

CHAPTER V

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

This comprehensive study on geopolymer mortars using fly ash (FA) and calcium carbonate sludge (CCS) has yielded several significant findings regarding the relationships between composition, processing parameters, and performance characteristics:

1) The setting time of geopolymer mortars was significantly influenced by the liquid-to-binder ratio, alkaline activator composition, and precursor materials. Higher NaOH concentrations (15M) consistently produced shorter setting times compared to lower molarities (5M and 10M), attributed to enhanced dissolution of aluminosilicate species and accelerated geopolymerization. The incorporation of CCS further accelerated setting times, with 30% CCS replacement showing the most pronounced effect.

2) Compressive strength development showed optimal performance at a liquid-to-binder ratio of 0.4, with several mix designs exceeding the reference cement mortar strength of 24.5 MPa. The most effective compositions featured a sodium silicate to sodium hydroxide ratio of 60:40, achieving strengths of 25-40 MPa. This optimal ratio represented the ideal balance between silicate species and hydroxide ions for maximizing network formation and structural densification.

3) The incorporation of CCS with FA resulted in the formation of a sophisticated hybrid binding system containing both N-A-S-H and C-A-S-H gels. This synergistic effect was most pronounced at 20-30% CCS replacement and 15M NaOH concentration, where formulations demonstrated up to 63% higher strength compared to conventional cement mortar (40 MPa vs 24.5 MPa).

4) Microstructural analysis revealed that higher NaOH concentrations (15M) produced denser and more compact matrices, particularly in specimens containing both FA and CCS. The presence of both N-A-S-H and C-A-S-H gels in hybrid systems resulted in more homogeneous microstructures compared to systems with FA alone, providing the structural foundation for enhanced mechanical properties.

5) XRD analysis confirmed the formation of complex reaction products, with higher NaOH molarities leading to more pronounced amorphous characteristics, indicating more extensive dissolution of precursor materials. The incorporation of CCS introduced additional calcium-bearing phases, supporting the formation of C-A-S-H gel observed in microscopic analysis.

6) Machine learning analysis using XGBoost demonstrated exceptional predictive accuracy ($R^2=0.998$) for compressive strength based on compositional parameters. SHAP analysis revealed that the SS:SH ratio was the most influential parameter (approximately 70% importance), followed by NaOH molarity (15%), with liquid-to-binder ratio and FA ratio showing substantially lower importance (approximately 5% each). These findings challenge conventional mix design approaches that often prioritize solid precursor ratios and suggest that optimizing the alkaline activator should be the primary focus for enhancing geopolymer performance. While the machine learning models demonstrated exceptional predictive accuracy within the studied parameter ranges, future research should validate these models with expanded datasets or external data from different raw material sources to confirm their broader applicability and generalizability across various geopolymer systems.

From a practical implementation perspective, this research provides valuable guidelines for developing geopolymer mortars tailored to specific applications. For rapid-setting applications, formulations with 20-30% CCS activated with 15M NaOH at $V/b=0.3$ offer optimal performance. For applications requiring higher strength, the 70FA:30CCS formulation with 15M NaOH and 60:40 SS:SH ratio at $V/b=0.4$ provides exceptional mechanical properties.

5.2 Recommendation

Future research should comprehensively address several critical aspects for practical implementation:

1) Long-term durability characteristics, including resistance to aggressive environments (sulfate and acid attack, freeze-thaw cycling), dimensional stability (drying shrinkage), and carbonation resistance under various exposure conditions;

2) Quantitative environmental and economic assessments through life cycle analysis (LCA) and detailed cost comparisons with conventional cement, considering raw material costs, processing energy, and carbon credits;

3) Scale-up challenges, including raw material variability between different sources of FA and CCS, industrial-scale mixing procedures, quality control protocols, and optimization of curing conditions for large-scale production.

Addressing these aspects systematically would provide a complete evaluation of the commercial viability and further advance the practical implementation of this sustainable construction technology. Future research should focus on long-term durability characteristics, including resistance to aggressive environments, dimensional stability, and performance under varying environmental conditions. Additionally, scaling these optimized formulations for commercial applications and evaluating their economic feasibility compared to conventional cementitious materials would further advance the practical implementation of this sustainable construction technology.