

CHAPTER III

METHODOLOGY

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

3.1 Introduction

The construction industry, particularly road construction, faces significant challenges in sustainability due to its reliance on traditional materials such as natural aggregates and Portland cement. These materials are associated with high 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 (Giunta, 2023; Hoy et al., 2024; Salehi, Arashpour, Kodikara, & Guppy, 2021; Sha et al., 2021).

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

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

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

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

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

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

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

This research aims to address this research gap by investigating the influence of various RCA:BA ratios and alkaline activators with different $\text{Na}_2\text{SiO}_3\text{:NaOH}$ (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.

3.2 Materials and methods

3.2.1 Materials

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

3.2.1.1 Recycled concrete aggregate

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

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

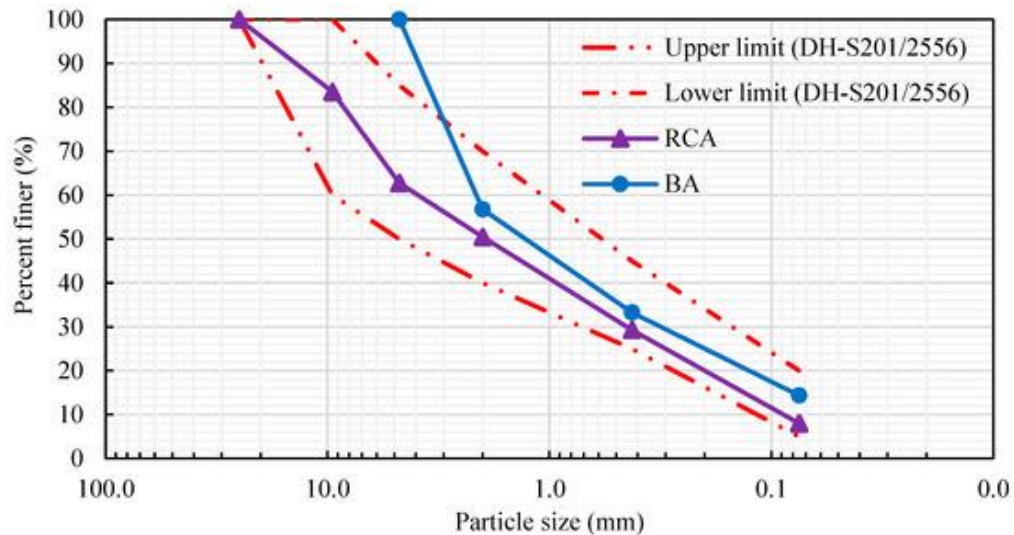


Figure 3.1 Graduation of RCA and BA.

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

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

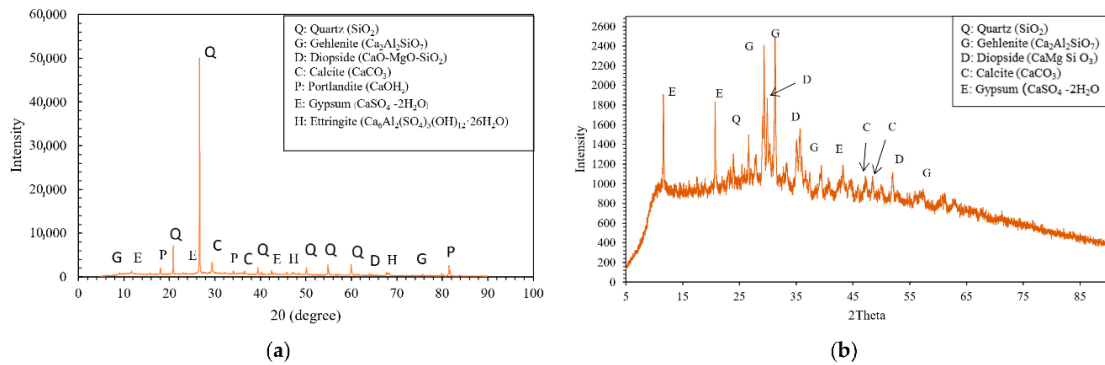


Figure 3.2 XRD patterns of (a) RCA and (b) BA.

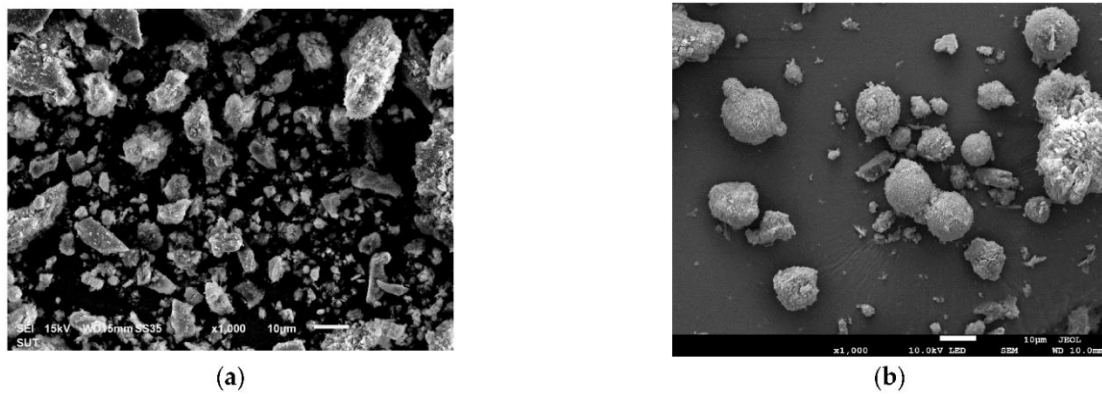


Figure 3.3 SEM images of (a) RCA and (b) BA.

Energy-dispersive X-ray spectroscopy (EDX) analysis was performed using a scanning electron microscope equipped with an EDX detector. Multiple point analyses were conducted on polished sample surfaces to ensure representative elemental composition data. The chemical compositions are presented in Figure 3.4 and demonstrate complementary profiles essential for geopolymer synthesis. RCA exhibited a calcium-rich elemental composition typical of concrete materials, with calcium (Ca) and oxygen (O) as the predominant elements, indicating the presence of unhydrated cement particles and calcium-based compounds such as $\text{Ca}(\text{OH})_2$ 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).

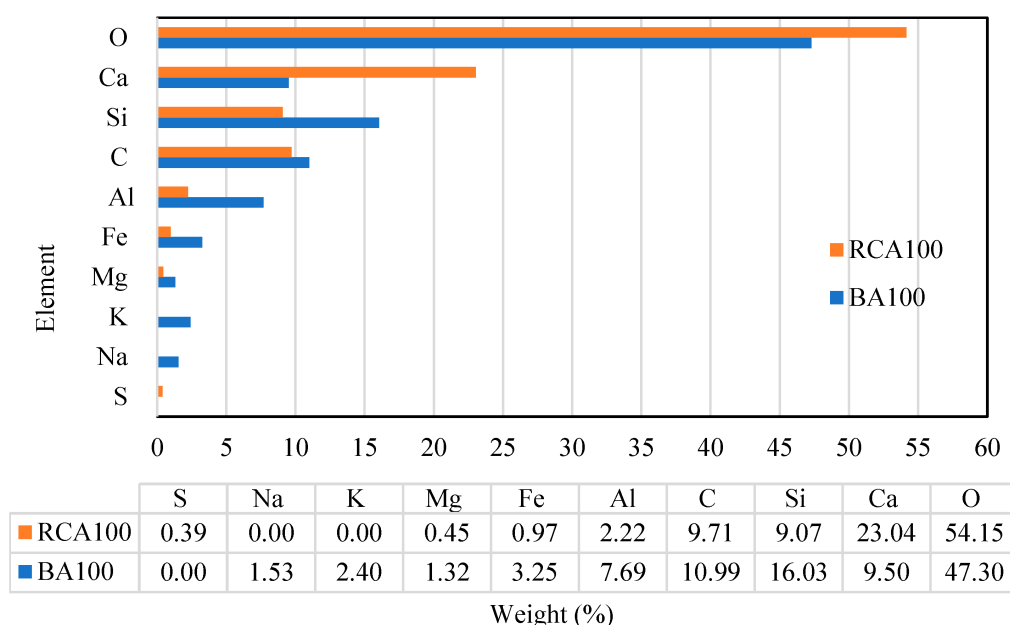


Figure 3.4 Chemical compositions RCA and BA obtained from EDX.

3.2.1.2 Bottom ash (BA)

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

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

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

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

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

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

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

3.2.1.3 Alkaline activators (L)

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

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

Commercial-grade Na_2SiO_3 (type CR53) was used with the following compositional specifications: 14.5–16.5 wt% Na_2O , 31.5–34.0 wt% SiO_2 , H_2O balance, silica modulus (M_s) 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 hr 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.

3.2.2 Mix Design and Sample Preparation

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

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

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

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

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

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

RCA and BA were first dry-mixed for 2 min to achieve uniform distribution. The alkaline activator solution was then gradually added while continuously mixing for 3 min until a homogeneous paste was achieved. The mixtures were immediately transferred to standard Proctor molds (101.6 mm diameter × 116.4 mm height) and compacted under a modified standard Proctor test following ASTM D1557 in five equal layers to determine the maximum dry density (MDD) and optimum liquid content (OLC) for each composition. Specimens were prepared at their respective MDD and OLC conditions for mechanical testing. A $\pm 2\%$ 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.

3.3 Laboratory Experimental Program

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

3.3.1 Unconfined Compressive Strength (UCS)

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

3.3.2 Scanning Electron Microscopy (SEM) Analysis

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

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

3.3.3 X-Ray Diffraction (XRD) Analysis

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

3.4 Results and Discussion

3.4.1 UCS Development

3.4.1.1 Strength Performance and Standard Compliance

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

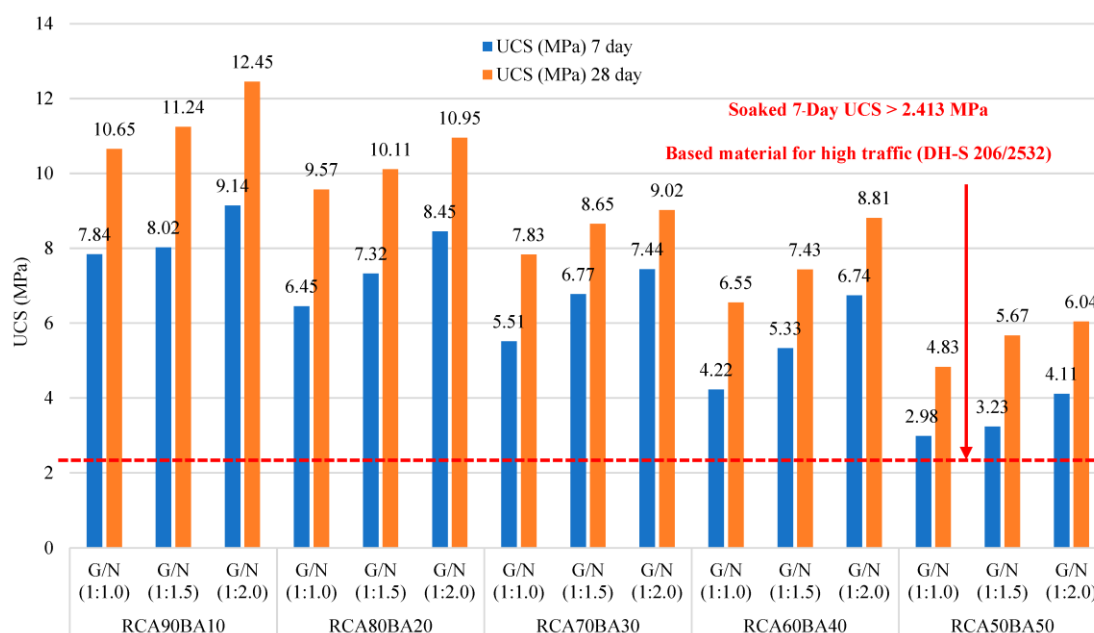


Figure 3.5 UCS of BA-based geopolymer-stabilized RCA samples at 7 and 28 days of ambient curing

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

3.4.1.2 Influence of RCA:BA Ratio on Strength Development

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

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

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

3.4.1.3 Alkaline Activator Optimization and Geopolymerization Mechanisms

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

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

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

Jeyalakshmi, 2021) and Provis and van Deventer (Kim, Dang, & Do, 2016) showed that the $\text{SiO}_2/\text{Na}_2\text{O}$ 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 (Singh & Subramaniam, 2017), who reported that an increased silicate concentration accelerates the dissolution–precipitation mechanism essential for geopolymer formation. Additionally, a higher silicate content promotes the formation of more stable and cross-linked gel structures, as demonstrated by Lahoti et al. (Lahoti, Wong, Yang, & Tan, 2018) in their investigation of fly ash-based geopolymers.

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

3.4.1.4 Toughness Properties of BA-Based Geopolymer-Stabilized RCA

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

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

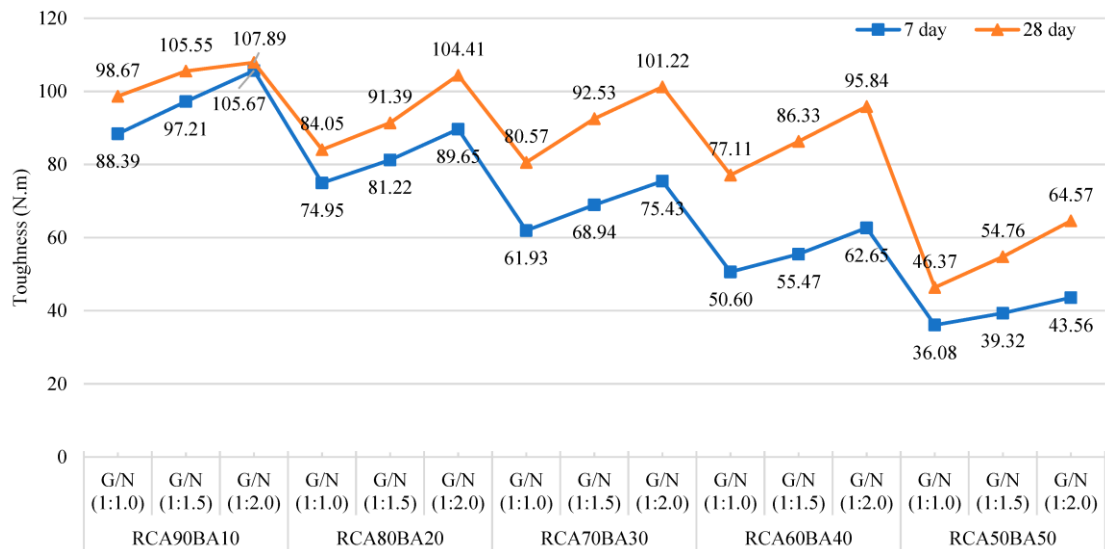


Figure 3.6 Toughness of BA-based geopolymer-stabilized RCA samples.

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

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

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

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

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

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

3.4.2 Microstructural Analysis

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

3.4.2.1 Microstructural Development in Systems with a Low Bottom Ash Content

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

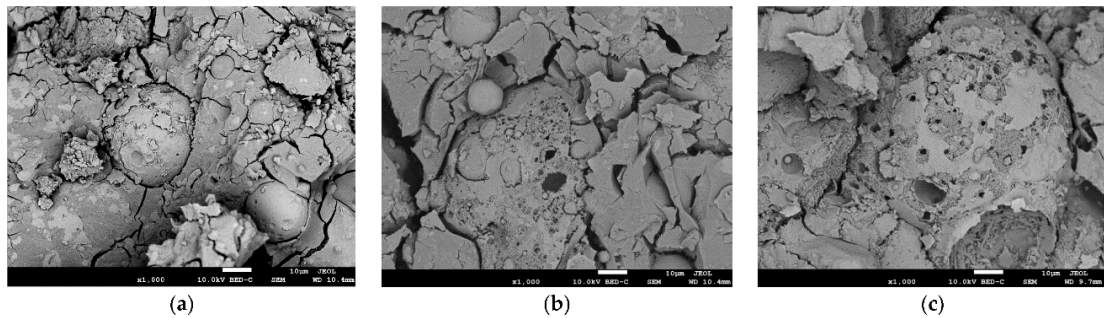


Figure 3.7 SEM images of RCA90BA10: (a) G/N ratio of 1:1, (b) G/N ratio of 1:1.5, and (c) G/N ratio of 1:2 at 28 days of curing.

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

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

3.4.2.2 Microstructural Development in Systems with a High Bottom Ash Content

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

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

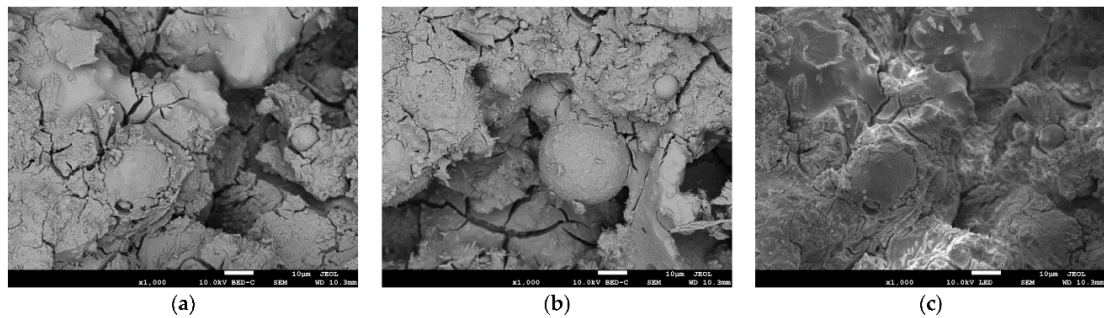


Figure 3.8 SEM images of RCA60BA40: (a) G/N ratio of 1:1, (b) G/N ratio of 1:1.5, and (c) G/N ratio of 1:2 at 28 days of curing.

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

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

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

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

3.4.3 EDX Analysis

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

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

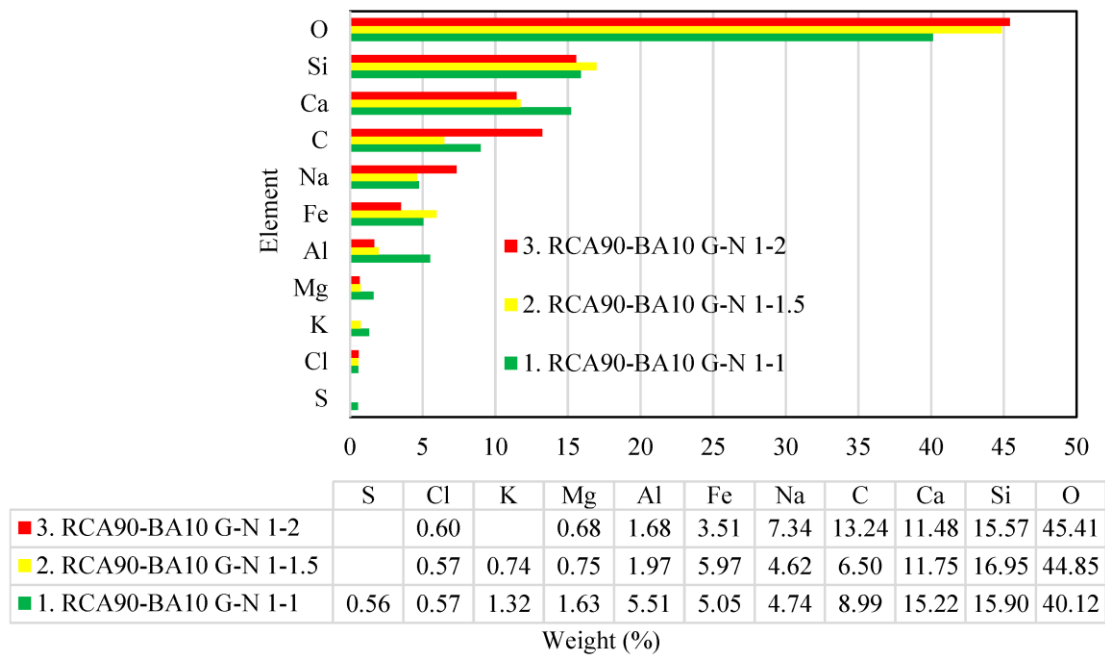


Figure 3.9 Chemical compositions of RCA90BA10 formulations at various G/N ratios.

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

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

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

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

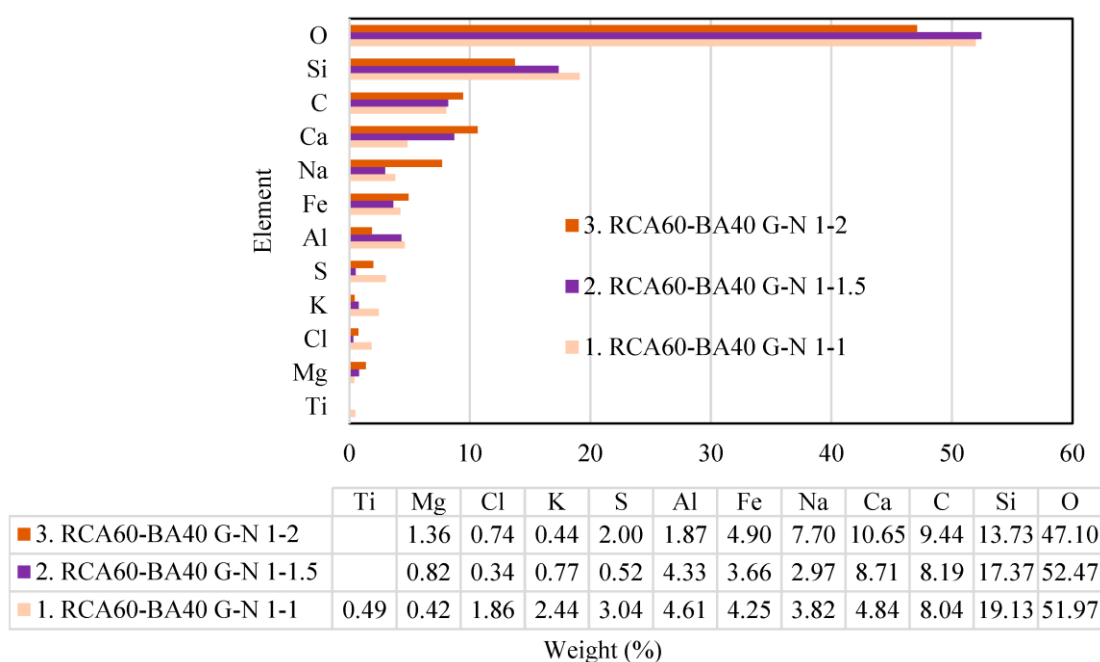


Figure 3.10 Chemical compositions of RCA60BA40 formulations at various G/N ratios.

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

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

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

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

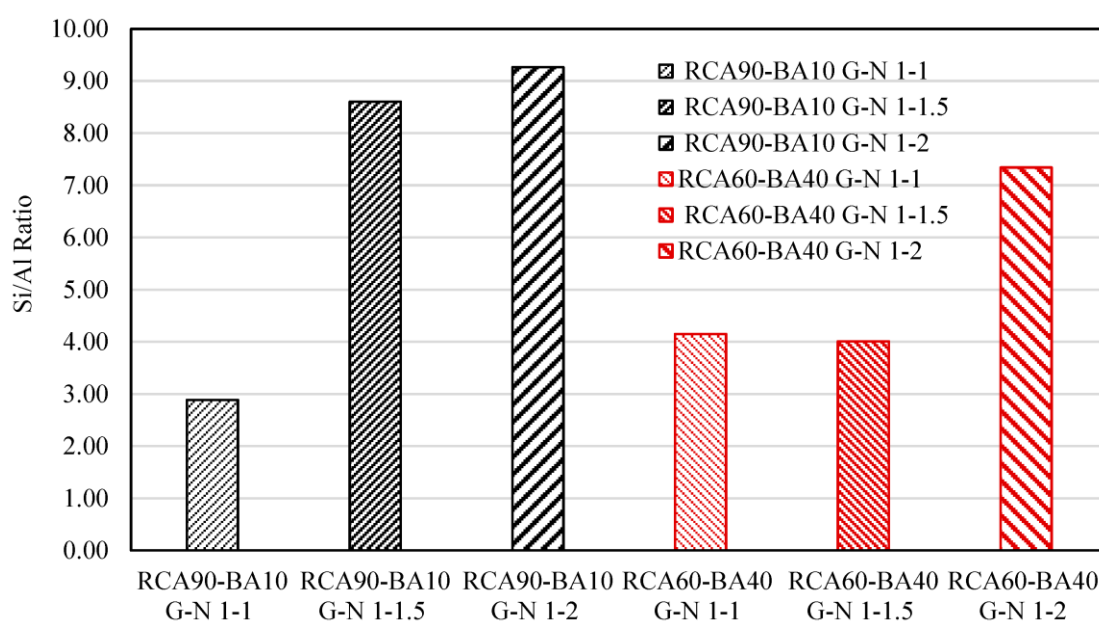


Figure 3.11 Si/Al ratios of RCA90BA10 and RCA60BA40 with various G/N ratios.

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

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

3.4.4 XRD Analysis

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

The XRD patterns in Figure 12 identified four primary crystalline phases across all formulations: quartz (SiO_2), calcite (CaCO_3), gehlenite ($\text{Ca}_2\text{Al}_2\text{SiO}_7$), 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 (Cristelo et al., 2012; Kumar & Revathi, 2020).

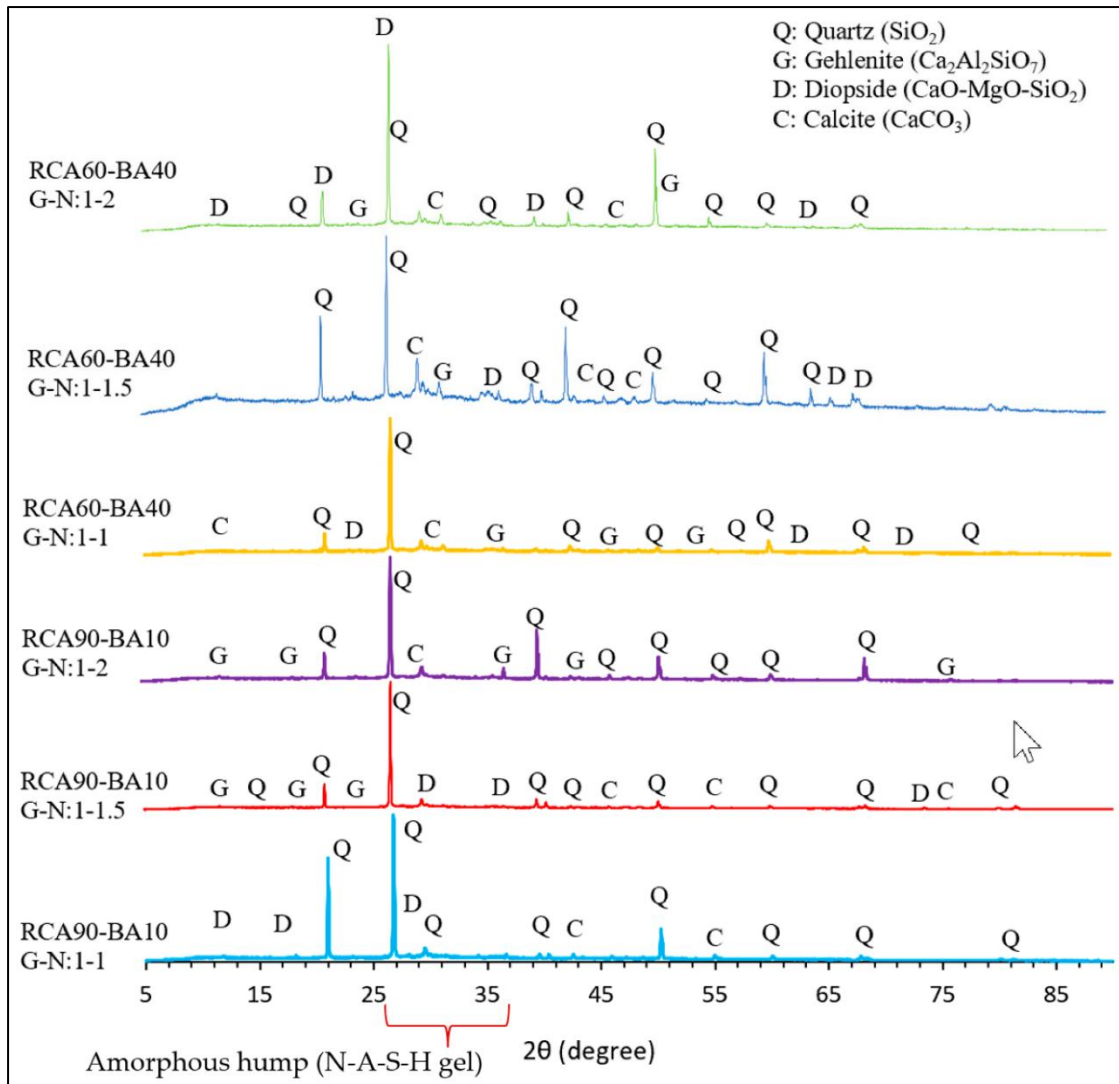


Figure 3.12 XRD patterns of RCA90BA10 and RCA60BA40 with various G/N ratios.

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

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

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

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

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

Utilizing 1 ton of RCA in place of natural aggregate can reduce landfill waste by approximately 0.8 tons and save up to 20–25 kg of CO₂ compared to virgin aggregate processing (Limbachiya, Meddah, & Ouchagour, 2012). 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 (Nakararoj et al., 2022). Therefore, the use of 100% waste-derived RCA and BA in this study potentially contributed to a reduction of over 200 kg of CO₂ emissions and diverted over 1.5 tons of industrial waste from the landfills per ton of stabilized base material produced.

3.5 Conclusions

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

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

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

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

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

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

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

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

3.6 Reference

- Bobirică, C., Orbeci, C., Bobirică, 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. *Scientific Reports*, 10(1), 19827.
- Buritatum, A., Suddeepong, A., Horpibulsuk, S., Akkharawongwhatthana, K., Yaowarat, T., Hoy, M., Arulrajah, A. (2022). Improved performance of asphalt concretes using bottom ash as an alternative aggregate. *Sustainability*, 14(12), 7033.

- Chindaprasirt, P., Jaturapitakkul, C., Chalee, W., & Rattanasak, U. (2009). Comparative study on the characteristics of fly ash and bottom ash geopolymers. *Waste Management*, 29(2), 539-543.
- Cristelo, N., Glendinning, S., Fernandes, L., & Pinto, A. T. (2012). Effect of calcium content on soil stabilisation with alkaline activation. *Construction and building materials*, 29, 167-174.
- Davidovits, J. (2005). *Geopolymer, green chemistry and sustainable development solutions: proceedings of the world congress geopolymer 2005*: Geopolymer Institute.
- Davidovits, J. (2008). *Geopolymer chemistry and applications*: Geopolymer Institute.
- Duxson, P., Fernández-Jiménez, A., Provis, J. L., Lukey, G. C., Palomo, A., & van Deventer, J. S. (2007). Geopolymer technology: the current state of the art. *Journal of Materials Science*, 42(9), 2917-2933.
- Duxson, P., Mallicoat, S. W., Lukey, G. C., Kriven, W. M., & Van Deventer, J. S. (2007). The effect of alkali and Si/Al ratio on the development of mechanical properties of metakaolin-based geopolymers. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 292(1), 8-20.
- El Alouani, M., Saufi, H., Aouan, B., Bassam, R., Alehyen, S., Rachdi, Y., Belaaouad, S. (2024). A comprehensive review of synthesis, characterization, and applications of aluminosilicate materials-based geopolymers. *Environmental Advances*, 16, 100524.
- Farooq, F., Jin, X., Javed, M. F., Akbar, A., Shah, M. I., Aslam, F., & Alyousef, R. (2021). Geopolymer concrete as sustainable material: A state of the art review. *Construction and building materials*, 306, 124762.
- Giunta, M. (2023). Sustainable Practices in Road Constructions: Estimation and Mitigation of Impact on Air Quality. *Transportation Research Procedia*, 69, 139-146.
- Hanjitsuwan, S., Hunpratub, S., Thongbai, P., Maensiri, S., Sata, V., & Chindaprasirt, P. (2014). Effects of NaOH concentrations on physical and electrical properties of high calcium fly ash geopolymer paste. *Cement and Concrete Composites*, 45, 9-14.
- Hassan, A., Arif, M., & Shariq, M. (2019). Use of geopolymer concrete for a cleaner and sustainable environment—A review of mechanical properties and microstructure. *Journal of cleaner production*, 223, 704-728.
- Horpibulsuk, S., Hoy, M., Suddepong, A., Udomchai, A., Buritatum, A., Yaowarat, T., Mobkrathok, M. (2024). A 10-Year Research on Sustainable Pavement Materials.

- In *Recent Advances and Innovative Developments in Transportation Geotechnics: Keynote Volume ICTG 2024* (pp. 129-139): Springer.
- Hoy, M., Horpibulsuk, S., Chinkulkijniwat, A., Suddeepong, A., Buritatum, A., Yaowarat, T., Kantatham, K. (2024). Innovations in recycled construction materials: paving the way towards sustainable road infrastructure. *Frontiers in Built Environment*, 10, 1449970.
- Jurič, B., Hanžič, L., Ilić, R., & Samec, N. (2006). Utilization of municipal solid waste bottom ash and recycled aggregate in concrete. *Waste Management*, 26(12), 1436-1442.
- Khale, D., & Chaudhary, R. (2007). Mechanism of geopolymerization and factors influencing its development: a review. *Journal of Materials Science*, 42(3), 729-746.
- 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. *International Journal of Geo-Engineering*, 7(1), 15.
- Kovalchuk, G., Fernández-Jiménez, A., & Palomo, A. (2007). Alkali-activated fly ash: Effect of thermal curing conditions on mechanical and microstructural development–Part II. *Fuel*, 86(3), 315-322.
- Kumar, M. L., & Revathi, V. (2020). Microstructural properties of alkali-activated metakaolin and bottom ash geopolymer. *Arabian Journal for Science and Engineering*, 45(5), 4235-4246.
- Lahoti, M., Wong, K. K., Yang, E.-H., & Tan, K. H. (2018). Effects of Si/Al molar ratio on strength endurance and volume stability of metakaolin geopolymers subject to elevated temperature. *Ceramics International*, 44(5), 5726-5734.
- Limbachiya, M., Meddah, M. S., & Ouchagour, Y. (2012). Performance of Portland/Silica Fume Cement Concrete Produced with Recycled Concrete Aggregate. *ACI Materials Journal*, 109(1).
- Liu, J., Doh, J.-H., Dinh, H. L., Ong, D. E., Zi, G., & You, I. (2022). Effect of Si/Al molar ratio on the strength behavior of geopolymer derived from various industrial waste: A current state of the art review. *Construction and building materials*, 329, 127134.
- Moazami, D., Yusoff, Z. M., Muniandy, R., & Hamid, H. (2013). Effect of stabilizers on stiffness modulus of soil layers: A review. *Int. J. Phys. Sci*, 8(32), 1602-1610.

- Nakararoj, N., Tran, T. N. H., Sukontasukkul, P., Attachaiyawuth, A., Tangchirapat, W., Ban, C. C., Jaturapitakkul, C. (2022). Effects of High-Volume bottom ash on Strength, Shrinkage, and creep of High-Strength recycled concrete aggregate. *Construction and building materials*, 356, 129233.
- Nanda, R. P., & Priya, N. (2024). Geopolymer as stabilising materials in pavement constructions: A review. *Cleaner Waste Systems*, 7, 100134.
- Nuaklong, P., Wongs, A., Sata, V., Boonserm, K., Sanjayan, J., & Chindaprasirt, P. (2019). Properties of high-calcium and low-calcium fly ash combination geopolymer mortar containing recycled aggregate. *Heliyon*, 5(9).
- Phoo-ngernkham, T., Chindaprasirt, P., Sata, V., Hanjitsuwan, S., & Hatanaka, S. (2014). The effect of adding nano-SiO₂ and nano-Al₂O₃ on properties of high calcium fly ash geopolymer cured at ambient temperature. *Materials & Design*, 55, 58-65.
- Phummiphan, I., Horpibulsuk, S., Rachan, R., Arulrajah, A., Shen, S.-L., & Chindaprasirt, P. (2018). High calcium fly ash geopolymer stabilized lateritic soil and granulated blast furnace slag blends as a pavement base material. *Journal of Hazardous Materials*, 341, 257-267.
- Polue, T., Suddeepong, A., Horpibulsuk, S., Samingthong, W., Arulrajah, A., & Rashid, A. S. A. (2020). Strength development of recycled concrete aggregate stabilized with fly ash-rice husk ash based geopolymer as pavement base material. *Road Materials and Pavement Design*, 21(8), 2344-2355.
- Provis, J. L., & Van Deventer, J. S. J. (2009). *Geopolymers: structures, processing, properties and industrial applications*: Elsevier.
- Ramadan, S., Kassem, H., Elkordi, A., & Joumbat, R. (2025). Advancing Pavement Sustainability: Assessing Recycled Aggregates as Substitutes in Hot Mix Asphalt. *Sustainability*, 17(12), 5472.
- Salehi, S., Arashpour, M., Kodikara, J., & Guppy, R. (2021). Sustainable pavement construction: A systematic literature review of environmental and economic analysis of recycled materials. *Journal of cleaner production*, 313, 127936.
- 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. *Journal of cleaner production*, 278, 123437.
- Sata, V., Sathonsaowaphak, A., & Chindaprasirt, P. (2012). Resistance of lignite bottom ash geopolymer mortar to sulfate and sulfuric acid attack. *Cement and Concrete Composites*, 34(5), 700-708.

- Sha, A., Liu, Z., Jiang, W., Qi, L., Hu, L., Jiao, W., & Barbieri, D. M. (2021). Advances and development trends in eco-friendly pavements. *Journal of Road Engineering*, 1, 1-42.
- Singh, G. B., & Subramaniam, K. V. (2017). Evaluation of sodium content and sodium hydroxide molarity on compressive strength of alkali activated low-calcium fly ash. *Cement and Concrete Composites*, 81, 122-132.
- Sinha, D. K., Kumar, A., & Kumar, S. (2014). Development of geopolymer concrete from fly ash and bottom ash mixture. *Transactions of the Indian Ceramic Society*, 73(2), 143-148.
- Sivasakthi, M., & Jeyalakshmi, R. (2021). Effect of change in the silica modulus of sodium silicate solution on the microstructure of fly ash geopolymers. *Journal of Building Engineering*, 44, 102939.
- Temuujin, J., Minjigmaa, A., Lee, M., Chen-Tan, N., & Van Riessen, A. (2011). Characterisation of class F fly ash geopolymer pastes immersed in acid and alkaline solutions. *Cement and Concrete Composites*, 33(10), 1086-1091.
- Tiyasangthong, S., Yoosuk, P., Krosoongnorn, K., Sakdinakorn, R., Tabyang, W., Phojan, W., & Suksiripattanapong, C. (2022). Stabilization of recycled concrete aggregate using high calcium fly ash geopolymer as pavement base material. *Infrastructures*, 7(9), 117.
- Tran, N. Q., Hoy, M., Suddeepong, A., Horpibulsuk, S., Kantathum, K., & Arulrajah, A. (2022). Improved mechanical and microstructure of cement-stabilized lateritic soil using recycled materials replacement and natural rubber latex for pavement applications. *Construction and building materials*, 347, 128547.
- Xiao, R., Polaczyk, P., Zhang, M., Jiang, X., Zhang, Y., Huang, B., & Hu, W. (2020). Evaluation of glass powder-based geopolymer stabilized road bases containing recycled waste glass aggregate. *Transportation research record*, 2674(1), 22-32.
- Xie, T., & Ozbakkaloglu, T. (2015). Behavior of low-calcium fly and bottom ash-based geopolymer concrete cured at ambient temperature. *Ceramics International*, 41(4), 5945-5958.
- Xu, H., & Van Deventer, J. (2000). The geopolymerisation of alumino-silicate minerals. *International journal of mineral processing*, 59(3), 247-266.
- Yip, C. K., Lukey, G. C., Provis, J. L., & Van Deventer, J. S. (2008). Effect of calcium silicate sources on geopolymerisation. *Cement and concrete research*, 38(4), 554-564.
- Yoon, J. Y., Lee, J. Y., & Kim, J. H. (2019). Use of raw-state bottom ash for aggregates in construction materials. *Journal of material cycles and waste management*, 21(4), 838-849.

- Zakka, W. P., Lim, N. H. A. S., & Khun, M. C. (2021). A scientometric review of geopolymer concrete. *Journal of cleaner production*, 280, 124353.
- Zhang, Z., Provis, J. L., Reid, A., & Wang, H. (2014). Geopolymer foam concrete: An emerging material for sustainable construction. *Construction and building materials*, 56, 113-127.