

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

5.1 Summarization

Very recent decades, the rapid expansion of infrastructure in Thailand and other developing nations has created an increasing demand for natural aggregates in highway and pavement construction. This demand has accelerated the exploitation of quarries and gravel pits, leading to significant environmental degradation and depletion of finite natural resources. Simultaneously, the global imperative to mitigate climate change and reduce greenhouse gas emissions has intensified the pursuit of more sustainable construction practices. Within the field of pavement engineering, the use of recycled construction and demolition waste materials, such as Recycled Concrete Aggregate (RCA), along with industrial byproducts like bottom ash (BA), has gained attention as a potential substitute for conventional aggregates. Nevertheless, these materials in their untreated state often exhibit insufficient strength and durability to ensure long-term road performance. Traditional stabilization using Portland cement can enhance their engineering properties but contributes substantially to CO₂ emissions, thereby aggravating environmental concerns.

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

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

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

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

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

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

Overall, the study demonstrates that the utilization of RCA and BA, two abundant waste-derived materials, can be successfully converted into high-performance pavement subbase materials through geopolymer technology. When combined with NRL, the system not only enhances mechanical and durability properties but also contributes to broader environmental benefits by reducing the consumption of virgin aggregates, minimizing landfill disposal, and lowering CO₂ emissions. These outcomes strongly align with Thailand's national objectives of promoting sustainable construction practices and reducing the environmental footprint of road infrastructure.

5.2 Recommendation for future work

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

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

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

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

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

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

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

Scaling toward sustainable infrastructure policymakers and engineers are encouraged to incorporate geopolymer technology and NRL-modified waste-based materials into Thailand’s broader sustainability roadmap. This will contribute to reducing dependence on natural aggregates, minimizing landfill disposal, and lowering CO₂ emissions from road construction.