CHAPTER I
INTRODUCTION

1.1 Introduction

Cement production plays a crucial role in modern infrastructure development as the primary binder in concrete and other construction materials. However, it is also one of the most significant contributors to global carbon dioxide (CO2) emissions, accounting for nearly 8% of total anthropogenic CO2 emissions (Andrew, 2018; Olivier et al., 2017). The calcination of limestone, an energy-intensive process, is the primary source of these emissions, releasing nearly 900 kg of CO2 per ton of cement produced (Barcelo et al., 2014; Miller et al., 2018). This environmental impact, combined with extensive natural resources use and high energy consumption in cement manufacturing, makes the transition toward sustainable alternatives imperative (Barcelo & Kline, 2012; Elshabrawy, 2025; Environment et al., 2018).

Geopolymer-based materials have emerged as promising alternatives to traditional Portland cement by harnessing alkali-activated polymerization reactions, offering significant environmental benefits while maintaining or exceeding conventional mechanical properties (Barcelo et al., 2014; Provis, 2018). Through the elimination of energy-intensive limestone calcination and the strategic utilization of industrial by-products, these materials can reduce CO2 emissions by up to 80% compared to Portland cement-based products, representing a significant step toward sustainable construction practice (Habert et al., 2011; McLellan et al., 2011). Recent studies have expanded the application of geopolymers to lightweight and high-strength concrete, including performance under elevated temperatures and the use of advanced additives like nanomaterials, fibers, and industrial by-products (Amin et al., 2022; Amin et al., 2021; Tayeh et al., 2022; Tayeh et al., 2021; Zeyad et al., 2024; Zeyad, Bayagoob, et al., 2025; Zeyad, Magbool, et al., 2025).

Geopolymer synthesis occurs through alkali activation of aluminosilicate materials at lower temperatures (typically 60-80oC), significantly reducing energy consumption. The process involves the dissolution of industrial by-products like fly ash or slag in an alkaline solution, followed by polycondensation reactions that form three-dimensional aluminosilicate networks. Beyond their environmental advantages, geopolymers have demonstrated superior performance characteristics under aggregative conditions, including enhanced durability with compressive strength exceeding 70 MPa and stability at temperature up to 800oC (Tanya Bakharev, 2005; Kong & Sanjayan, 2010).

Various industrial by-products have been investigated as potential precursors for geopolymer synthesis, with fly ash (FA) establishing itself as a cornerstone material due to its unique chemical composition and widespread accessibility (Davidovits, 2008; Provis, 2018). The effectiveness of FA in geopolymer systems stems from its high concentrations of reactive silica (SiO2, 40-60%) and alumina (Al2O3, 20-30%), spherical particle morphology, and optimized particle size distribution, creating ideal conditions for geopolymerization reactions (Fernández-Jiménez & Palomo, 2003; Kutchko & Kim, 2006). Recent research has indicated the critical influence of reactive Si/Al ratios on geopolymers' mechanical performance and consistency. Liu et al. (2022) offer a comprehensive review linking Si/Al ratios to strength across various industrial residues, while Liu et al. (2023) correlate reactive Si, Al, and Fe dissolution to compressive strength in fly ash–based systems. However, the accelerating global shift away from coal-fired power generation threatens both the availability and consistency of FA supply (Clark et al., 2020; Oberschelp et al., 2019), necessitating exploration of alternative and complementary precursor materials to ensure continued development of sustainable construction technologies.

Calcium carbonate sludge (CCS) from the sugar industry presents a particularly promising solution, offering both environmental and technical advantages. As a waste product from sugarcane juice clarification, CCS is generated in large quantities globally and typically discarded in landfills or waste ponds, creating environmental pollution and waste management challenges for the sugar industry (Kumar et al., 2021). The incorporation of CCS into geopolymer systems thus addresses two sustainability challenges simultaneously: reducing cement-related CO2 emissions while diverting an industrial waste stream from landfills (Gopinath et al., 2018; Kumari et al., 2024).

While various Ca-rich precursors, such as ground granulated blast furnace slag, cement kiln dust, and limestone powder, have been widely studied for enhancing geopolymer performance through C-A-S-H gel formation, CCS remains underexplored. CCS is primarily a calcite-based waste material generated during sugar clarification processes. It contains over 90% CaO but lacks aluminosilicates, requiring hybridization with sources like fly ash.

1.2 Problem Statement

Previous research has shown that calcium carbide slag with high calcium oxide (CaO) content, similar to CCS, promoted the formation of calcium aluminosilicate hydrate (C-A-S-H) gels, which significantly enhanced early strength development and durability in geopolymer systems (Hanifa et al., 2025; Qiu et al., 2022). When combined with FA, the calcium-rich nature of this material complemented FA's silica and alumina contents, enabling the formation of a sophisticated hybrid binding system containing both sodium aluminosilicate hydrate (N-A-S-H) and C-A-S-H gels (Narani & Siddiqua, 2024; Yang et al., 2024; Zhang et al., 2023). This dual gel formation mechanism enhanced mechanical properties and promoted microstructural homogeneity in the final material.

The successful development of geopolymer systems demanded understanding the complex interplay between alkaline activation parameters and precursor characteristics (Krivenko et al., 2014). The activation process, involving aluminosilicate dissolution and subsequent gel formation (Duxson & Provis, 2008), remains inadequately explored for hybrid FA-CCS systems despite existing research on traditional FA-based geopolymers. Additionally, the liquid-to-binder (l/b) ratio critically influences workability and mechanical properties, with optimal ranges typically between 0.3-0.5 (Chindaprasirt & Rattanasak, 2023; Li et al., 2019; Xie et al., 2020), requiring careful control to balance performance and practical application requirements.

While previous research has established the influence of alkaline activator concentration and composition on traditional FA-based geopolymers, the interaction between activator parameters and hybrid FA-CCS systems remains largely unexplored. This research addressed these knowledge gaps by investigating the effects of alkaline activation and precursor proportions on hybrid FA-CCS geopolymer mortars. This study examined the influence of NaOH molarity (5M, 10M, and 15M), sodium silicate-to-sodium hydroxide (SS:SH) ratio (0:100 to 90:10), FA:CCS ratio (100:0 to 70:30), and liquid-to-binder (l/b) ratio (0.3, 0.4, 0.5) on setting time and compressive strength development. In recent years, machine learning has emerged as a powerful tool in materials science for uncovering complex relationships among input parameters and predicting mechanical properties of advanced materials (Khaled & Singla, 2025). In this study, four machine learning algorithms (XGBoost, CatBoost, AdaBoost, and Support Vector Machine) were systematically evaluated based on their established capabilities for handling complex, non-linear materials science data. These algorithms were employed to quantify feature influence on strength predictions, providing a mechanistic interpretation of compositional effects on geopolymer properties. This research hypothesized that calcium-rich CCS will accelerate setting times and enhance early strength when optimally combined with FA and appropriate alkaline activators. Our objectives are to determine the optimal FA-CCS combination and most effective alkaline activator composition for these hybrid systems, thereby establishing fundamental relationships between composition, processing, and performance for sustainable construction materials.

1.3 Purpose of the Research

This study contributes to the advancement of sustainable construction materials by introducing a novel hybrid geopolymer system using FA and CCS, an underutilized industrial by-product. Furthermore, the integration of machine learning provides a predictive framework and mechanistic insight into parameter sensitivity, which enhances mix optimization and promotes data-driven material design. These findings bridge experimental material science and AI-based modeling to support the development of high-performance, low-carbon construction materials aligned with circular economy goals.

Specifically, the research seeks to achieve the following objectives:

1) To determine the optimal mix proportions of fly ash and calcium carbonate sludge in geopolymer mortars that result in improved setting times, compressive strength, and durability. By investigating different ratios of these materials, the study aims to identify formulations that provide the best performance characteristics for various construction applications.

2) To investigate the effects of varying molarities of sodium hydroxide (NaOH) and different ratios of NaOH to sodium silicate on the properties of the geopolymer mortars. Understanding how these alkaline solutions influence setting times, compressive strength, and workability will provide valuable insights into developing high-performance geopolymer mortars.

3) To compare the performance of different geopolymer mortars in terms of their mechanical properties, such as setting time and 7-day compressive strength. This comparison will help evaluate the effectiveness of various binder ratios and alkaline solutions, allowing for the identification of the most suitable formulations for practical use.

4) To assess the feasibility of using fly ash and calcium carbonate sludge-based geopolymer mortars in real-world construction scenarios. The study will explore

the potential of these materials to replace or partially substitute traditional cement-based mortars in infrastructure development, precast concrete products, and the repair and rehabilitation of existing structures.

5) To contribute to the advancement of sustainable construction practices by demonstrating the viability of geopolymers as an alternative to OPC. The research aims to provide evidence that geopolymers can offer comparable or superior performance while significantly reducing the environmental impact of construction activities.

1.4 Scope of the Research

This research addresses the growing demand for sustainable construction materials by investigating the development of geopolymer mortars as an alternative to conventional Ordinary Portland Cement (OPC) binders. The study focuses on the valorization of industrial by-products, systematically evaluating the performance of a geopolymer system synthesized from fly ash (FA), a primary aluminosilicate precursor, and calcium carbonate sludge (CCS), a secondary additive. The core of this investigation is a comprehensive parametric study designed to elucidate the influence of key mix design variables on the material's behavior. The experimental program meticulously examines the effects of varying the FA-to-CCS replacement level to understand the synergistic interactions between the precursors. Concurrently, the composition of the alkaline activator solution is systematically adjusted by varying the sodium hydroxide (NaOH) molarity at 5 M, 10 M, and 15 M, as well as the mass ratio of sodium silicate (Na_2SiO_3) to the NaOH solution.

Performance assessment will encompass the characterization of both fresh properties, primarily setting time, and the development of hardened properties, particularly the compressive strength at various curing ages. The ultimate aim is to establish robust correlations between the mix proportions and the resultant engineering properties. This will provide a foundational understanding of the governing mechanisms and deliver the technical data necessary to assess the viability of FA-CCS based geopolymers for specific construction applications, including precast elements and materials for structural repair and rehabilitation.