

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>
- Traiyasut, C., Hoy, M., Horpibulsuk, S., Suddeepong, A., Buritatum, A., Yaowarat, T., Udomchai, A., Arulrajah, A., Chinkulkijniwat, A., & Choenklang, P. (2025). Performance of natural rubber latex modified bottom ash-based geopolymer stabilized recycled concrete aggregate as a pavement base material. *Cleaner Engineering and Technology*. <https://doi.org/10.1016/j.clet.2025.101080>



Article

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

Menglim Hoy^{1,2,*}, Chokchai Traiyasut³, Suksun Horpibulsuk^{1,2,3,4,5}, Avirut Chinkulkijniwat^{1,*}, Apichat Suddeepong⁶, Apinun Buritatum^{2,5}, Teerasak Yaowarat^{2,5}, Mantana Julvorawong¹ and Thanaset Savetviwat¹

¹ Institute of Engineering, School of Civil Engineering, Suranaree University of Technology, Nakhon Ratchasima 30000, Thailand; suksun@g.sut.ac.th (S.H.); mantana.ju@sut.ac.th (M.J.); thanasetbookz@gmail.com (T.S.)

² Center of Excellence in Innovation for Sustainable Infrastructure Development, Suranaree University of Technology, Nakhon Ratchasima 30000, Thailand; apinun_ce@sut.ac.th (A.B.); yaowarat@sut.ac.th (T.Y.)

³ Graduate Program in Civil Engineering and Construction Management, Suranaree University of Technology, Nakhon Ratchasima 30000, Thailand; ts.chokchai@gmail.com

⁴ The Royal Society of Thailand, Bangkok 10300, Thailand

⁵ Program in Civil and Infrastructure Engineering, Suranaree University of Technology, Nakhon Ratchasima 30000, Thailand

⁶ Institute of Research and Development, Suranaree University of Technology, Nakhon Ratchasima 30000, Thailand; suddeepong@g.sut.ac.th

* Correspondence: menglim@g.sut.ac.th (M.H.); avirut@sut.ac.th (A.C.)

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 Na₂SiO₃: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.



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>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

Keywords: recycle concrete aggregate; bottom ash; geopolymers; 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 CO₂ 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 CO₂ 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 $\text{Na}_2\text{SiO}_3\text{:NaOH}$ (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.

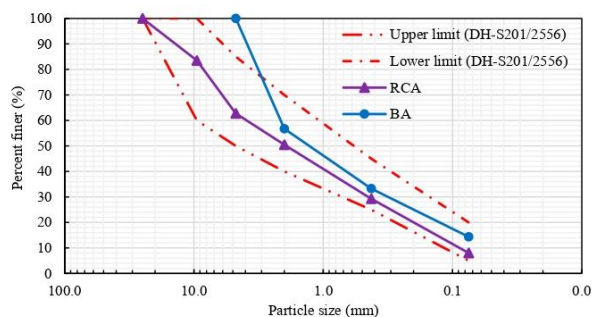


Figure 1. Graduation of RCA and BA.

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).

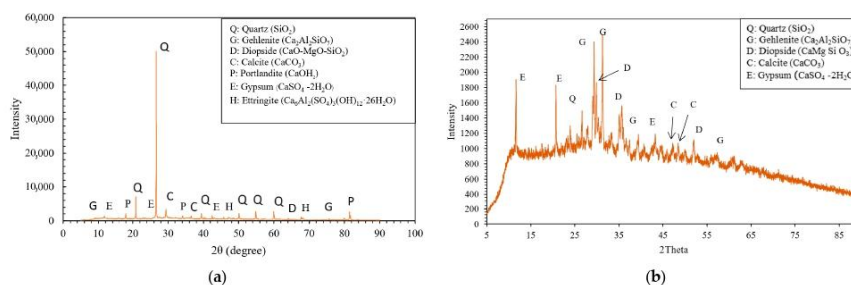


Figure 2. XRD patterns of (a) RCA and (b) BA.

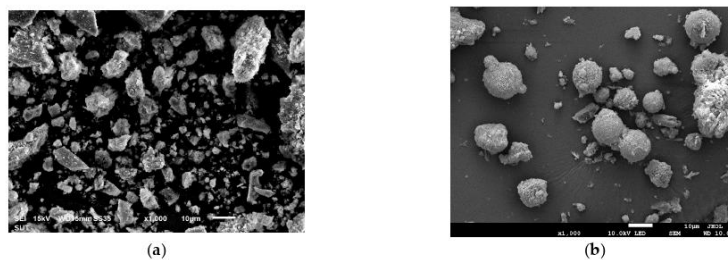


Figure 3. SEM images of (a) RCA and (b) BA.

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 $\text{Ca}(\text{OH})_2$ 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).

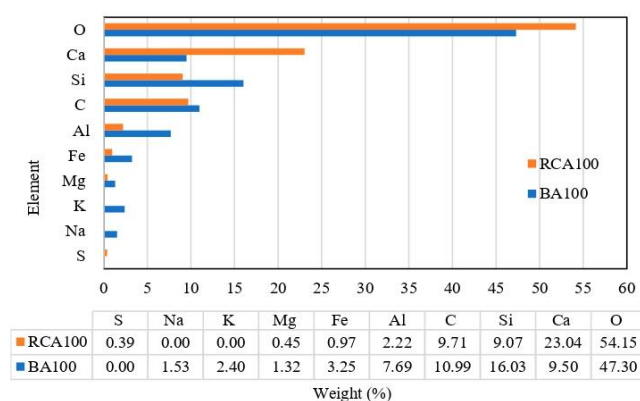


Figure 4. Chemical compositions RCA and BA obtained from EDX.

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: $1.52 \pm 0.02 \text{ g/cm}^3$, and viscosity of 400–600 cP. The NaOH solution was prepared by dissolving analytical-grade NaOH pellets ($\geq 99\%$ purity) in distilled water to achieve a concentration of 10 M (400 g/L). Both solutions were equilibrated for 24 h at ambient temperature ($25 \pm 2 \text{ °C}$) 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 $\text{Na}_2\text{SiO}_3\text{:NaOH}$ (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 $\times$ 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 $\pm 2\%$ 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 $\times$ 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 2θ 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.

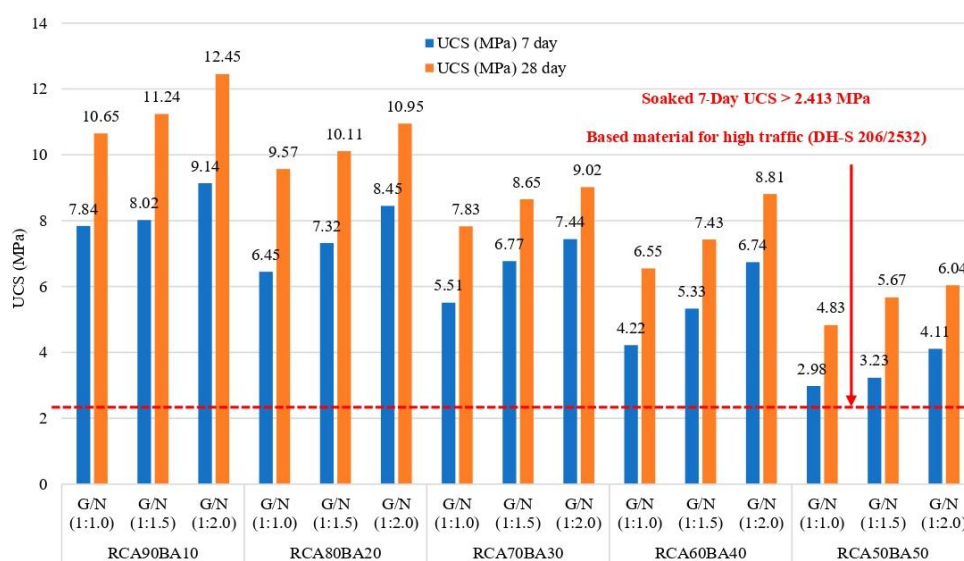


Figure 5. UCS of BA-based geopolymer-stabilized RCA samples at 7 and 28 days of ambient curing.

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 $\text{SiO}_2/\text{Na}_2\text{O}$ 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].

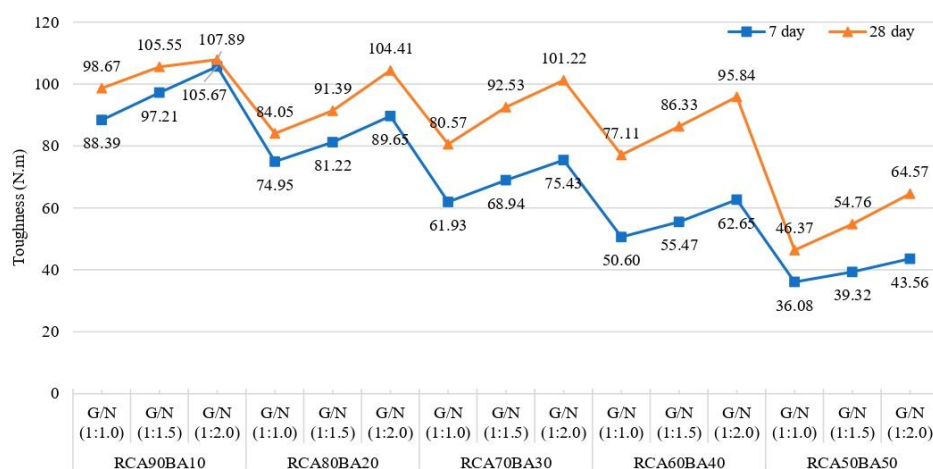


Figure 6. Toughness of BA-based geopolymer-stabilized RCA samples.

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.

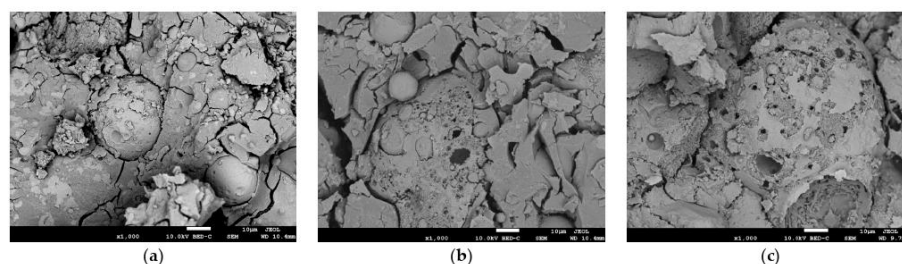


Figure 7. SEM images of RCA90BA10: (a) G/N ratio of 1:1, (b) G/N ratio of 1:1.5, and (c) G/N ratio of 1:2 at 28 days of curing.

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.

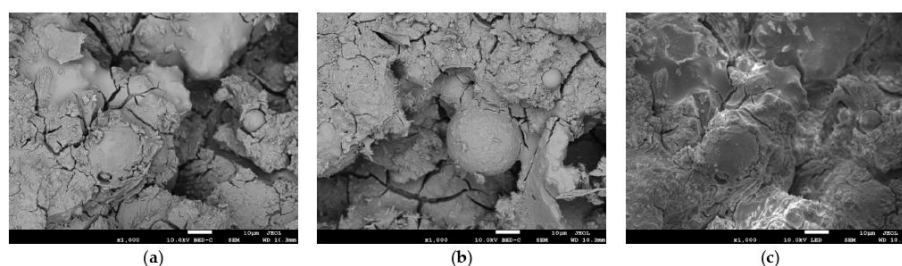


Figure 8. SEM images of RCA60BA40: (a) G/N ratio of 1:1, (b) G/N ratio of 1:1.5, and (c) G/N ratio of 1:2 at 28 days of curing.

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].

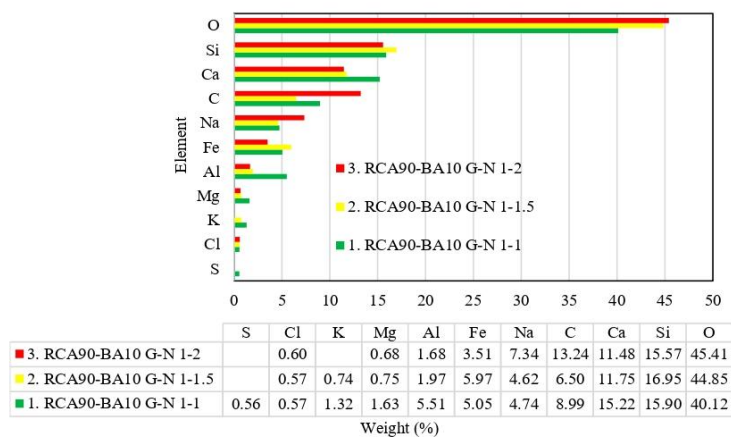


Figure 9. Chemical compositions of RCA90BA10 formulations at various G/N ratios.

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.

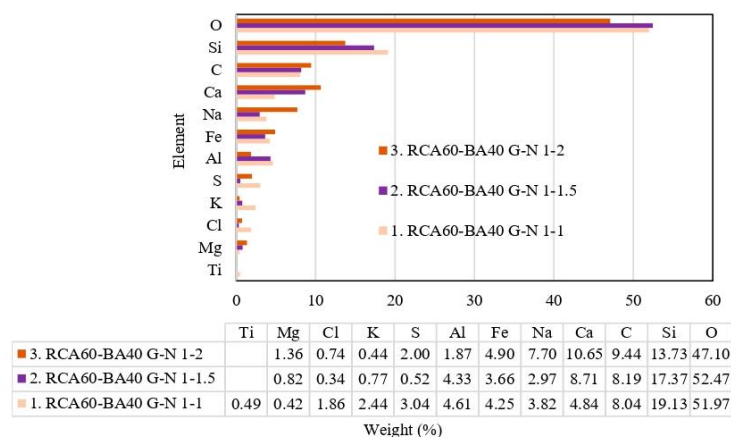


Figure 10. Chemical compositions of RCA60BA40 formulations at various G/N ratios.

The silicon content in RCA60BA40 systems indicated less pronounced variation across G/N ratios compared to RCA90BA10, ranging from approximately 13% to 16%. This 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.

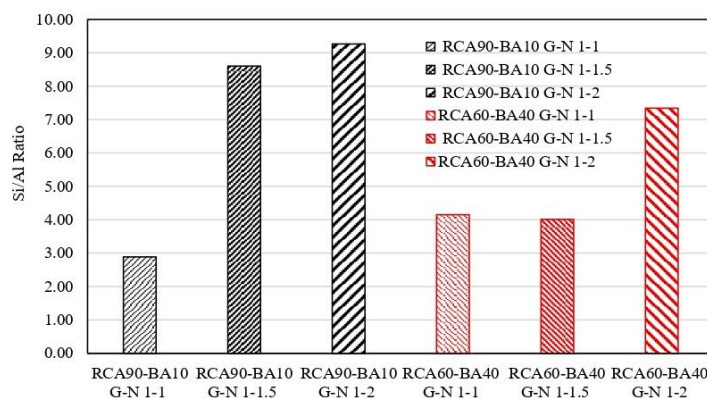


Figure 11. Si/Al ratios of RCA90BA10 and RCA60BA40 with various G/N ratios.

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 ($\text{Ca}_2\text{Al}_2\text{SiO}_7$), 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].

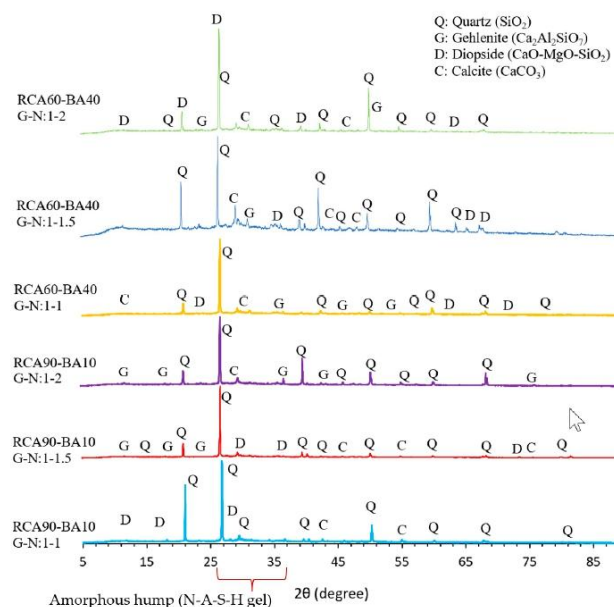


Figure 12. XRD patterns of RCA90BA10 and RCA60BA40 with various G/N ratios.

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 Bobirić 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 CO₂ compared to virgin aggregate processing [47]. Moreover, using BA in place of cement or virgin binders can further reduce CO₂ emissions by 150–200 kg of CO₂ 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 CO₂ 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

References

- Giunta, M. Sustainable Practices in Road Constructions: Estimation and Mitigation of Impact on Air Quality. *Transp. Res. Procedia* **2023**, *69*, 139–146. [\[CrossRef\]](#)
- Hoy, M.; Horpibulsuk, S.; Chinkulkijniwat, A.; Suddepong, A.; Buritatum, A.; Yaowarat, T.; Choenklang, P.; Udomchai, A.; Kantatham, K. Innovations in recycled construction materials: Paving the way towards sustainable road infrastructure. *Front. Built Environ.* **2024**, *10*, 1449970. [\[CrossRef\]](#)
- Salehi, S.; Arashpour, M.; Kodikara, J.; Guppy, R. Sustainable pavement construction: A systematic literature review of environmental and economic analysis of recycled materials. *J. Clean. Prod.* **2021**, *313*, 127936. [\[CrossRef\]](#)
- Sha, A.; Liu, Z.; Jiang, W.; Qi, L.; Hu, L.; Jiao, W.; Barbieri, D.M. Advances and development trends in eco-friendly pavements. *J. Road Eng.* **2021**, *1*, 1–42. [\[CrossRef\]](#)
- Buritatum, A.; Suddepong, A.; Horpibulsuk, S.; Akkharawongwhattana, K.; Yaowarat, T.; Hoy, M.; Bunsong, C.; Arulrajah, A. Improved performance of asphalt concretes using bottom ash as an alternative aggregate. *Sustainability* **2022**, *14*, 7033. [\[CrossRef\]](#)
- Jurić, B.; Hanžić, L.; Ilić, R.; Samec, N. Utilization of municipal solid waste bottom ash and recycled aggregate in concrete. *Waste Manag.* **2006**, *26*, 1436–1442. [\[CrossRef\]](#)
- Yoon, J.Y.; Lee, J.Y.; Kim, J.H. Use of raw-state bottom ash for aggregates in construction materials. *J. Mater. Cycles Waste Manag.* **2019**, *21*, 838–849. [\[CrossRef\]](#)
- Tiysangthong, S.; Yoosuk, P.; Krosoongnem, K.; Sakdinakorn, R.; Tabyang, W.; Phojan, W.; Suksiripattanapong, C. Stabilization of recycled concrete aggregate using high calcium fly ash geopolymer as pavement base material. *Infrastructures* **2022**, *7*, 117. [\[CrossRef\]](#)
- Poltue, T.; Suddepong, A.; Horpibulsuk, S.; Samingthong, W.; Arulrajah, A.; Rashid, A.S.A. Strength development of recycled concrete aggregate stabilized with fly ash-rice husk ash based geopolymer as pavement base material. *Road Mater. Pavement Des.* **2020**, *21*, 2344–2355. [\[CrossRef\]](#)
- Nanda, R.P.; Priya, N. Geopolymer as stabilising materials in pavement constructions: A review. *Clean. Waste Syst.* **2024**, *7*, 100134. [\[CrossRef\]](#)
- Xiao, P.; Polaczyk, P.; Zhang, M.; Jiang, X.; Zhang, Y.; Huang, B.; Hu, W. Evaluation of glass powder-based geopolymer stabilized road bases containing recycled waste glass aggregate. *Transp. Res. Rec.* **2020**, *2674*, 22–32. [\[CrossRef\]](#)
- Davidovits, J. *Geopolymer Chemistry and Applications*; Geopolymer Institute: Saint-Quentin, France, 2008.
- Farooq, F.; Jin, X.; Javed, M.F.; Akbar, A.; Shah, M.I.; Aslam, F.; Alyousef, R. Geopolymer concrete as sustainable material: A state of the art review. *Constr. Build. Mater.* **2021**, *306*, 124762. [\[CrossRef\]](#)
- Hassan, A.; Arif, M.; Shariq, M. Use of geopolymer concrete for a cleaner and sustainable environment—A review of mechanical properties and microstructure. *J. Clean. Prod.* **2019**, *223*, 704–728. [\[CrossRef\]](#)
- Zakka, W.P.; Lim, N.H.A.S.; Khun, M.C. A scientometric review of geopolymer concrete. *J. Clean. Prod.* **2021**, *280*, 124353. [\[CrossRef\]](#)
- Zhang, Z.; Provis, J.L.; Reid, A.; Wang, H. Geopolymer foam concrete: An emerging material for sustainable construction. *Constr. Build. Mater.* **2014**, *56*, 113–127. [\[CrossRef\]](#)
- Phummiphan, I.; Horpibulsuk, S.; Rachan, R.; Arulrajah, A.; Shen, S.-L.; Chindaprasirt, P. High calcium fly ash geopolymer stabilized lateritic soil and granulated blast furnace slag blends as a pavement base material. *J. Hazard. Mater.* **2018**, *341*, 257–267. [\[CrossRef\]](#)
- Nuaklong, P.; Wongsu, A.; Sata, V.; Boonserm, K.; Sanjayan, J.; Chindaprasirt, P. Properties of high-calcium and low-calcium fly ash combination geopolymer mortar containing recycled aggregate. *Heliyon* **2019**, *5*, e02513. [\[CrossRef\]](#)
- Phoo-ngernkham, T.; Chindaprasirt, P.; Sata, V.; Hanjitsuwan, S.; Hatanaka, S. The effect of adding nano-SiO₂ and nano-Al₂O₃ on properties of high calcium fly ash geopolymer cured at ambient temperature. *Mater. Des.* **2014**, *55*, 58–65. [\[CrossRef\]](#)
- Horpibulsuk, S.; Hoy, M.; Suddepong, A.; Udomchai, A.; Buritatum, A.; Yaowarat, T.; Akkharawongwhattana, K.; Yeanyong, C.; Horpibulsuk, J.; Mobkrathok, M. A 10-Year Research on Sustainable Pavement Materials. In *Recent Advances and Innovative Developments in Transportation Geotechnics: Keynote Volume ICTG 2024*; Springer: Berlin/Heidelberg, Germany, 2024; pp. 129–139.
- Chindaprasirt, P.; Jaturapitakkul, C.; Chalee, W.; Rattanasak, U. Comparative study on the characteristics of fly ash and bottom ash geopolymers. *Waste Manag.* **2009**, *29*, 539–543. [\[CrossRef\]](#)
- Sata, V.; Sathonsaowaphak, A.; Chindaprasirt, P. Resistance of lignite bottom ash geopolymer mortar to sulfate and sulfuric acid attack. *Cem. Concr. Compos.* **2012**, *34*, 700–708. [\[CrossRef\]](#)
- Xie, T.; Ozbakkaloglu, T. Behavior of low-calcium fly and bottom ash-based geopolymer concrete cured at ambient temperature. *Ceram. Int.* **2015**, *41*, 5945–5958. [\[CrossRef\]](#)
- Temuujin, J.; Minjigmaa, A.; Lee, M.; Chen-Tan, N.; Van Riessen, A. Characterisation of class F fly ash geopolymer pastes immersed in acid and alkaline solutions. *Cem. Concr. Compos.* **2011**, *33*, 1086–1091. [\[CrossRef\]](#)
- Yip, C.K.; Lukey, G.C.; Provis, J.L.; Van Deventer, J.S. Effect of calcium silicate sources on geopolymerisation. *Cem. Concr. Res.* **2008**, *38*, 554–564. [\[CrossRef\]](#)

26. Provis, J.L.; Van Deventer, J.S.J. *Geopolymers: Structures, Processing, Properties and Industrial Applications*; Elsevier: Amsterdam, The Netherlands, 2009.
27. Santa, R.A.A.B.; Padoin, N.; Soares, C.; Riella, H.G. Microstructural characteristics of geopolymer materials with twenty eight days of curing and after eight years stored at room temperature. *J. Clean. Prod.* **2021**, *278*, 123437. [\[CrossRef\]](#)
28. Duxson, P.; Mallicoat, S.W.; Lukey, G.C.; Kriven, W.M.; Van Deventer, J.S. The effect of alkali and Si/Al ratio on the development of mechanical properties of metakaolin-based geopolymers. *Colloids Surf. A Physicochem. Eng. Asp.* **2007**, *292*, 8–20. [\[CrossRef\]](#)
29. Davidovits, J. Geopolymer, green chemistry and sustainable development solutions. In Proceedings of the World Congress Geopolymer 2005, Saint-Quentin, France, 29 June–1 July 2005; Geopolymer Institute: Saint-Quentin, France, 2005.
30. Sivasakthi, M.; Jeyalakshmi, R. Effect of change in the silica modulus of sodium silicate solution on the microstructure of fly ash geopolymers. *J. Build. Eng.* **2021**, *44*, 102939. [\[CrossRef\]](#)
31. Kim, Y.-S.; Dang, M.Q.; Do, T.M. Studies on compressive strength of sand stabilized by alkali-activated ground bottom ash and cured at the ambient conditions. *Int. J. Geo-Eng.* **2016**, *7*, 15. [\[CrossRef\]](#)
32. Singh, G.B.; Subramaniam, K.V. Evaluation of sodium content and sodium hydroxide molarity on compressive strength of alkali activated low-calcium fly ash. *Cem. Concr. Compos.* **2017**, *81*, 122–132. [\[CrossRef\]](#)
33. Lahoti, M.; Wong, K.K.; Yang, E.-H.; Tan, K.H. Effects of Si/Al molar ratio on strength endurance and volume stability of metakaolin geopolymers subject to elevated temperature. *Ceram. Int.* **2018**, *44*, 5726–5734. [\[CrossRef\]](#)
34. Moazami, D.; Yusoff, Z.M.; Muniandy, R.; Hamid, H. Effect of stabilizers on stiffness modulus of soil layers: A review. *Int. J. Phys. Sci.* **2013**, *8*, 1602–1610.
35. Tran, N.Q.; Hoy, M.; Suddepong, A.; Horpibulsuk, S.; Kantathum, K.; Arulrajah, A. Improved mechanical and microstructure of cement-stabilized lateritic soil using recycled materials replacement and natural rubber latex for pavement applications. *Constr. Build. Mater.* **2022**, *347*, 128547. [\[CrossRef\]](#)
36. Cristelo, N.; Glendinning, S.; Fernandes, L.; Pinto, A.T. Effect of calcium content on soil stabilisation with alkaline activation. *Constr. Build. Mater.* **2012**, *29*, 167–174. [\[CrossRef\]](#)
37. Hanjitsuwan, S.; Hunpratub, S.; Thongbai, P.; Maensiri, S.; Sata, V.; Chindaprasit, P. Effects of NaOH concentrations on physical and electrical properties of high calcium fly ash geopolymer paste. *Cem. Concr. Compos.* **2014**, *45*, 9–14. [\[CrossRef\]](#)
38. Duxson, P.; Fernández-Jiménez, A.; Provis, J.L.; Lukey, G.C.; Palomo, A.; van Deventer, J.S.J. Geopolymer technology: The current state of the art. *J. Mater. Sci.* **2007**, *42*, 2917–2933. [\[CrossRef\]](#)
39. Khale, D.; Chaudhary, R. Mechanism of geopolymerization and factors influencing its development: A review. *J. Mater. Sci.* **2007**, *42*, 729–746. [\[CrossRef\]](#)
40. Kovalchuk, G.; Fernández-Jiménez, A.; Palomo, A. Alkali-activated fly ash: Effect of thermal curing conditions on mechanical and microstructural development—Part II. *Fuel* **2007**, *86*, 315–322. [\[CrossRef\]](#)
41. Xu, H.; Van Deventer, J.S.J. The geopolymerisation of aluminosilicate minerals. *Int. J. Miner. Process.* **2000**, *59*, 247–266. [\[CrossRef\]](#)
42. Liu, J.; Doh, J.-H.; Dinh, H.L.; Ong, D.E.L.; Zi, G.; You, I. Effect of Si/Al molar ratio on the strength behavior of geopolymer derived from various industrial waste: A current state of the art review. *Constr. Build. Mater.* **2022**, *329*, 127134. [\[CrossRef\]](#)
43. Kumar, M.L.; Revathi, V. Microstructural Properties of Alkali-Activated Metakaolin and Bottom Ash Geopolymer. *Arab. J. Sci. Eng.* **2020**, *45*, 4235–4246. [\[CrossRef\]](#)
44. El Alouani, M.; Saufi, H.; Aouan, B.; Bassam, R.; Alehyen, S.; Rachdi, Y.; El Hadki, H.; El Hadki, A.; Mabrouki, J.; Belaouad, S.; et al. A comprehensive review of synthesis, characterization, and applications of aluminosilicate materials-based geopolymers. *Environ. Adv.* **2024**, *16*, 100524. [\[CrossRef\]](#)
45. Sinha, D.K.; Kumar, A.; Kumar, S. Development of Geopolymer Concrete from Fly Ash and Bottom Ash Mixture. *Trans. Indian Ceram. Soc.* **2014**, *73*, 143–148. [\[CrossRef\]](#)
46. Bobirić, C.; Orbeci, C.; Bobirić, L.; Palade, P.; Deleanu, C.; Pantilimon, C.M.; Pîrvu, C.; Radu, I.C. Influence of red mud and waste glass on the microstructure, strength, and leaching behavior of bottom ash-based geopolymer composites. *Sci. Rep.* **2020**, *10*, 19827. [\[CrossRef\]](#) [\[PubMed\]](#)
47. Limbachiya, M.; Meddah, M.S.; Ouchagour, Y. Performance of Portland/Silica Fume Cement Concrete Produced with Recycled Concrete Aggregate. *ACI Mater. J.* **2012**, *109*, 91–100. [\[CrossRef\]](#)
48. Nakararaj, N.; Tran, T.N.H.; Sukontasukkul, P.; Attachaiyawuth, A.; Tangchirapat, W.; Ban, C.C.; Rattanachu, P.; Jaturapitakkul, C. Effects of High-Volume bottom ash on Strength, Shrinkage, and creep of High-Strength recycled concrete aggregate. *Constr. Build. Mater.* **2022**, *356*, 129233. [\[CrossRef\]](#)
49. Ramadan, S.; Kassem, H.; Elkordi, A.; Joumbat, R. Advancing Pavement Sustainability: Assessing Recycled Aggregates as Substitutes in Hot Mix Asphalt. *Sustainability* **2025**, *17*, 5472. [\[CrossRef\]](#)

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.



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

Chokchai Traiyasut^a, Menglim Hoy^{b,c,*}, Suksun Horpibulsuk^{a,b,c,d,f,g,h},
Apichat Suddeepong^e, Apinun Buritatatum^{c,f}, Teerasak Yaowarat^{c,f}, Artit Udomchai^c,
Arul Arulrajah^g, Avirut Chinkulkijniwat^{b,h}, Punvalai Choenklang^c

^a Graduate Program in Civil Engineering and Construction Management, Institute of Engineering, Suranaree University of Technology, Nakhon Ratchasima 30000, Thailand

^b School of Civil Engineering, Institute of Engineering, Suranaree University of Technology, Nakhon Ratchasima 30000, Thailand

^c Center of Excellence in Innovation for Sustainable Infrastructure Development, Suranaree University of Technology, Nakhon Ratchasima 30000, Thailand

^d Academy of Science, The Royal Society of Thailand, Bangkok 10300, Thailand

^e Institute of Research and Development, Suranaree University of Technology, Nakhon Ratchasima 30000, Thailand

^f Program in Civil and Infrastructure Engineering, Institute of Engineering, Suranaree University of Technology 30000, Thailand

^g Department of Civil and Construction Engineering, Swinburne University of Technology, Hawthorn, Victoria 3122, Australia

^h Center of Excellence in Civil Engineering, Suranaree University of Technology, Nakhon Ratchasima 30000, Thailand

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:Na₂SiO₃, 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.

* Corresponding author. School of Civil Engineering, Institute of Engineering, Suranaree University of Technology, Nakhon Ratchasima, 30000, Thailand.

** Corresponding author. School of Civil Engineering, Institute of Engineering, Suranaree University of Technology, Nakhon Ratchasima, 30000, Thailand.

E-mail addresses: d6400385@g.sut.ac.th (C. Traiyasut), menglim@g.sut.ac.th (M. Hoy), suksun@g.sut.ac.th (S. Horpibulsuk), suddeepong@g.sut.ac.th (A. Suddeepong), apinun_ce@g.sut.ac.th (A. Buritatatum), yaowarat@g.sut.ac.th (T. Yaowarat), artit.u@g.sut.ac.th (A. Udomchai), arulrajah@swin.edu.au (A. Arulrajah), avirut@g.sut.ac.th (A. Chinkulkijniwat), punvalai@g.sut.ac.th (P. Choenklang).

<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

2666-7908/© 2025 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

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 CO₂ 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 CO₂ 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 (Chindaprasit 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 through the reaction of an aluminosilicate source, such as bottom ash (precursor), with an alkaline activator solution containing sodium hydroxide (NaOH) and sodium silicate (Na₂SiO₃).

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.

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 (Chindaprasit 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 ($\text{NaOH}:\text{Na}_2\text{SiO}_3$, 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 (Chindaprasit et al., 2009; Suksiripattanasong 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 pre-determined 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

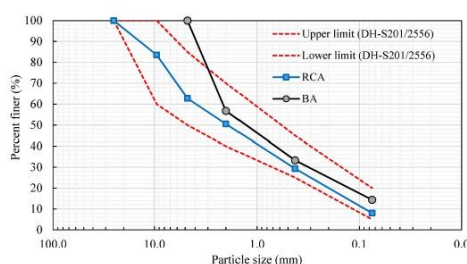


Fig. 1. Gradation of RCA-BA compared to the boundary of subgrade material Type D.

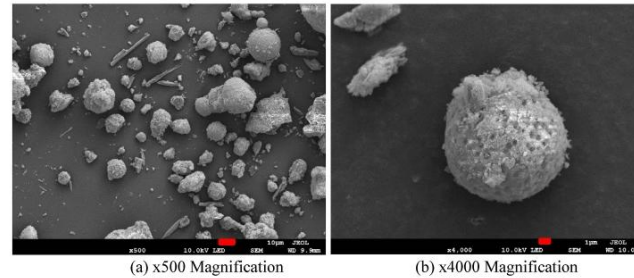


Fig. 2. SEM image of bottom ash.

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

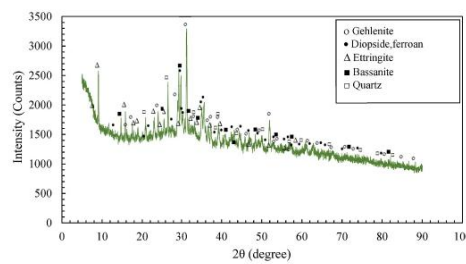


Fig. 3. XRD pattern of bottom ash.

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 ($25 \pm 2^\circ$) 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 NaOH/ Na_2SiO_3 (G/N) ratio	NRL (%) 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 Na₂SiO₃ 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 1:2), 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 (AASHTO) 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 1.04 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

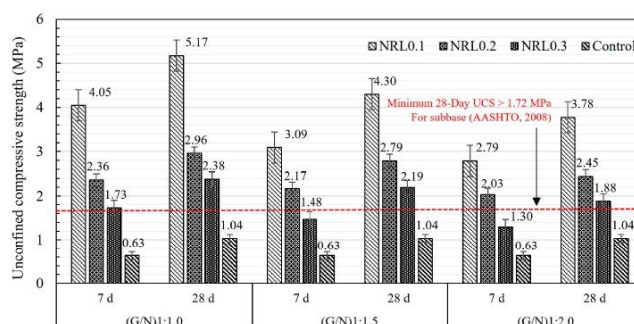


Fig. 4. UCS of NRL-modified BA-based geopolymer stabilized RCA.

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

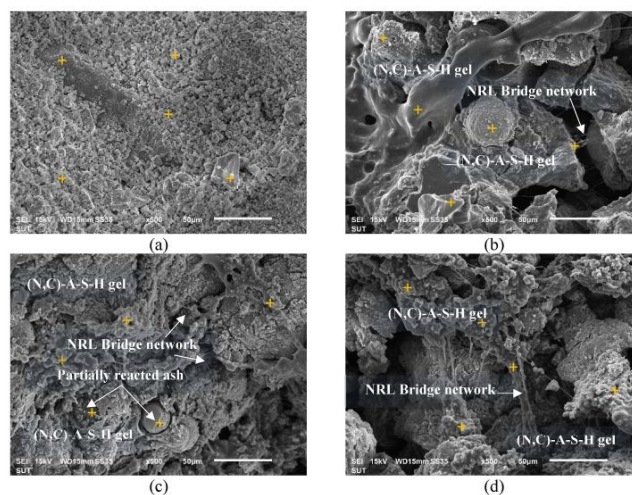


Fig. 5. SEM-EDX analysis of NRL-modified BA-based geopolymer stabilized RCA samples: a) RCA70BA30 (Control), b) G/N1:1.0NRL0.1, c) G/N1:1.5NRL0.1, and d) G/N1:2.0NRL0.1.

(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:NRL0.1 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:NRL0.1 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:NRL0.1 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 NRL 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.

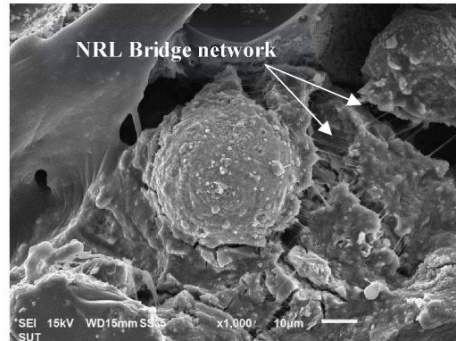
Fig. 8 demonstrates the XRD patterns of the NRL-modified BA-based geopolymer stabilized RCA samples with varying G/N ratios (1:1, 1:1.5, and 1:2) at a constant NRL content of 0.1 %. The XRD patterns of the NRL-modified samples exhibited a notable abatement in the intensity of the crystalline peaks compared 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 (Bobirica 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

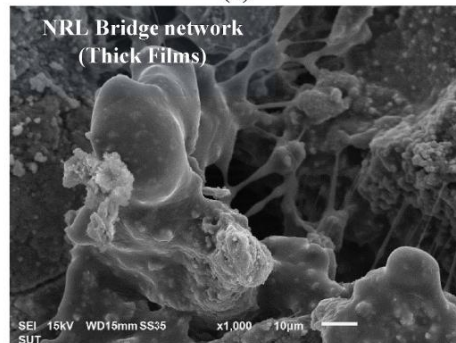
Table 3

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

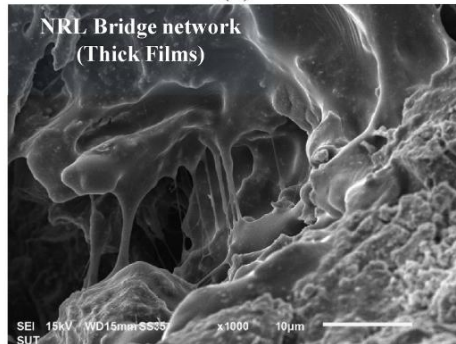
Sample IDs	Major elements analyzed (all results in weight%)							Si/Al ratio
	C	O	Fe	Na	Ca	Al	Si	
70RCA30BA (control)	9.57	51.82	1.07	4.87	1.83	1.75	30.74	17.6
G/N1:1.0NRL0.1	37.90	31.15	1.05	2.54	6.69	3.03	17.62	5.80
G/N1:1.5NRL0.1	39.28	32.67	1.33	2.63	6.75	2.38	16.79	7.10
G/N1:2.0NRL0.1	38.94	33.34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



(a)



(b)



(c)

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.

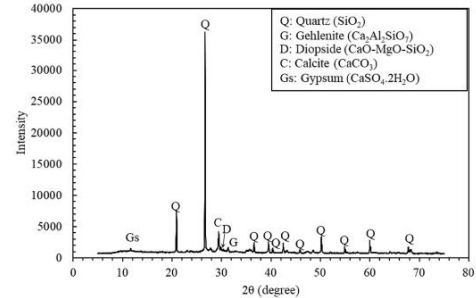


Fig. 7. XRD patterns of RCA70BA30 (Control sample).

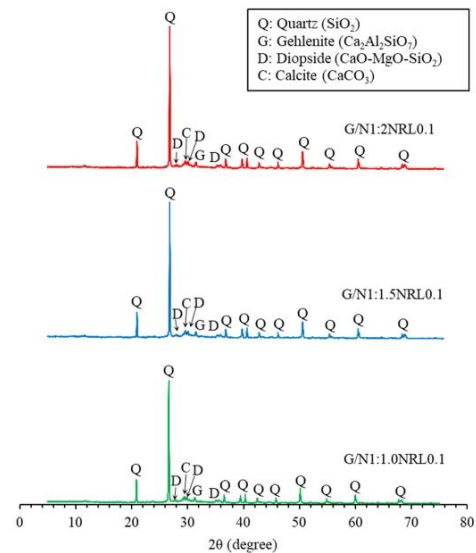
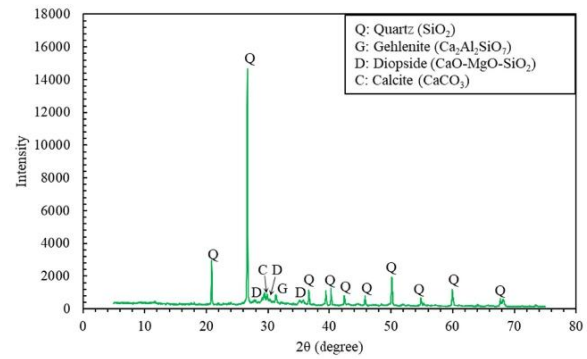


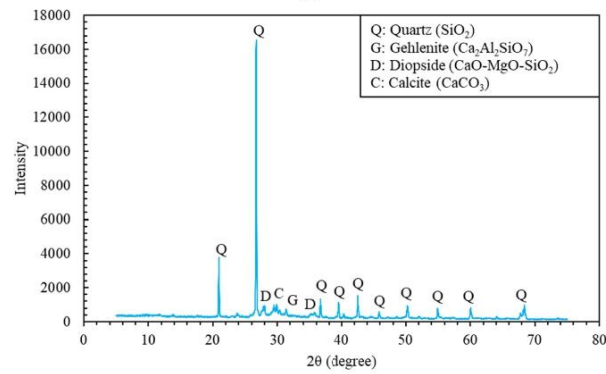
Fig. 8. XRD patterns of NRL-modified BA-based geopolymer stabilized RCA samples.

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.

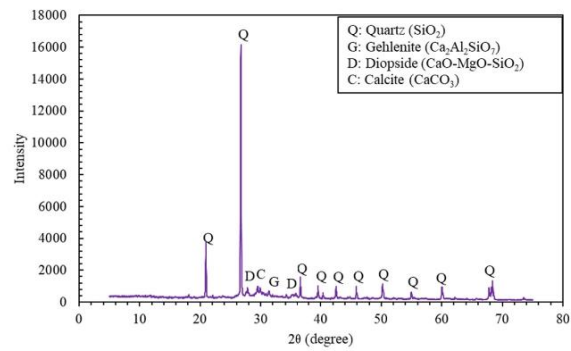
The XRD analysis supported the findings from the microstructural characterization by SEM analysis and the mechanical testing that G/N ratio and NRL content played a significant role in the geopolymerization process. It was found that the sample containing 0.1 % NRL and a G/N ratio of 1:1 exhibiting the 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.



(a)



(b)



(c)

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.

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.

References

- AASHTO, 2008. Mechanistic-Empirical Pavement Design Guide: a Manual of Practice. American Association of State Highway and Transportation Officials.
- Alamgir, M., Campbell, M.J., Sloan, S., Goosen, M., Clements, G.R., Mahmoud, M.I., Laurance, W.F., 2017. Economic, socio-political and environmental risks of road development in the tropics. *Curr. Biol.* 27 (20), R1130–R1140. <https://doi.org/10.1016/j.cub.2017.08.067>.
- Amran, M., Debbarma, S., Ozbakkaloglu, T., 2021. Fly ash-based eco-friendly geopolymer concrete: a critical review of the long-term durability properties. *Constr. Build. Mater.* 270, 121857. <https://doi.org/10.1016/j.conbuildmat.2020.121857>.
- ASTM-D422-63, 2007. Standard Test Method for Particle-Size Analysis of Soils. ASTM International West Conshohocken ePA.
- ASTM-D1557-12, 2012. Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft³ (2,700 kN-m/m³)). ASTM International, West Conshohocken, PA, USA.
- ASTM-D2166-06, 2006. Standard Test Method for Unconfined Compressive Strength of Cohesive Soil. ASTM International, West Conshohocken, PA, USA.
- ASTM-D2487-17, 2017. Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System). ASTM International, West Conshohocken, PA.
- Bajpai, R., Shrivastava, A., Singh, M., 2020. Properties of fly ash geopolymer modified with red mud and silica fume: a comparative study. *SN Appl. Sci.* 2 (11), 1846. <https://doi.org/10.1007/s42452-020-03665-3>.
- Bhagath Singh, G.V.P., Subramanian, K.V.L., 2017. Evaluation of sodium content and sodium hydroxide molarity on compressive strength of alkali activated low-calcium fly ash. *Cement Concr. Compos.* 81, 122–132. <https://doi.org/10.1016/j.cemconcomp.2017.05.001>.
- Bobitica, C., Orbeci, C., Bobitica, L., Palade, P., Deleanu, C., Pantilimon, C.M., Radu, I.C., 2020. Influence of red mud and waste glass on the microstructure, strength, and leaching behavior of bottom ash-based geopolymer composites. *Sci. Rep.* 10 (1), 19827. <https://doi.org/10.1038/s41598-020-76818-4>.
- Bottier, C., 2020. Chapter seven - biochemical composition of Hevea brasiliensis latex: a focus on the protein, lipid, carbohydrate and mineral contents. In: Nawrot, R. (Ed.), *Advances in Botanical Research*, vol. 93. Academic Press, pp. 201–237.
- Chindaprasit, P., Jaturapitakul, C., Chalee, W., Rattanasak, U., 2009. Comparative study on the characteristics of fly ash and bottom ash geopolymers. *Waste Manag.* 29 (2), 539–543. <https://doi.org/10.1016/j.wasman.2008.06.023>.
- Chiranjeevi, K., Abraham, M., Rath, B., Praveenkumar, T.R., 2023. Enhancing the properties of geopolymer concrete using nano-silica and microstructure assessment: a sustainable approach. *Sci. Rep.* 13 (1), 17302. <https://doi.org/10.1038/s41598-023-44491-y>.
- Das, D., Gotabiewska, A., Rout, P.K., 2024. Geopolymer bricks: the next generation of construction materials for sustainable environment. *Constr. Build. Mater.* 445, 137876. <https://doi.org/10.1016/j.conbuildmat.2024.137876>.
- Davidovits, J., 2005. Geopolymer, Green Chemistry and Sustainable Development Solutions: Proceedings of the World Congress Geopolymer 2005. Geopolymer Institute.
- Duxson, P., Fernández-Jiménez, A., Provis, J.L., Lukey, G.C., Palomo, A., van Deventer, J.S., 2007a. Geopolymer technology: the current state of the art. *J. Mater. Sci.* 42, 2917–2933.
- Duxson, P., Mallicoate, S.W., Lukey, G.C., Kriven, W.M., Van Deventer, J.S., 2007b. The effect of alkali and Si/Al ratio on the development of mechanical properties of metakaolin-based geopolymers. *Colloids Surf. A Physicochem. Eng. Asp.* 292 (1), 8–20.
- El Alouani, M., Sauf, H., Aouan, B., Bassam, R., Alehyen, S., Rachdi, Y., Barka, N., 2024. A comprehensive review of synthesis, characterization, and applications of aluminosilicate materials-based geopolymers. *Environ. Adv.* 16, 100524. <https://doi.org/10.1016/j.envadv.2024.100524>.
- Hoy, M., Tran, N.Q., Suddeepong, A., Horpibulsuk, S., Mobkrathok, M., Chinkulkijniwat, A., Arulrajah, A., 2023. Improved fatigue properties of cement-stabilized recycled materials – lateritic soil using natural rubber latex for sustainable pavement applications. *Transport. Geotech.* 40, 100959. <https://doi.org/10.1016/j.trgeo.2023.100959>.
- Ige, O.E., Von Kallon, D.V., Desai, D., 2024. Carbon emissions mitigation methods for cement industry using a systems dynamics model. *Clean Technol. Environ. Policy* 26 (3), 579–597. <https://doi.org/10.1007/s10098-023-02683-0>.
- Jitsangiam, P., Pachana, P.K., Rattanasak, U., Chindaprasit, P., 2022. Effect of surfactants on the distribution of natural rubber latex in cement and geopolymer composites based on X-ray computed tomography. *J. Mater. Res. Technol.* 21, 3625–3635. <https://doi.org/10.1016/j.jmrt.2022.10.155>.
- Kim, Y.-s., Dang, M.Q., Do, T.M., 2016. Studies on compressive strength of sand stabilized by alkali-activated ground bottom ash and cured at the ambient conditions. *Int. J. of Geo Eng. Geo-Eng* 7 (1), 15. <https://doi.org/10.1186/s40703-016-0029-4>.
- Klima, K.M., Schollbach, K., Brouwers, H.J.H., Yu, Q., 2022. Thermal and fire resistance of class F fly ash based geopolymers – a review. *Constr. Build. Mater.* 323, 126529. <https://doi.org/10.1016/j.conbuildmat.2022.126529>.

- Kumar, M.L., Revathi, V., 2020. Microstructural properties of alkali-activated Metakaolin and bottom ash geopolymers. *Arabian J. Sci. Eng.* 45 (5), 4235–4246. <https://doi.org/10.1007/s13369-020-04417-6>.
- Li, X., Bai, C., Qiao, Y., Wang, X., Yang, K., Colombo, P., 2022. Preparation, properties and applications of fly ash-based porous geopolymers: a review. *J. Clean. Prod.* 359, 132043. <https://doi.org/10.1016/j.jclepro.2022.132043>.
- Mohammadnia, A., Arulrajah, A., Sanjayan, J., Disfani, M.M., Bo, M.W., Darmawan, S., 2016. Stabilization of demolition materials for pavement base/subbase applications using fly ash and slag geopolymers: laboratory investigation. *J. Mater. Civ. Eng.* 28 (7), 04016033. [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0001526](https://doi.org/10.1061/(ASCE)MT.1943-5533.0001526).
- Muhammad, B., Ismail, M., 2012. Performance of natural rubber latex modified concrete in acidic and sulfated environments. *Constr. Build. Mater.* 31, 129–134. <https://doi.org/10.1016/j.conbuildmat.2011.12.099>.
- Nhieu, D.V., Hoy, M., Horpibulsuk, S., Karntatam, K., Arulrajah, A., Horpibulsuk, J., 2023. Cement – natural rubber latex stabilised recycled concrete aggregate as a pavement base material. *Road Mater. Pavement Des.* 24 (6), 1636–1650. <https://doi.org/10.1080/14680629.2022.2072755>.
- Provis, J.L., Van Deventer, J.S.J., 2009. *Geopolymers: Structures, Processing, Properties and Industrial Applications*. Elsevier.
- Pu, S., Zhu, Z., Song, W., Huo, W., Zhang, C., 2022. A eco-friendly acid fly ash geopolymer with a higher strength. *Constr. Build. Mater.* 335, 127450. <https://doi.org/10.1016/j.conbuildmat.2022.127450>.
- Rathnayaka, M., Karunasinghe, D., Gunasekara, C., Wijesundara, K., Lokuge, W., Law, D. W., 2024. Machine learning approaches to predict compressive strength of fly ash-based geopolymer concrete: a comprehensive review. *Constr. Build. Mater.* 419, 135519. <https://doi.org/10.1016/j.conbuildmat.2024.135519>.
- Sae-Long, W., Chompoorat, T., Limkatanyu, S., Damrongwiriyanupap, N., Sukontasukkul, P., Chub-Uppakarn, T., Thepumong, T., 2024. Experimental and simulation analysis of RCA and para-wood ash as partial substitutes for NCA and cement in recycled aggregate concrete. *Case Stud. Constr. Mater.* 21, e03716. <https://doi.org/10.1016/j.cscm.2024.e03716>.
- Santa, R.A.A.B., Padoin, N., Soares, C., Riella, H.G., 2021. Microstructural characteristics of geopolymer materials with twenty eight days of curing and after eight years stored at room temperature. *J. Clean. Prod.* 278, 123437. <https://doi.org/10.1016/j.jclepro.2020.123437>.
- Shehata, N., Mohamed, O.A., Sayed, E.T., Abdelkareem, M.A., Olabi, A.G., 2022. Geopolymer concrete as green building materials: recent applications, sustainable development and circular economy potentials. *Sci. Total Environ.* 836, 155577. <https://doi.org/10.1016/j.scitotenv.2022.155577>.
- Sinha, D.K., Kumar, A., Kumar, S., 2014. Development of geopolymer concrete from fly ash and bottom ash mixture. *Trans. Indian Ceram. Soc.* 73 (2), 143–148. <https://doi.org/10.1080/0371750X.2014.922427>.
- Sivasakthi, M., Jeyalakshmi, R., Rajamane, N.P., 2021. Effect of change in the silica modulus of sodium silicate solution on the microstructure of fly ash geopolymers. *J. Build. Eng.* 44, 102939. <https://doi.org/10.1016/j.jobe.2021.102939>.
- Saldo, A., Miletić, M., Auad, M.L., 2020. Biopolymers as a sustainable solution for the enhancement of soil mechanical properties. *Sci. Rep.* 10 (1), 267. <https://doi.org/10.1038/s41598-019-57135-x>.
- Suksiripattanasong, C., Tuntawoot, N., Thumrongvut, J., Wonglakorn, N., Chongutah, S., Tabyang, W., 2019. Compressive strength of marginal lateritic soil stabilized with bottom ash geopolymer as a pavement material. *Int. J. Eng. Technol.* 11, 177–180.
- ul Haq, E., Kunjalukkal Padmanabhan, S., Licciulli, A., 2014. Synthesis and characteristics of fly ash and bottom ash based geopolymers-A comparative study. *Ceram. Int.* 40 (2), 2965–2971. <https://doi.org/10.1016/j.ceramint.2013.10.012>.
- Xie, J., Zhang, J., Cao, Z., Blom, J., Vuye, C., Gu, F., 2024. Feasibility of using building-related construction and demolition waste-derived geopolymer for subgrade soil stabilization. *J. Clean. Prod.* 450, 142001. <https://doi.org/10.1016/j.jclepro.2024.142001>.
- Yip, C.K., Lukay, G.C., Provis, J.L., Van Deventer, J.S., 2008. Effect of calcium silicate sources on geopolymerisation. *Cement Concr. Res.* 38 (4), 554–564.
- Zhang, Y., Gong, H., Jiang, X., Lv, X., Xiao, R., Huang, B., 2021. Environmental impact assessment of pavement road bases with reuse and recycling strategies: a comparative study on geopolymer stabilized macadam and conventional alternatives. *Transport. Res. Transport Environ.* 93, 102749. <https://doi.org/10.1016/j.trd.2021.102749>.