the geopolymer gel. This mechanism increases the material's energy absorption capacity despite its reduced peak load-bearing capacity, a phenomenon similarly observed in other waste-based geopolymer systems [36,39].

4.2. Microstructural Analysis

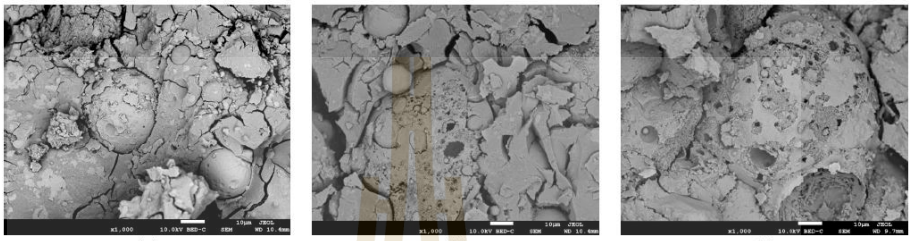
Scanning electron microscopy analysis provides comprehensive insights into the microstructural development mechanisms governing the performance of BA-based geopolymer-stabilized RCA systems. The systematic examination of specimens with varying RCA:BA ratios and alkaline activator compositions reveals fundamental structure–property relationships that establish the scientific basis for mechanical performance optimization.

4.2.1. Microstructural Development in Systems with a Low Bottom Ash Content

The microstructural characteristics of RCA90BA10 specimens demonstrated a clear correlation between alkaline activator composition and geopolymer network development. Figure 7a presents the formulation with a G/N ratio of 1:1, which exhibited incomplete geopolymerization characterized by heterogeneous matrix formation and extensive unreacted bottom ash particles. The microstructure revealed limited gel formation with discontinuous binding phases, resulting in a porous structure with weak interfacial bonding between aggregate and binder components. This incomplete activation aligned with the established geopolymerization principles described by Provis and van Deventer [26], where an insufficient alkaline concentration restricted aluminosilicate dissolution and subsequent network formation.

The formulation with a G/N ratio of 1:1.5 shown in Figure 7b demonstrated significant microstructural advancement with enhanced geopolymer gel formation and improved matrix cohesion. The increased alkaline activator content promotes more complete dissolution of aluminosilicate precursors, resulting in abundant formation of calcium silicate hydrate

(C-S-H) and sodium aluminosilicate hydrate (N-A-S-H) gel phases. The microstructure exhibits reduced porosity and more continuous binding networks, indicating improved activation efficiency consistent with the findings reported by Duxson et al. [28] regarding optimal activator composition effects on matrix development.



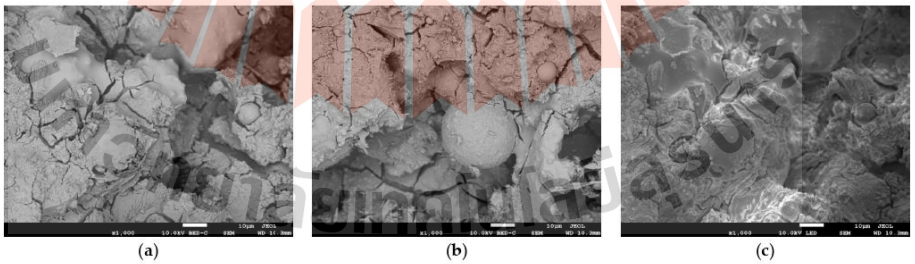
(a) (b) (c)

Figure 7. SEM images of RCA90BA10: (**a**) G/N ratio of 1:1, (**b**) G/N ratio of 1:1.5, and (**c**) G/N ratio of 1:2 at 28 days of curing.

Figure 7c presents the formulation with a G/N ratio of 1:2, which achieved the most advanced microstructural development characterized by extensive geopolymer gel formation and optimal matrix densification. The higher sodium silicate content promoted complete dissolution of bottom ash particles and facilitated the formation of well-integrated three-dimensional geopolymer networks. The microstructure demonstrated superior particle encapsulation and binding, creating a dense composite material with enhanced load transfer characteristics. This microstructural optimization validated the mechanical performance results and supported the geopolymerization mechanisms described by Fernández-Jiménez and Palomo [40].

4.2.2. Microstructural Development in Systems with a High Bottom Ash Content

The examination of RCA60BA40 specimens revealed the challenges and optimization requirements associated with increased bottom ash utilization. Figure 8a demonstrates that the formulation with a G/N ratio of 1:1 produced inadequate microstructural development when applied to systems with a higher bottom ash content. The SEM analysis revealed extensive microcracking, incomplete geopolymerization, and poor matrix cohesion, indicating that the activator concentration was insufficient for the elevated aluminosilicate content. This observation aligns with the research by Chindaprasirt et al. [21], who established that bottom ash-based systems require enhanced activation to overcome inherent reactivity limitations.



(a) (b) (c)

Figure 8. SEM images of RCA60BA40: (**a**) G/N ratio of 1:1, (**b**) G/N ratio of 1:1.5, and (**c**) G/N ratio of 1:2 at 28 days of curing.

The formulation with a G/N ratio of 1:1.5 shown in Figure 8b exhibited marked microstructural improvement with enhanced gel formation and reduced porosity compared to the lower activator ratio. The increased alkaline content promoted better dissolution of the higher bottom ash content, resulting in more extensive geopolymer network development. However, the microstructure still exhibited some limitations in terms of complete matrix integration, suggesting that further optimization remains beneficial for systems with a high bottom ash content.

Figure 8c presents the formulation with a G/N ratio of 1:2 applied to RCA60BA40, which demonstrated successful activation of the system with a high bottom ash content. The microstructure exhibited well-developed geopolymer networks with effective particle binding and matrix densification. The higher sodium silicate content provided sufficient alkaline activation to promote complete geopolymerization despite the increased aluminosilicate demand, resulting in microstructural characteristics comparable to systems with a lower bottom ash content. This finding validated the optimization approach described by Xu et al. [41], who demonstrated that enhanced silicate availability becomes essential for systems with a high aluminosilicate content.

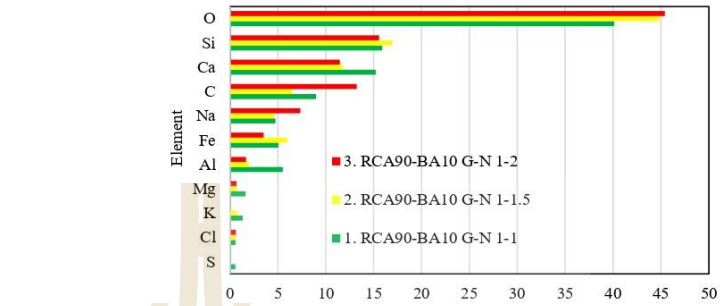
The SEM analysis indicated that the porous BA surface promotes extensive geopolymer gel coating and interfacial bonding, forming a continuous and relatively ductile gel network. This morphology enables microcrack bridging and deflection, forcing cracks to follow tortuous paths and dissipating more energy before failure. Although these BA-rich systems exhibit lower peak compressive strength due to reduced aggregate skeleton rigidity, the interconnected gel network facilitates gradual stress transfer post-peak, thereby improving energy absorption and post-failure ductility.

The microstructural evidence demonstrated that optimal geopolymer formation requires balanced dissolution of aluminosilicate precursors and adequate silicate availability for network formation. The formulation with a G/N ratio of 1:2 consistently produced superior microstructural characteristics across both bottom ash content levels, indicating that this activator composition provided optimal conditions for geopolymerization in waste-derived systems. The research by Singh and Subramaniam [42] supported these findings, demonstrating similar optimization requirements for alkali-activated systems with varying precursor compositions.

4.3. EDX Analysis

EDX analysis provides a quantitative assessment of elemental distributions within the geopolymer matrices and establishes critical relationships between chemical composition and mechanical performance. The systematic evaluation of the RCA90BA10 and RCA60BA40 systems across varying alkaline activator ratios revealed fundamental insights into geopolymerization chemistry and optimization principles for waste-derived construction materials.

The EDX analysis of RCA90BA10 specimens demonstrates systematic chemical composition changes that correlate directly with the observed mechanical performance improvements. Figure 9 reveals that oxygen constitutes the predominant element across all formulations, comprising approximately 45%–48% by weight, which reflects the extensive oxide formation essential for geopolymer network development. This high oxygen content indicates the successful formation of silicate and aluminate networks that constitute the structural backbone of the geopolymer matrix, consistent with the fundamental geopolymer chemistry principles established by Davidovits [12,29].



	S	Cl	K	Mg	Al	Fe	Na	C	Ca	Si	O
3. RCA90-BA10 G-N 1-2		0.60		0.68	1.68	3.51	7.34	13.24	11.48	15.57	45.41
2. RCA90-BA10 G-N 1-1.5		0.57	0.74	0.75	1.97	5.97	4.62	6.50	11.75	16.95	44.85
1. RCA90-BA10 G-N 1-1	0.56	0.57	1.32	1.63	5.51	5.05	4.74	8.99	15.22	15.90	40.12

Figure 9. Chemical compositions of RCA90BA10 formulations at various G/N ratios.

The silicon content exhibited progressive increase with advancing G/N ratios, rising from approximately 12% in the formulation with a G/N ratio of 1:1 to 15% in that with a G/N ratio of 1:2. This enhancement is attributed to the increased availability of dissolved silicate species in higher G/N ratios, which promoted gel formation and improved strength development. The research by Fernández-Jiménez and Palomo [40] demonstrated that elevated silicate availability promotes more extensive polycondensation reactions, which explains the superior mechanical performance observed in formulations with a G/N ratio of 1:2. The concurrent increase in sodium content from 4% to 6% reflects the enhanced alkaline environment necessary for optimal aluminosilicate dissolution and subsequent geopolymer gel formation.

The calcium content demonstrated interesting variation across the G/N series, decreasing from approximately 11% in the formulation with a G/N ratio of 1:1 to 9% in that with a G/N ratio of 1:2. This trend indicates that calcium-based phases, primarily calcium silicate hydrate formations, become relatively less prominent as sodium aluminosilicate hydrate gel formation increased with enhanced silicate availability. The study by Yip et al. [25] confirmed that balanced activator compositions promote synergistic formation of both calcium-based and sodium-based gel phases, optimizing the hybrid binding characteristics observed in the superior performing formulations.

The EDX examination of RCA60BA40 specimens revealed distinct chemical composition patterns that reflect the challenges and optimization requirements associated with increased bottom ash utilization. Figure 10 demonstrates that the oxygen content remains consistently high across all formulations, indicating successful oxide network formation despite the elevated aluminosilicate content. However, the overall distribution of other elements exhibited different patterns compared to the RCA90BA10 system, highlighting the compositional adjustments required for optimal performance in formulations with a high bottom ash content.

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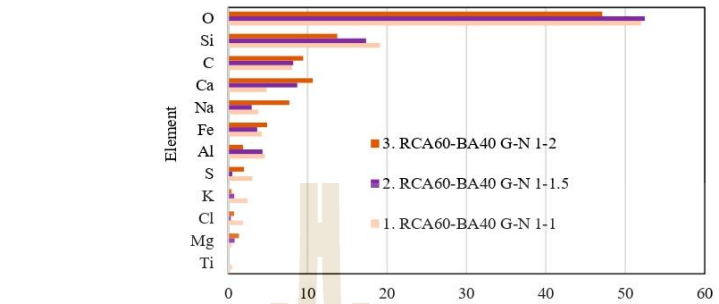

	Ti	Mg	Cl	K	S	Al	Fe	Na	Ca	C	Si	O
3. RCA60-BA40 G-N 1-2		1.36	0.74	0.44	2.00	1.87	4.90	7.70	10.65	9.44	13.73	47.10
2. RCA60-BA40 G-N 1-1.5		0.82	0.34	0.77	0.52	4.33	3.66	2.97	8.71	8.19	17.37	52.47
1. RCA60-BA40 G-N 1-1	0.49	0.42	1.86	2.44	3.04	4.61	4.25	3.82	4.84	8.04	19.13	51.97

Figure 10. Chemical compositions of RCA60BA40 formulations at various G/N ratios.

The silicon content in RCA60BA40 systems indicated less pronounced variation across G/N ratios compared to RCA90BA10, ranging from approximately 13% to 16%. This more moderate increase implies that the higher aluminosilicate content from increased bottom ash provides additional reactive sites that consume the available silicate species more effectively. The research by Singh and Subramaniam [32] established that systems with an elevated aluminosilicate content required enhanced silicate availability to achieve optimal Si/Al ratios for geopolymer formation, which explained the mechanical performance improvements observed with higher G/N ratios in these formulations.

The sodium content progression in RCA60BA40 systems exhibited similar trends to RCA90BA10 but with slightly higher absolute values, reflecting the increased alkaline demand for activating the higher bottom ash content. The aluminum content showed moderate increases across the G/N series, consistent with the enhanced dissolution of aluminosilicate species from the bottom ash under more aggressive alkaline conditions. The study by Lahoti et al. [33] demonstrated that optimal geopolymer formation required balanced dissolution of both silicate and aluminate species, which was achieved through careful activator optimization.

The Si/Al ratio analysis presented in Figure 11 provides critical insights into the geopolymerization optimization principles governing these waste-derived systems. The RCA90BA10 formulations demonstrated that the progressive Si/Al ratio increased from approximately 2.9 with a G/N ratio of 1:1 to 9.3 with a G/N ratio of 1:2, indicating enhanced silicate availability relative to the aluminate content. The research by Lahoti et al. [33] established that Si/Al ratios in the range of 1.5 to 4.0 promote optimal geopolymer network formation, suggesting that the formulations with G/N ratios of 1:1 and 1:1.5 achieve more balanced stoichiometry for geopolymerization compared to the system with a G/N ratio of 1:2.

However, the mechanical performance results indicate that the formulation with the G/N ratio of 1:2 achieved superior strength characteristics despite the elevated Si/Al ratio. This apparent contradiction can be explained by the formation of hybrid gel systems that incorporate both sodium aluminosilicate hydrate and calcium silicate hydrate phases, as described by Cristelo et al. [36]. The excess silicate availability in formulations with a G/N ratio of 1:2 promoted enhanced formation of calcium silicate hydrate phases that com-

plement the primary geopolymer network, resulting in superior mechanical performance through synergistic binding mechanisms.

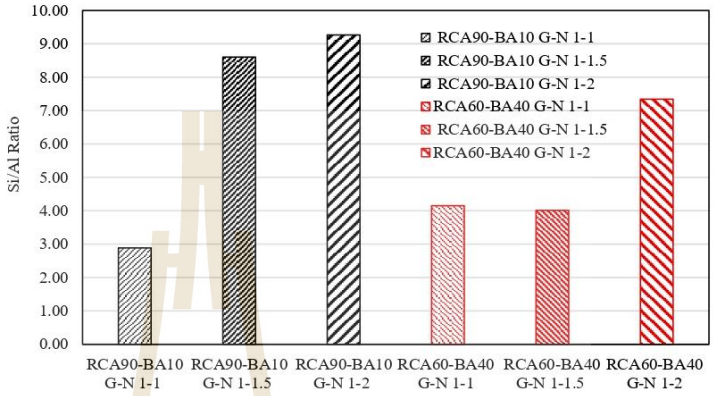

Figure 11. Si/Al ratios of RCA90BA10 and RCA60BA40 with various G/N ratios.

The RCA60BA40 systems exhibited lower Si/Al ratios across all G/N formulations, ranging from approximately 4.2 to 7.4, which reflected the higher aluminosilicate content from increased bottom ash utilization. These ratios remain within ranges that promote effective geopolymer formation while requiring higher activator concentrations to achieve optimal performance. The study by Liu et al. [42] confirmed that Si/Al ratios between 2.0 and 8.0 can produce effective geopolymer systems when properly activated, validating the mechanical performance improvements observed in optimized RCA60BA40 formulations.

4.4. XRD Analysis

The XRD analysis revealed systematic mineralogical transformations that directly correlate with the superior mechanical performance of RCA90BA10 formulations compared to RCA60BA40 systems. The diffraction patterns demonstrated clear evidence of geopolymerization progression and established the crystalline–amorphous phase relationships governing these waste-derived systems.

The XRD patterns in Figure 12 identified four primary crystalline phases across all formulations: quartz (SiO_2), calcite ($CaCO_3$), gehlenite ($Ca_2Al_2SiO_7$), and diopside (CaO-MgO-SiO_2). Quartz exhibited the most prominent peaks at 21°, 27°, and 50° 2θ, remaining stable throughout geopolymerization and serving as an inert aggregate framework. Calcite phases, originating from carbonated cement in the RCA, displayed characteristic peaks at 23°, 29°, and 36° 2θ and contributed to hybrid binding mechanisms through both physical and chemical interactions. The calcium-bearing phases (gehlenite and diopside) show evidence of partial dissolution, particularly in formulations with a higher G/N ratio, indicating their participation in secondary geopolymerization reactions [36,43].

The most significant mineralogical indicator of successful geopolymerization appeared as a broad diffraction hump between 20° and 35° 2θ, representing amorphous sodium aluminosilicate hydrate gel formation. The RCA90BA10 series demonstrated optimal amorphous content development with progressive enhancement from a G/N ratio of 1:1 to 1:2, directly correlating with the superior UCS values achieved by these formulations. The RCA90BA10 composition with a G/N ratio of 1:2 exhibited the most pronounced and well-defined amorphous hump, corresponding to its exceptional compressive strength of 12.45 MPa at 28 days [44,45].

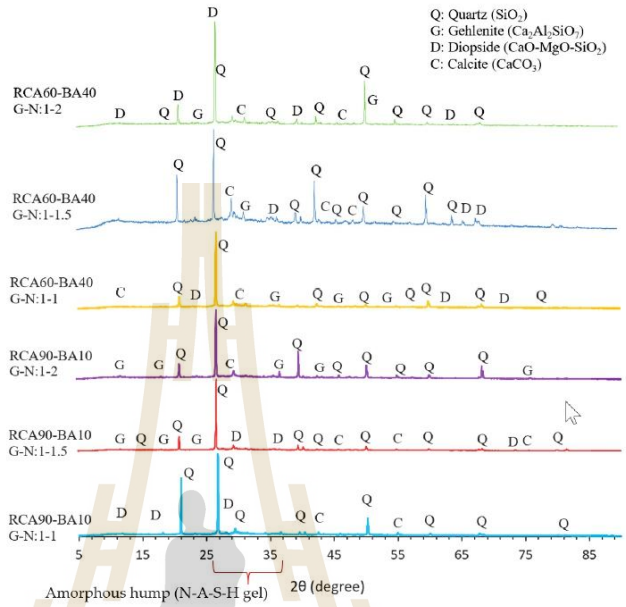

Figure 12. XRD patterns of RCA90BA10 and RCA60BA40 with various G/N ratios.

The comparison between the RCA90BA10 and RCA60BA40 systems revealed fundamental differences in mineralogical development that explain the superior performance of formulations with a lower bottom ash content. While RCA60BA40 compositions show evidence of amorphous gel formation, the patterns indicated less efficient geopolymerization compared to RCA90BA10 systems. The higher bottom ash content in RCA60BA40 formulations created challenges in achieving complete activation, resulting in more persistent crystalline phases and less extensive amorphous network development.

The RCA90BA10 formulations demonstrated a more refined amorphous content with sharper, more defined humps between 20° and 35° 2θ, indicating superior gel quality and network connectivity. This enhanced amorphous content directly correlated with the higher UCS values achieved by RCA90BA10 formulations across all G/N ratios. The research by Bobirică et al. [46] confirmed that an optimal bottom ash content enables more effective geopolymerization, supporting the observed performance superiority of the 10% bottom ash replacement level.

The correlation between amorphous content quality and mechanical strength established clear optimization principles for waste-derived geopolymer systems. The findings demonstrate that a controlled bottom ash content combined with appropriate alkaline activation enables superior mineralogical development and exceptional performance characteristics suitable for demanding pavement applications.

Compared to fly ash (FA)-based geopolymers, BA-based systems exhibit distinct differences in material characteristics and performance. FA consists of fine, spherical particles with high amorphous SiO_2 and Al_2O_3 contents, which enhance reactivity and promote extensive gel formation, resulting in higher UCS. It was seen that its UCS exceeded 15 MPa at 7 days under similar curing conditions [8]. Consequently, an increasing FA content generally leads to higher UCS due to the progressive development of C-S-H and

N-A-S-H gels. In contrast, BA comprises coarser, angular, and more porous particles with higher crystalline quartz and calcite contents, which limit its reactivity. Increasing the BA content beyond 20% reduces UCS as the weaker BA particles and their higher crystalline fraction compromise the aggregate skeleton's load-bearing capacity despite additional gel formation. However, the BA-based geopolymer-stabilized RCA demonstrated adequate structural performance, meeting pavement base strength requirements even at 50% BA replacement, while offering enhanced toughness and significant sustainability benefits through the utilization of 100% waste-derived materials.

Utilizing 1 ton of RCA in place of natural aggregate can reduce landfill waste by approximately 0.8 tons and save up to 20–25 kg of CO_2 compared to virgin aggregate processing [47]. Moreover, using BA in place of cement or virgin binders can further reduce CO_2 emissions by 150–200 kg of CO_2 per ton of cement avoided [48]. Therefore, the use of 100% waste-derived RCA and BA in this study potentially contributed to a reduction of over 200 kg of CO_2 emissions and diverted over 1.5 tons of industrial waste from the landfills per ton of stabilized base material produced.

5. Conclusions

This research successfully demonstrated the viability of BA-based geopolymer stabilized RCA as a high-performance, sustainable pavement subbase material utilizing 100% waste-derived components.

The formulation of RCA90BA10 with a G/N ratio of 1:2 achieved exceptional performance, reaching 9.14 MPa UCS at 7 days and exceeding the Department of Highways, Thailand, requirement of 2.413 MPa. All studied mixtures surpassed minimum specifications regardless of the alkaline activator ratio, demonstrating the robustness of the geopolymer stabilization approach. Toughness evaluation confirmed superior energy absorption capacity of 107.89 N·m for the optimal composition, indicating excellent durability for pavement applications.

Microstructural characterization revealed that higher G/N ratios promoted extensive sodium aluminosilicate hydrate and calcium silicate hydrate gel formation, creating dense matrices that directly correlated with mechanical performance. XRD analysis confirmed successful geopolymerization through pronounced amorphous gel development between 20° and 35° 2θ. The research established that RCA90BA10 achieved optimal balance between reactive aluminosilicate content and structural aggregate framework, while higher bottom ash contents beyond 10% resulted in systematic strength reduction.

The environmental benefits are substantial, with this technology diverting construction demolition waste and power plant byproducts from landfills while reducing greenhouse gas emissions compared to conventional cement-stabilized materials. The superior performance characteristics achieved through waste utilization provide compelling evidence for policy makers and industry practitioners to adopt geopolymer technology for sustainable infrastructure development.

This research advances sustainable construction materials technology by demonstrating that waste-derived geopolymer systems can exceed conventional material performance while addressing critical environmental challenges, providing a viable pathway for next-generation pavement materials that balance structural requirements with environmental responsibility.

While this study demonstrates the mechanical suitability of BA-based geopolymer-stabilized RCA for pavement base applications, further durability validation is essential for real-world deployment. Future research should include freeze–thaw resistance, wet–dry cycling, water absorption, sulfate attack, and acid resistance testing to simulate environmental exposure conditions. In addition, future studies could apply ML models (e.g., ANN and RF) to predict strength and durability based on BA properties, mix ratios, and curing conditions,

aiding in efficient design and quality control [49]. Given the inherent porosity of BA and the alkaline nature of geopolymer matrices, these assessments will provide critical insights into the long-term integrity, dimensional stability, and chemical durability of the developed material in both temperate and tropical field conditions. Furthermore, the variability of BA from different power plants, driven by differences in fuel and combustion conditions, may influence its reactivity and strength development. To ensure consistent performance, source-specific characterization and mix design adjustments are recommended. Developing classification guidelines for BA could support broader and more reliable application in geopolymer stabilization.

The performance of RCA-BA geopolymer mixes can be influenced by the variability of RCA sources. Factors such as the original concrete strength, residual cement content, and particle porosity affect both mechanical properties and alkali activation potential. Stronger or less-weathered RCA may contribute to improved bonding and strength through continued hydration or secondary reactions, potentially shifting the optimal RCA:BA or G/N ratios. Therefore, mix designs should be tailored to specific RCA sources for consistent field performance.

Author Contributions: Conceptualization, M.H. and C.T.; methodology, C.T.; software, C.T.; validation, M.H. and C.T.; formal analysis, M.H.; investigation, C.T.; resources, C.T.; data curation, C.T.; writing—original draft preparation, C.T.; writing—review and editing, M.H.; S.H., A.C., A.S., A.B., T.Y., M.J., and T.S.; visualization, C.T. and M.J.; supervision, M.H. and S.H.; project administration, M.H.; funding acquisition, S.H. and A.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Suranaree University of Technology and the National Research Council of Thailand under the Chair Professor Program, grant number N42A67063.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Acknowledgments: This work was financially supported by the Suranaree University of Technology and the National Research Council of Thailand under the Chair Professor Program [Grant No. N42A670631], Thailand, and by Thailand Science Research and Innovation (TSRI).

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

BA	Bottom ash
C-A-S-H	Calcium aluminosilicate hydrate
C-S-H	Calcium silicate hydrate
DOH	Department of Highways
EDX	Energy-dispersive X-ray spectroscopy
G/N	Sodium silicate to sodium hydroxide
MDD	Maximum dry density
N-A-S-H	Sodium aluminosilicate hydrate
OLC	Optimum liquid content
RCA	Recycled concrete aggregate
SEM	Scanning electron microscopic
UCS	Unconfined compressive strength
XRD	X-ray diffraction

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Cleaner Engineering and Technology 29 (2025) 101080

Contents lists available at ScienceDirect

Cleaner Engineering and Technology

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Performance of natural rubber latex modified bottom ash-based geopolymer stabilized recycled concrete aggregate as a pavement base material

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ARTICLE INFO

Keywords:
Recycled concrete aggregate
Bottom ash
Natural rubber latex
Geopolymer
Microstructure
Unconfined compressive strength
Pavement geotechnics
Ground improvement

ABSTRACT

The present research assessed the performance of natural rubber latex (NRL) modified bottom ash (BA)-based geopolymer stabilized recycled concrete aggregate (RCA) as a sustainable pavement base material. Effects of NRL content (0.1, 0.2 %, and 0.3 % by weight of aggregate) and alkaline activator ratios ($NaOH:Na_2SiO_3$, G/N = 1:1, 1:1., and 1:2) in strength development and microstructure of the stabilized mixtures were evaluated. Unconfined compressive strength (UCS) tests were carried out at 7 and 28 days of curing, and the results were correlated with microstructural analyses using scanning electron microscopy (SEM), energy dispersive X-ray spectroscopy (EDX), and X-ray diffraction (XRD). The findings revealed that the mixture containing 0.1 % NRL and a G/N ratio of 1:1 exhibited the highest UCS values of 4.0 MPa and 5.17 MPa at 7 and 28 days respectively, surpassing the minimum strength requirement for pavement subbase materials. The microstructural analyses confirmed the constitution of a dense and homogeneous geopolymer matrix, with NRL films acting as bridging structures that enhanced the bonding between RCA particles and the matrix. Higher ratios of G/N led to a silica-rich gel that hindered further geopolymerization and strength gain. Meanwhile, a higher ratio of NRL resulted in the formation of thicker NRL films that interfered with the geopolymerization process, resulting in a subsequent strength reduction. The study demonstrates the potential of NRL-modified BA-based geopolymer stabilized RCA as an environmentally friendly and high-performance alternative to conventional cement-stabilized pavement base materials.

1. Introduction

The construction and maintenance of roadway pavements require substantial amounts of raw materials and energy, resulting in significant environmental impacts. Conventional pavements utilize virgin aggregates and cement, which deplete natural resources and produce greenhouse gas emissions. As a result, there is an urgent need for a sustainable pavement material option that minimizes ecological footprints.

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https://doi.org/10.1016/j.clet.2025.101080
Received 13 March 2025; Received in revised form 3 July 2025; Accepted 12 September 2025
Available online 13 September 2025
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Recent estimates indicate that upgrading roadway infrastructure worldwide requires billions of metric tons of concrete and asphalt (Alamgir et al., 2017). The extraction, processing, and transport of raw virgin materials contribute to resource depletion. Cement production alone is responsible for 5–8 % of global carbon dioxide emissions (Ige et al., 2024). Furthermore, the disposal of old pavement material burdens landfills, exacerbating environmental concerns.

In this context, developing alternative eco-friendly pavement solutions has become a priority. The utilization of industrial by-products and recycled waste materials offers prospects for reducing the reliance on virgin resources. Recycled concrete aggregate (RCA) is acquired through the process of recycling concrete from demolished buildings, road infrastructure, and other concrete structures. The reuse and recycling of RCA in new pavement structures not only contributes to reducing waste in landfills but also conserves natural resources by reducing the need for virgin aggregate materials (Sae-Long et al., 2024). However, RCA has some limitations in mechanical performance, necessitating the development of effective geochemical stabilization methods.

The adoption of natural rubber latex (NRL) to modify cement-stabilized RCA has been found to be an innovative approach to enhance the performance and sustainability of pavement base materials (Nhieu et al., 2023). NRL is a milky white liquid extracted from the bark of the rubber tree (Hevea brasiliensis). It is a natural polymer consisting of rubber particles suspended in an aqueous medium. The composition of NRL includes water (50–70 %), rubber particles (30–40 %), and small amounts of proteins, lipids, and other substances (Bottier, 2020).

NRL-modified cement stabilization addresses key limitations of conventional cement-stabilized RCA, including brittle behavior and low tensile strength. The incorporation of NRL improved engineering performance by enhancing compressive and tensile strengths, strain capacity, and toughness.

Similar studies (Hoy et al., 2023) initiated the innovative utilization of NRL to enhance mechanical properties and service life of cement-stabilized recycled materials, particularly RCA and steel slag blended with lateritic soil. It represents a significant advancement in sustainable pavement engineering. This eco-friendly approach combines the benefits of using recycled materials with the unique properties of NRL to create high-performing, resilient, and durable pavement base layers that can withstand the detrimental effects of wetting and drying cycles. The optimization of NRL content in cement-stabilized recycled materials from demolition wastes is crucial to achieving the desired performance improvements. The optimal NRL-to-cement ratios maximize the beneficial effects of NRL while avoiding excessive amounts that can hinder cement hydration and strength development.

Geopolymer technology represents a revolutionary approach in the field of construction materials, offering a sustainable alternative to traditional cement. Geopolymers are formed by the chemical reaction of aluminosilicate materials, such as fly ash (FA) or slag, with alkaline solutions. This reaction produces a dense, three-dimensional network structure that provides excellent mechanical strength, durability, and resistance to chemical attack. In addition, recent studies have also demonstrated the viability of acid-based geopolymer systems, particularly those activated by phosphoric acid or aluminum dihydrogen phosphate, which offer favorable mechanical strength and environmental performance (Pu et al., 2022). Das et al. (2024) reported the potential of compacted geopolymer bricks made from various waste materials for structural and infrastructure applications, including paving units and load-bearing masonry components. The environmental benefits of geopolymer technology are significant, as it utilizes industrial by-products and reduces CO_2 emissions associated with cement production. Several studies have reported on the success of geopolymer-stabilized recycled materials in pavement applications. Mohammadinia et al. (2016) demonstrated that FA and slag-based geopolymers significantly improve the strength of recycled aggregates, particularly RCA. Xie et al. (2024) showed that construction and demolition waste-derived geopolymers effectively enhance subgrade soil properties while reducing environmental impacts. Zhang et al. (2021) confirmed through life cycle assessment that geopolymer road bases can reduce global warming potential by up to 17.9 % compared to cement-stabilized bases. These findings highlight the potential of geopolymer technology in advancing sustainable pavement infrastructure.

The widespread adoption of FA in Portland cement concrete has led to extensive research on FA-based geopolymers, resulting in a comprehensive body of literature. Amran et al. (2021) reported that FA-based geopolymer concrete offers high early strength and durability while significantly reducing CO_2 emissions and landfill disposal. Klima et al. (2022) reviewed the thermal performance of FA geopolymers, noting that potassium-based activators improve fire resistance, making them suitable for high-temperature applications. Li et al. (2022) explored the conversion of FA into porous geopolymers for insulation, filtration, and sound absorption, demonstrating its high-value reuse potential. Rathnayaka et al. (2024) examined machine learning approaches to predict the compressive strength of FA-based geopolymer concrete, addressing the lack of standard mix design procedures. Together, these studies establish FA-based geopolymers as a promising and versatile material for sustainable construction.

However, it was reported that bottom ash (BA)-based geopolymers may exhibit poorer mechanical properties and durability than FA-based geopolymers owing to the lower reactivity and coarser particle size of BA (Chindaprasirt et al., 2009; ul Haq et al., 2014). These performance concerns have hindered the adoption of bottom ash in geopolymer production.

Various additives have been explored to enhance the performance of geopolymer concrete systems while maintaining or improving their sustainability credentials. These additives can be categorized into polymer-based, biopolymer-based, and mineral-based modifiers, each offering distinct benefits for mechanical properties and environmental performance. Polymer modifications effectively overcome brittleness, with metakaolin-based geopolymers modified with epoxy resin showing significant improvements in mechanical performance (Shehata et al., 2022). Biopolymers offer more environmentally responsible alternatives to petroleum-based polymers, making them suitable for green construction (Soldo et al., 2020). Mineral additives also enhance geopolymer performance, with nano-silica improving durability and mechanical properties due to its high surface area (Chiranjeevi et al., 2023). Synthetic polymers like styrene-butadiene rubber have been studied extensively, with latex modified geopolymer concrete demonstrating superior behavior under both static and dynamic loads (Muhammad and Ismail, 2012).

Within the context of sustainable material innovation, the integration of NRL-modified BA in geopolymer stabilization of RCA opens new avenues for high-performance base materials. The inclusion of NRL in the bottom ash geopolymer matrix introduces unique properties to the pavement base material. NRL, known for its elasticity and water resistance, imparts flexibility and resilience to the geopolymer-stabilized RCA. This modification is particularly beneficial for pavement applications, where pavement materials are subjected to dynamic loads and environmental stresses. The NRL not only helps absorb and distribute these loads more effectively, reducing the risk of cracking, but also provides a barrier against moisture infiltration, enhancing the durability of the pavement base.

Despite the advances in geopolymer technology and polymer-modified cementitious systems, significant research gaps remain. While natural rubber latex has been successfully used to modify cement-stabilized materials and FA-based geopolymers separately, the specific combination of NRL-modified bottom ash-based geopolymer for RCA stabilization has not been investigated. The current research attempts to explore the strength development of NRL-modified BA based geopolymer stabilized RCA as a greener material in pavement applications. Geopolymer is formed though the reaction of an aluminosilicate source, such as bottom ash (precursor), with an alkaline activator solution containing sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3).

The alkaline activator solutions were prepared with various Na_2SiO_3: NaOH (G/N) ratios of 1:1, 1:1.5, and 1:2, while the mixtures were modified with NRL at contents of 0.1, 0.2, and 0.3 by weight of the aggregate. The unconfined compressive strength (UCS) test was carried out to determine the strength of the studied mixtures at 7 and 28 days of curing. The strength development was examined through microstructural and mineralogical analyses using scanning electron microscopy (SEM), energy dispersive x-ray spectroscopy (EDS) and x-ray diffraction (XRD), respectively.

As the outcome of this study, linking NRL-modification with the stabilization of RCA with bottom ash geopolymer technology represents a newly frontier in pavement engineering. This collaboration could lead to the development of advanced pavement materials that meet the dual demands of sustainability and performance, catering to the infrastructure needs of the future while adhering to the principles of green construction.

2. Materials and mix design

RCA and BA were used as aggregate and precursor in this research. RCA was collected from construction projects in Ubonratchatani and Sisaket Provinces, Thailand. The RCA had low moisture content (less than 0.3 wt%). Particle size distribution of air-dried RCA was figured out by sieve analysis per ASTM D422-63 (ASTM-D422-63, 2007). Fig. 1 shows that the grading curve of RCA met specifications for subbase material designated by the Department of Highways (DOH), Thailand. RCA had 48.6 % gravel, 47.9 % sand, and 3.5 % fines (passing No. 200 sieve) and no plasticity. In regard to the unified soil classification system (USCS) (ASTM-D2487-17, 2017), RCA was as well-graded gravel (GW). The specific gravity of RCA was 2.7. RCA had Los Angeles abrasion and flakiness index values of 38.1 and 15.6, respectively. The maximum dry unit weight was 18.70 kN/m^3 at an optimum moisture content of 12 % based on a modified Proctor compaction test. Water absorption for coarse and fine RCA was 6.42 % and 7.83 %, respectively.

BA was sourced from the Mae Moh mine, the largest lignite power plant located in northern Thailand. BA particles were irregularly shaped with agglomerations, pores, and angular, rough surfaces, as observed by scanning electron microscopy (SEM) analysis (Fig. 2). Table 1 compiles chemical composition of BA detected by X-ray fluorescent (XRF) analysis. The predominant component in the BA comprised the highest percentage of silicon dioxide (59.50 %), which is a key ingredient that contributes to the pozzolanic activity of the ash. Another main component was aluminum oxide (25.7 %), which has a central role in the geopolymerization process, reacting with silicon dioxide and alkaline activator to form the geopolymer matrix. Constituting a low percentage (2.92 %) of the ash, calcium oxide is known to influence the setting period and strength development in geopolymer. Fig. 3 illustrates the X-ray diffraction (XRD) pattern of BA. The peak intensities, denoted by their counts, showed the relative abundance of the minerals, with gehlenite and diopside being the most prominent. The diversity of crystalline phases indicates that BA can provide a key role when adopted as a precursor in geopolymer manufacturing.

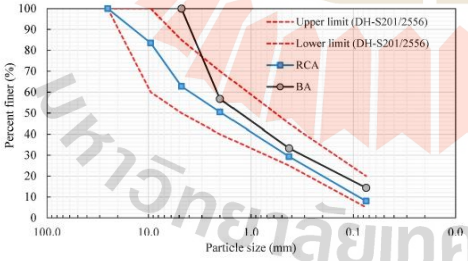


Fig. 1. Gradation of RCA-BA compared to the boundary of subgrade material Type D.

Natural rubber latex (NRL) used in this study was of a low ammonia concentrated latex type, conforming to ISO 2004-1988. The NRL was used as a modifier to boost up the strength of BA-based geopolymer stabilized RCA. NRL was treated with deproteinization agent to remove allergenic proteins, improve latex stability, enhance compatibility with other components, and ultimately contribute to better mechanical properties in the final product. The NRL in this study was in a liquid form, containing both solid and liquid constituents. The total solid content of NRL accounted for 33.06 % of its weight, comprising primarily of dry rubber (30.8 %), sludge (2.46 %), and a minimal coagulum content (0.024 %). The NRL had a specific gravity of 0.96 and pH of 8.

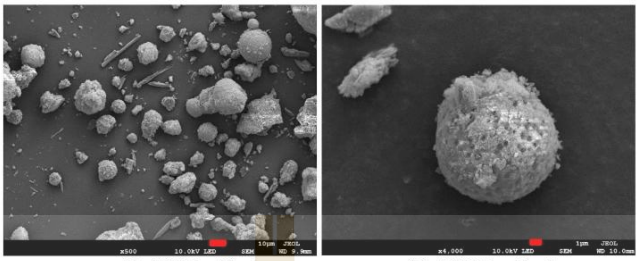
The formulation of the alkaline activator was a critical step in the geopolymer preparation process. It required careful consideration of the chemical composition to ensure effective geopolymerization while minimizing potential hazards.

In this study, an alkaline activator was formulated by blending sodium silicate (Na_2SiO_3) solution with 5M sodium hydroxide (NaOH) solution. The selected Na_2SiO_3 was Type CR53, which contained about 14.5–16.5 wt% Na_2O (sodium oxide) and 31.5–34 wt% SiO_2 (silicon dioxide). This composition provided an optimal balance of silica and sodium necessary for the geopolymerization process. The selection of a 5M NaOH solution was particularly informed by considerations regarding human safety and handling hazards. Previous study (Chindaprasirt et al., 2009) have indicated that higher concentrations of NaOH could pose increased risks due to its highly caustic nature. Hence, the 5M concentration was deemed effective in initiating the dissolution of aluminosilicate materials while maintaining a safer profile for practical use.

The mix design was systematically developed to assess the impact of NRL modification in the properties of BA-based geopolymer stabilized RCA (Table 2). This experimental design methodology followed a systematic parametric approach to optimize the NRL-modified BA-based geopolymer stabilized RCA. The mix design variables were carefully selected to investigate two critical parameters: (1) alkaline activator ratio ($NaOH_2SiO_3$, G/N = 1:1, 1:1.5, and 1:2) and (2) NRL content (0.1 %, 0.2 %, and 0.3 % by weight of aggregate). This factorial experimental design allowed for the evaluation of both individual and interactive effects of these parameters on the mechanical and microstructural properties of the stabilized mixtures. The G/N ratios were selected based on preliminary studies indicating that the optimal range for BA-based geopolymer typically falls between 1:1 and 1:2. Ratios below 1:1 may provide insufficient silica for complete geopolymerization, while ratios above 1:2 can lead to excess unreacted silica that could impair strength development (Chindaprasirt et al., 2009; Suksiripattanapong et al., 2019). The NRL content range (0.1–0.3 %) was determined through preliminary testing to identify the threshold at which NRL begins to adversely affect geopolymer formation. The contents above 0.3 % showed significant reduction in mechanical strength.

The control mixture (70 % RCA + 30 % BA + water) served as a baseline for comparative analysis, allowing for the quantification of performance enhancement achieved through geopolymer and NRL modification. This methodical approach enabled us to identify the optimal combination of alkaline activator ratio and NRL content for achieving the desired balance between mechanical strength, durability, and economic viability for pavement subbase applications.

The RCA and BA were first dry-mixed to achieve a uniform distribution. The alkaline activator solution was then gradually added and stirred until a homogenous. Finally, NRL was incorporated at the predetermined percentage with thorough blending to ensure even distribution. The resulting mixtures were cast into a cylindrical mold with 101.6 mm in diameter and 116.4 mm in height. Each mixture was compacted under a modified Proctor compaction effort to determine its maximum dry density (MDD) and optimum liquid content (OLC). The



(a) x500 Magnification (b) x4000 Magnification

Fig. 2. SEM image of bottom ash.

Table 1
Chemical compositions of bottom ash.

Component (%)	Value
Silicon dioxide (SiO_2)	59.50
Aluminum oxide (Al_2O_3)	25.70
Iron oxide (Fe_2O_3)	6.07
Calcium oxide (CaO)	2.92
Magnesium oxide (MgO)	0.80
Potassium oxide (K_2O)	1.56

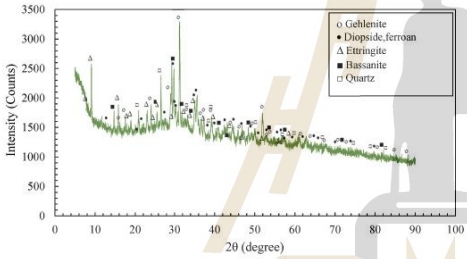


Fig. 3. XRD pattern of bottom ash.

sample was then prepared at MDD and OLC of each studied mixture for unconfined compressive strength test. Samples were mantled with plastic sheeting to forbid moisture evaporation. After one day the samples were demolded and further cured at a room temperature (25±2°) until the testing ages at 7 and 28 days.

3. Laboratory experimental program

The experimental program was meticulously designed to evaluate the strength and microstructure of NRL-modified BA-based geopolymer stabilized RCA. The program consisted of two main testing categories: mechanical tests and microstructural analysis.

3.1. Modified compaction test

Samples were compacted in accordance with ASTM D1557 (ASTM-D1557-12, 2012), ensuring optimal compaction and consistent density across all samples. The compaction procedure was instrumental in simulating field compaction conditions and providing samples that represent MDD and OLC.

Table 2
The mix design of NRL-modified BA-based geopolymer stabilized RCA in this study.

Sample ID	Mixture ingredient	Alkaline Activator	NRL (%)
		$NaOH/Na_2SiO_3$ (G/N) ratio	By weight of aggregate
70RCA30BA (Control)	70RCA + 30BA + water	–	–
G/N1:1NRL0.1	70RCA + 30BA + (1) NaOH + (1) Na_2SiO_3 + NRL (0.1)	1	0.1
G/N1:1NRL0.2	70RCA + 30BA + (1) NaOH + (1) Na_2SiO_3 + NRL (0.2)	1	0.2
G/N1:1NRL0.3	70RCA + 30BA + (1) NaOH + (1) Na_2SiO_3 + NRL (0.3)	1	0.3
G/N1:1.5NRL0.1	70RCA + 30BA + (1) NaOH + (1.5) Na_2SiO_3 + NRL (0.1)	1.5	0.1
G/N1:1.5NRL0.2	70RCA + 30BA + (1) NaOH + (1.5) Na_2SiO_3 + NRL (0.2)	1.5	0.2
G/N1:1.5NRL0.3	70RCA + 30BA + (1) NaOH + (1.5) Na_2SiO_3 + NRL (0.3)	1.5	0.3
G/N1:2NRL0.1	70RCA + 30BA + (1) NaOH + (2) Na_2SiO_3 + NRL (0.1)	2	0.1
G/N1:2NRL0.2	70RCA + 30BA + (1) NaOH + (2) Na_2SiO_3 + NRL (0.2)	2	0.2
G/N1:2NRL0.3	70RCA + 30BA + (1) NaOH + (2) Na_2SiO_3 + NRL (0.3)	2	0.3

3.2. Unconfined compressive strength

At the target curing time, the samples were subjected to an unconfined compressive strength (UCS) test. Cylindrical specimens with dimensions of 101.6 mm diameter and 116.4 mm height were used for testing. The UCS test was carried out in compliance with ASTM D2166 (ASTM-D2166-06, 2006) at a rate of 1 mm/min to track the strength development of geopolymer over time. The peak load was measured, and the compressive strength was calculated to assess the NRL's contribution to the overall structural integrity of the geopolymer matrix. Three replicate specimens were tested for each mixture at both 7 and 28 days of curing, and the average values along with standard deviations were reported to account for test variability.

3.3. Scanning electron microscopy (SEM) analysis

SEM analysis was employed to visualize the microstructure of the geopolymer samples at a high magnification. This analysis provides illumination in the dissemination of NRL within the matrix, the bonding at the RCA-BA interface, and the morphology of the geopolymer binder. The SEM examination was conducted on fractured samples post-UCS testing to identify the failure mechanisms and to correlate the mechanical test results with the microstructural characteristics.

3.4. X-ray diffraction (XRD) analysis

XRD analysis was utilized to diagnose the crystalline phases present within the geopolymer matrix and to observe the changes in mineralogy due to the addition of NRL and variation in the alkaline activator mixture. The XRD patterns were collected using a diffractometer, with samples being scanned in a 2Theta range typically between 5° and 80°. The resultant diffractograms were analyzed to determine the presence of specific crystalline compounds and to infer the geopolymerization process's effectiveness.

4. Results and discussion

This section presents the experimental findings and their interpretation, focusing on the mechanical performance and underlying microstructural mechanisms. The results demonstrate how NRL content and alkaline activator ratios influence strength development, with detailed microstructural and mineralogical analyses providing insights into the optimization mechanisms.

4.1. Unconfined compressive strength development

The UCS results, shown in Fig. 4, demonstrated the influence of NRL content and alkaline activator ratio on the strength development of BA-based geopolymer stabilized RCA mixtures at 7 and 28 days of curing.

At 7 days, the UCS of the NRL-modified mixtures ranged from 1.30 to 4.05 MPa, while the control mix (RCA70BA30 blend) exhibited a UCS of 0.63 MPa. The highest UCS was achieved by the mixture with 0.1 % NRL and a G/N ratio of 1:1, followed by the mixtures with 0.2 % and 0.3 % NRL at the same G/N ratio. This trend suggests that a lower NRL content and a balanced G/N ratio contribute to better early-age strength development.

After 28 days of curing, the UCS values of the NRL-modified mixtures increased significantly, ranging from 1.88 to 5.17 MPa, while the control mix reached 1.04 MPa. The mixture with 0.1 % NRL and a G/N ratio of 1:1 continued to exhibit the highest UCS, indicating its optimal composition for strength development. The mixtures with higher G/N ratios (1:1.5 and 1:2) showed relatively lower UCS values compared to those with a G/N ratio of 1:1. This implies that an excessive amount of Na_2SiO_3 in the alkaline activator may hinder the strength gain. This may be due to the optimal silica to alumina ratio, which is critical in forming a strong geopolymer network. However, as the silica content increased in the activator solution (G/N ration of 1:1.5 and 1:20), the UCS values tended to decrease. This decrease could be attributed to an excess of silica leading to a less reactive system where the silica is not effectively utilized, resulting in a weaker matrix (Bajpai et al., 2020).

The American Association of State Highway and Transportation Officials (AASTHO) provides guidance on the minimum strength requirements for pavement layers in their mechanics-empirical pavement design guide, which indicates that the minimum 28-day UCS requirement for a subbase material is 1.72 MPa (AASHTO, 2008). This strength criterion ensures that the subbase layer possesses sufficient bearing capacity and stability to support the upper layers and distribute the traffic loads effectively to underlying layers.

Fig. 4 is evident that all the NRL-modified BA-based geopolymer stabilized RCA mixtures, irrespective of the G/N ratio (1:1, 1:1/5, and 1:2) or NRL content (0.1 %, 0.2, and 0.3 %), surpass the minimum requirement of 1.72 MPa specified by AASHTO (2008) for subbase materials. It was noteworthy that even the control mixture (RCA70BA30 blend without geopolymer or NRL modification) achieved a 28-day UCS of 1.0 MPa, which is lower than the minimum requirement of 1.72 MPa for subbase materials. This indicated the significant enhancement in strength and performance brought about by the NRL-modified BA-based geopolymer stabilization of the RCA. The improvement in compressive strength at lower NRL content is likely due to the formation of thin polymer films that enhance particle bonding, as also reported by Jitsangiam et al. (2022).

The synergistic effect of the alkaline activator ratio (G/N) and NRL content on the strength development of BA-based geopolymer stabilized RCA mixture was evident from UCS results. The combination of a lower G/N ratio and an optimal NRL content led to a remarkable strength improvement of the stabilized mixtures. The lower G/N ratio of 1:1 ensured a sufficient concentration of sodium hydroxide, which is essential for the dissolution of precursors and the generation of a stable geopolymer gel. Simultaneously, the presence of NRL at an optimum content of 0.1 % or 0.2 % enhanced the interlink between RCA particles and geopolymer matrix, resulting in a more compact and resilient structure. This synergistic effect was particularly evident when comparing the UCS values of the mixtures with other G/N ratios and NRL contents. The mixture with 0.1 % NRL at a G/N = 1:1 achieved the highest UCS of 4.05 MPa at 7 days and 5.17 MPa at 28 days, surpassing the minimum requirement. In contrast, mixtures with higher G/N ratios

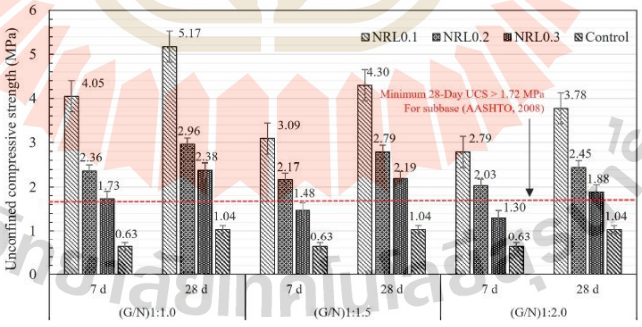


Fig. 4. UCS of NRL-modified BA-based geopolymer stabilized RCA.

or excessive NRL contents showed relatively lower UCS values, indicating the importance of optimizing both parameters simultaneously.

In other words, to investigate the influence of alkaline activator ratio on strength development, comparisons were made for mixtures containing 0.1 % NRL at different G/N ratios. The G/N ratio of 1:1 achieved the highest strength gain from 7 to 28 days (27.7 % increase, from 4.05 to 5.17 MPa), followed by G/N 1:1.5 (25.4 % increase, from 2.36 to 2.96 MPa) and G/N 1:2 (37.6 % increase, from 1.73 to 2.38 MPa). Although the G/N 1:2 ratio showed the highest percentage gain between 7 and 28 days, its absolute strength value remained significantly lower than the G/N 1:1 mixture.

When comparing across G/N ratios at 28 days for 0.1 % NRL content, the strength decreased progressively: 5.17 MPa (G/N 1:1) > 2.96 MPa (G/N 1:1.5) > 2.38 MPa (G/N 1:2), representing 42.7 % and 54.0 % strength reductions for G/N 1:1.5 and 1:2 respectively, compared to G/N 1:1. This trend demonstrates that increasing the Na_2SiO_3 content beyond the optimal ratio adversely affects strength development, likely due to excess silica hindering the geopolymerization process.

The synergy between the G/N ratio and NRL content enhances the strength development and contributes to the overall performance of the stabilized mixtures. The optimized combination of these two factors results in a geopolymer matrix with improved bonding, flexibility, and resistance to cracking, which are crucial for the long-term performance of subbase materials.

These results highlighted the potential of NRL modification in enhancing the strength of BA-based geopolymer stabilized RCA mixtures. The incorporation of NRL improves the bond strength between the RCA and the geopolymer matrix, leading to better load transfer and high compressive strength. The optimal NRL content and G/N ratio identified in this study, particularly the mixture with 0.1 % NRL at a G/N ratio of 1:1, demonstrated the potential for developing high-performance and sustainable subbase materials that can meet the strength requirement.

4.2. Microstructural analysis

SEM analysis provided valuable vision into the microstructural characteristics of the NRL-modified BA-based geopolymer stabilized RCA mixtures. The SEM images illustrated the impact of the G/N ratio and NRL content on the morphology, bonding, and formation of geopolymer products within the matrix.

4.2.1. Effect of G/N ratio on microstructural property

The effect of the G/N ratio on the microstructure is illustrated in Fig. 5, which depicts the SEM images of the control mixture (RCA70BA30) and NRL-modified BA-based geopolymer mixtures with varying G/N ratios (1:1, 1:1.5, and 1:2) at a constant NRL content of 0.1 %. The control mixture (Fig. 5a) exhibited a relatively porous and heterogeneous microstructure, with visible voids and weak bonding between the RCA and BA particles. This microstructural characteristic corresponds with its lower UCS values shown in Fig. 4.

In contrast, the NRL-modified BA-based geopolymer mixture with a G/N ratio of 1:1 (Fig. 5b) showed a more compact and denser microstructure, with enhanced bonding between the RCA particles and the matrix. This improvement in microstructural properties is attributed to the balanced combination of the alkaline activator (G/N), which facilitates effective geopolymerization and the formation of stable geopolymer products, such as C-A-S-H and N-A-S-H gels (Yip et al., 2008, Provis and Van Deventer, 2009, 2008). Santa et al. (2021) indicated that the geopolymerization of the BA-based geopolymer involves the dissolution of the aluminosilicate BA in an alkaline activator solution, followed by the polycondensation of the leached Al and Si species to form geopolymer gels. The presence of these gels is critical for the strength development and durability of the geopolymer matrix (Davidovits, 2005; Duxson et al., 2007a, 2007b). The NRL films could be observed as thin, bridging structures that heighten the interface bonding between the RCA particles and the geopolymer gel products.

As the G/N ratio increased to 1:1.5 (Figs. 5c) and 1:2 (Fig. 5d), the NRL films were still present, acting as bridging structures, but the overall microstructure notably changed compared to the mixture with a G/N ratio of 1:1. It was found that an overly high silica content could lead to the development of a silica-rich gel layer on the surface of the BA and RCA particles, hindering the further dissolution of aluminosilicate species and resulting in an incomplete geopolymerization reaction. In other words, the excess soluble silica provided by the sodium silicate

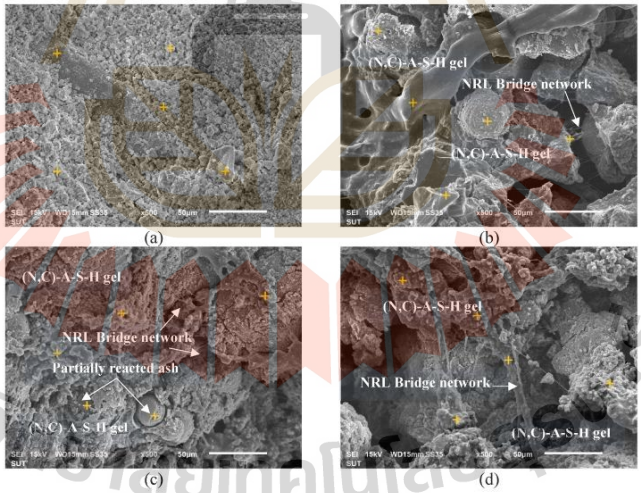


Fig. 5. SEM-EDX analysis of NRL-modified BA-based geopolymer stabilized RCA samples: a) RCA70BA30 (Control), b) G/N1:1.0NRL0.1, c) G/N1:1.5NRL0.1, and d) G/N1:2.0NRL0.1.

(Na_2SiO_3) contributes to the formation of a more silica-rich gel, known as poly(sialate-siloxo) or PSS gel (Bhagath Singh and Subramaniam, 2017; Kim et al., 2016; Sivasakthi et al., 2021). It can form a barrier layer on the surface of the unreacted grains, therefore weaken the overall strength and integrity of the geopolymer matrix.

The EDX analysis presented in Table 3 provided insights into the elemental composition of the NRL-modified BA-based geopolymer stabilized RCA mixtures. The major elements analyzed included carbon (C), oxygen (O), iron (Fe), sodium (Na), calcium (Ca), aluminum (Al), and silicon (Si). Several research reported that Si/Al ratio is a crucial parameter influencing the geopolymerization process and the properties of the geopolymer (Davidovits, 2005; Duxson et al., 2007a, 2007b).

The control mixture, consisting of 70 %RCA and 30 %BA without any geopolymer or NRL, serves as a baseline for comparison. The EDX analysis revealed that the control mixture had a high Si/Al ratio of 17.6, indicating a predominance of silicon-rich compounds in the blend. The presence of calcium (1.83 %) suggested the potential formation of calcium-containing phases, such as calcium silicate hydrate in the mixture.

The incorporation of the NRL and BA-based geopolymer in the RCA mixture led to significant changes in the elemental composition of G/N1:1NRL0.1 mixture compared to the control mixture. The Si/Al ratio decreased from 17.6 in the control mixtures to 5.80 in the G/N1:1NRL0.1 mixture. This decrease could result from the dissolution of aluminum-rich compounds from the BA during the geopolymer process, resulting in a less Si/Al in the geopolymer gel. Additionally, the G/N1:1NRL0.1 mixture exhibited a higher calcium content (6.69 %) benchmarked with the control mixture. The augmented calcium was attributed to the development of C-A-S-H gel alongside N-A-S-H gel in the geopolymer matrix.

As the G/N ratio augmented from 1:1 to 1:1.5, and 1:2, the Si/Al ratio in the stabilized mixtures also increased from 5.80 to 7.10 and 8.40, respectively. This rise in the Si/Al ratio was attributed to the higher amount of soluble silica provided by the increased Na_2SiO_3 content in the alkaline activator solution.

The optimized combination of NRL content and G/N ratio in the NRL-modified mixtures, particularly the mixture with 0.1 % NRL and a G/N ratio of 1:1, capitalized on the beneficial effects of a lower Si/Al ratio and the presence of calcium. This synergistic effect contributed to the enhanced mechanical properties and microstructural characteristics of the NRL-modified BA-based geopolymer stabilized RCA mixtures.

4.2.2. *Effect of NRL on microstructural property*

Fig. 6 presents the SEM images of NRL-modified mixtures with varying NRL contents (0.1 %, 0.2 %, and 0.3 %) at a constant G/N ratio of 1:1. The mixture with 0.1 % NRL (Fig. 6a) exhibited a dense and homogeneous microstructure, with a well-developed geopolymer gel network. The NRL films formed thin, continuous bridging structures that enhanced the interface bonding between the RCA particles and geopolymer matrix. The physical interaction is in reference to the mechanical interlocking of the NRL film with the rough and porous surface of the matrix. The NRL film penetrated the surface irregularities and pores of the RCA particles, creating a physical anchor that enhances the linkage between the particles and the matrix. This implies that the synergistic characteristic between the NRL films and geopolymer gels can lead to the strength development of BA-based geopolymer stabilized RCA.

As the NRL content increased to 0.2 % (Figs. 6b) and 0.3 % (Fig. 6c), the microstructure remained relatively compact and homogeneous, but the NRL films became thicker and more prominent. The thicker NRL films might contribute to a slightly more ductile behavior of the geopolymer matrix. However, the excessive thickness of the NLR films at higher content might lead to a decrease in dissolution of aluminosilicate-rich BA during the geopolymer process and resulted in sluggish strength development.

The findings indicated an intricate interplay between the G/N ratio, NRL content, and the resulting UCS. The microstructural observations from the SEM-EDX analysis corroborated the findings from the UCS results, where the mixture with 0.1 % NRL and a G/N ratio of 1:1 exhibited the paramount strength development. The dense and homogeneous microstructure, the existence of well-developed (N,C)-A-S-H gels, and the effective bridging mechanism provided by the thin NRL films contribute to the superior mechanical performance of this mixture.

4.3. *XRD analysis*

XRD analysis provides valuable information on the mineralogical composition and the formation of geopolymer reaction products in the NRL-modified BA-based geopolymer stabilized RCA mixtures. To examine the impact of NRL content and G/N ratios on the polymerization process and the resulting geopolymer products, the XRD patterns of NRL-modified samples with varying G/N ratios and NRL contents were examined and compared with the control sample (RCA70BA30).

Fig. 7 presents the XRD patterns of the control sample, which comprises 70 % RCA and 30 % BA without any geopolymer or NRL modification. The XRD pattern exhibited sharp humps relative to the crystalline phases available in the RCA and BA, such as quartz (SiO_2), calcite ($CaCO_3$), and hematite (Fe_2O_3). The absence of broad humps in the XRD pattern indicated the lack of amorphous geopolymer gel formation in the control sample.

Fig. 8 demonstrates the XRD patterns of the NRL-modified BA-based geopolymer stabilized RCA samples with varying G/N ratios (1:1, 1:1.5, and 1:2) at a constant NRL content of 0.1 %. The XRD patterns of the NRL-modified samples exhibited a notable abatement in the intensity of the crystalline peaks compared to the control sample. This reduction in peak intensity suggested the dissolution of the crystalline phases and the development of amorphous geopolymer gel products (El Alouani et al., 2024; Sinha et al., 2014). In addition, the XRD patterns showed a gradually increase in the background hump between 20° and 40° 2θ, indicating the formation of amorphous geopolymer gel (Bobirică et al., 2020). The broad hump was more pronounced in the sample with a G/N ratio of 1:1, implying a higher degree of geopolymerization and the formation of a more extensive amorphous geopolymer network.

Fig. 9 presents the XRD patterns of the NRL-modified BA-based geopolymer stabilized RCA samples with varying NRL contents (0.1 %, 0.2 %, and 0.3 %) at a constant G/N ratio of 1:1. The XRD patterns of the NRL-modified samples showed a significant abatement in the intensity of the crystalline peaks compared with the control sample, indicating the dissolution of the crystalline phases and the formation of amorphous geopolymer gel (Kumar and Revathi, 2020). The sample with 0.1 % NRL showed the lowest intensity of the crystalline peaks and most pronounced broad hump, indicating the optimal NRL content for promoting

Table 3
EDX analysis of NRL-modified BA-based geopolymer stabilized RCA mixtures.

Sample IDs	Major elements analyzed (all results in weight%)							Si/Al ratio
	C	O	Fe	Na	Ca	Al	Si	
70RCA30BA (control)	9.57	51.82	1.07	4.87	1.83	1.75	30.74	17.6
G/N1:1.0NRL0.1	37.90	31.15	1.05	2.54	6.69	3.03	17.62	5.80
G/N1:1.5NRL0.1	39.28	32.67	1.33	2.63	6.75	2.38	16.79	7.10
G/N1:2.0NRL0.1	38.94	33.34	1.45	2.79	6.81	1.88	15.72	8.40

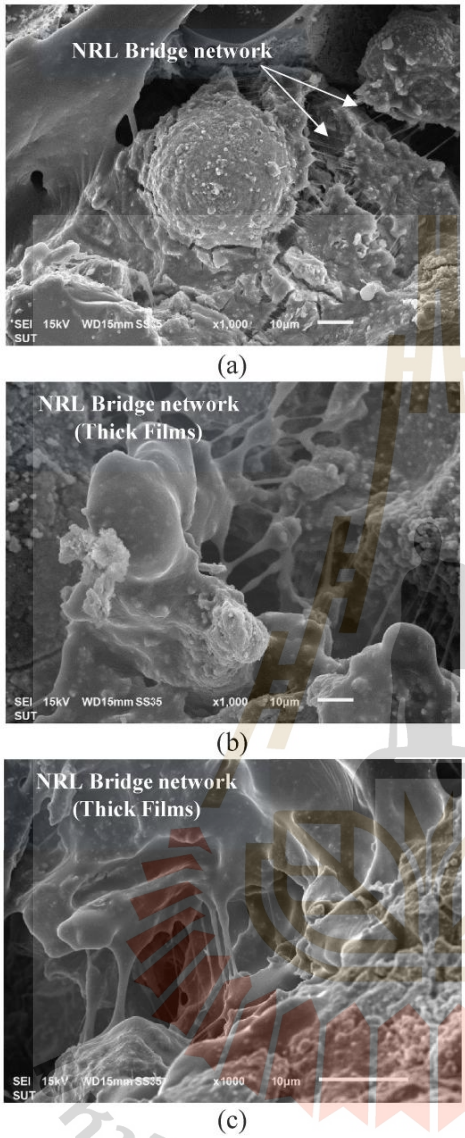


Fig. 6. SEM images of NRL-modified BA-based geopolymer stabilized RCA samples: a) G/N1:1.0NRL0.1, b) G/N1:1.0NRL0.2, and c) G/N1:1.0NRL0.3.

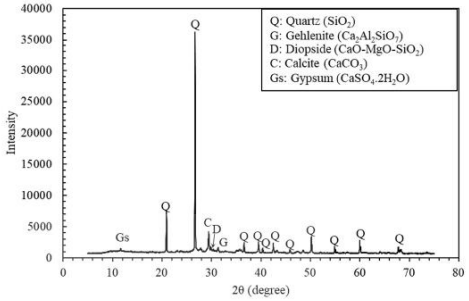


Fig. 7. XRD patterns of RCA70BA30 (Control sample).

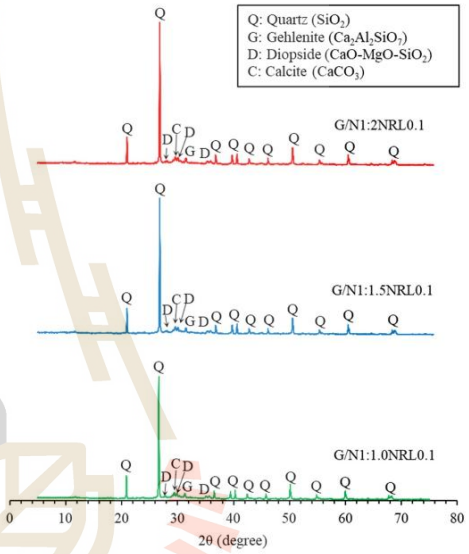


Fig. 8. XRD patterns of NRL-modified BA-based geopolymer stabilized RCA samples.

geopolymerization and the formation of amorphous geopolymer gel products. Furthermore, as the NRL content increased from 0.1 % to 0.3 %, the XRD patterns revealed the existence of residual crystalline phases, such as quartz and calcite, which have not been completely dissolved during the geopolymerization process. This resulted in a slow strength development.

The XRD analysis supported the findings from the microstructural characterization by SEM analysis and the mechanical testing that G/N ratio and NRL content played a significant role in the geopolymerization process. It was found that the sample containing 0.1 % NRL and a G/N ratio of 1:1 exhibiting the most pronounced geopolymerization and amorphous geopolymer gel formation. This finding highlighted the effectiveness of the NRL-modified BA-based geopolymer in stabilizing RCA and producing a sustainable and high-performance pavement base material.

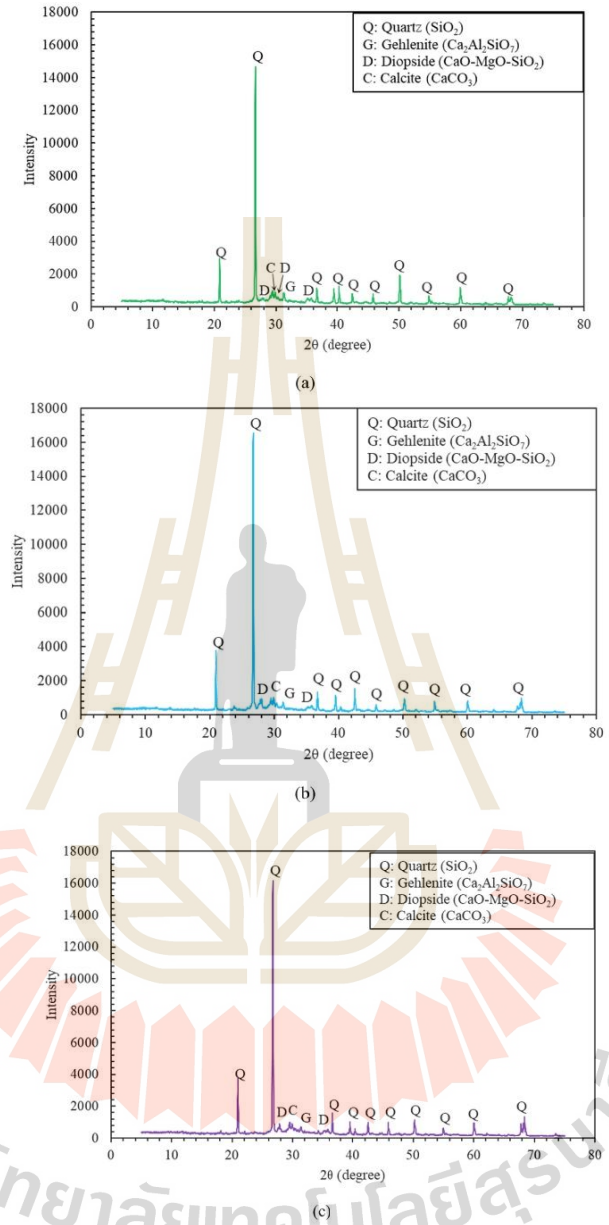


Fig. 9. XRD patterns of NRL-modified BA-based geopolymer stabilized RCA samples: a) G/N1:1.0NRL0.1, b) G/N1:1.0NRL0.2, c) G/N1:1.0NRL0.3.

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5. Conclusions

This study evaluated the performance of NRL modified BA-based geopolymer stabilized RCA as a sustainable subbase material. The influence of NRL content (0.1 %, 0.2 %, and 0.3 % by weight of aggregate) and alkaline activator ratios (G/N = 1:1, 1:1.5, and 1:2), on the strength development and microstructure characteristics was systematically investigated. The key conclusions are as follows:

1. The incorporation of NRL and the optimization of the alkaline activator ratio significantly influenced the UCS and microstructure of the geopolymer stabilized RCA. All the NRL-modified BA-based geopolymer stabilized RCA mixtures, irrespective of the G/N ratio (1:1, 1:1/5, and 1:2) or NRL content (0.1 %, 0.2, and 0.3 %), surpassed the minimum requirement of 1.72 MPa for subbase materials.
2. The optimum formulation, containing 0.1 % NRL and a G/N ratio of 1:1, achieved the highest UCS values of 4.05 MPa at 7 days and 5.17 MPa at 28 days, exceeding the AASTHO-recommended minimum strength (1.72 MPa) for subbase applications by 200 %.
3. Microstructure analyses (SEM, EDX, and XRD) confirmed that the NRL formed thin, elastic films that enhanced bonding at the RCA-geopolymer interface and contributed to the formation of a dense and homogeneous matrix.
4. Higher G/N ratios (1:1.5 and 1:2) led to the formation of a silica-rich gel, which limited precursor dissolution and suppressed strength gain. Similarly, excessive NRL content produced thicker films that interfered with the geopolymerization process.
5. The proposed stabilization approach utilizes locally available industrial by-products and renewable bio-based modifiers, offering a low-carbon high-performance alternative to conventional cement-stabilized subbase materials.

To further validate the applicability of this technique, future studies will focus on long-term durability, field performance under traffic loading, and the integration of logic-tree or AI-based optimization for broader engineering deployment.

CRediT authorship contribution statement

Chokchai Traiyasut: Writing – original draft, Methodology, Investigation, Data curation. **Menglim Hoy:** Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Conceptualization. **Suksun Horpibulsuk:** Writing – review & editing, Visualization, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Apichat Suddeepong:** Validation, Resources. **Apinun Buritatum:** Formal analysis, Data curation. **Teerasak Yaowarat:** Software, Formal analysis. **Artit Udomchai:** Visualization, Validation. **Arul Arulrajah:** Writing – review & editing, Validation. **Avirut Chinkulkijniwat:** Visualization, Validation, Data curation. **Punvalai Choenklang:** Writing – original draft, Validation, Investigation.

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 financially supported by National Research Council of Thailand under the Chair Professor program [Grant No. N42A670631] and Suranaree University of Technology.

Data availability

Data will be made available on request.

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