# 論 文 の 要 旨

題　目　Studies on Engineering Properties Improvement of Geopolymer and Alkali-Activated Slag
（ジオポリマー，アルカリ活性スラグの工学的特性改善に関する研究）

氏　名　Saludung Apriany

Climate change is one of the environmental issues caused by greenhouse gases, including carbon dioxide ($CO_2$). Portland cement, the most used binder in concrete, has been listed as one of the major contributors to climate change due to the high $CO_2$ emitted during its manufacture. Therefore, the need to conserve our environment has led to the search for a new alternative material that can be used to replace the Portland cement in concrete production. The use of byproducts such as fly ash and slag to replace OPC has been studied to improve the engineering properties and durability of concrete, but the amount of these byproducts allowed to replace OPC is typically less than 50%.

Alkali-activated materials (AAMs), including those classified as geopolymer, have appeared as alternative materials that can fully replace Portland cement in concrete production. Many researchers have proved that AAMs and geopolymer possessed better mechanical strengths and durability than OPC materials. As one of the crucial factors in designing a building, the fire resistance of geopolymers has been studied by several researchers. They found that geopolymer performed better mechanical strength than OPC at extremely high temperatures, but their studies focused on the fly ash and metakaolin-based geopolymer. Despite having excellent fire resistance, the extensive application of AAMs and geopolymers in the construction field is limited by several factors, including their brittle property and high tendency to efflorescence and alkali leaching. Moreover, the variation of starting materials has led the complex investigation on the engineering properties and durability of AAMs. This research aims to investigate the effect of slag on the heat resistance of fly ash-based geopolymer, compare the heat resistance of OPC paste and geopolymer pastes, investigate the efflorescence and alkali leaching behavior of alkali-activated slag (AAS), and investigate the alkali leaching behavior and mechanical performances of geopolymer reinforced by epoxy resin. To achieve these objectives, this thesis is organized as follows:

Chapter 1 provides the background, objectives, and scopes of this study.

Chapter 2 provides a brief overview of some crucial aspects of the traditional cement industry, AAMs, and geopolymer technology by reviewing some published literature. A brief historical development, basic theory, characteristics, durability, and the importance of AAMs and geopolymers are discussed.

Chapter 3 describes the methodology of the research, including the materials (precursors, alkali solutions, and epoxy resin) used, mixture proportions, synthesis procedures, curing conditions, characterizations, and measurement methods. The study on heat resistance utilized low-calcium fly ash and ground granulated blast-furnace slag (GGBS) to produce geopolymer pastes with the amount of GGBS used to replace fly ash being 0, 15, 30, 45, and 60%. The effect of alkali metal type on the heat resistance of geopolymer paste (containing only 45% GGBS) was also investigated by using two combinations of alkali solution, which are the combination of sodium hydroxide (NaOH) solution and water glass, and the combination of potassium hydroxide (KOH) solution with water glass. In addition, the heat resistance of geopolymer pastes was also compared with the OPC paste. Small amounts of silica fume (0, 5, 10, and 15 mass%) were used to replace

GGBS in the production of AAS in order to investigate the effect of silica fume on efflorescence formation on AAS. Moreover, the geopolymer composites were also prepared by incorporating epoxy resin (1% and 2.5% by binder mass) into the geopolymer system. Some characteristics, including alkali leaching behavior, thermal analysis, phase composition, mechanical strengths, microstructure, and porosity of epoxy resin-reinforced geopolymer were investigated.

Chapter 4 presents the investigation results on the properties of geopolymer at high temperatures. The composition of geopolymer is one of the crucial factors affecting the heat resistance of this material. The inclusion of GGBS could significantly increase the initial compressive strength, but once exposed to elevated temperature, severe damage was observed in geopolymer containing a high amount of GGBS (e.g., 45% and 60% replacements). The damages that occur in high-Ca geopolymer could be partially attributed to the dehydration of aluminate-substituted calcium silicate hydrate (C-A-S-H). Using activator solutions from the combination of KOH solution and water glass may improve the fire resistance of geopolymer, as the specimen exhibited densification of pores and a slight increase of compressive strength after exposure to 950 °C. Meanwhile, geopolymer made from the alkali solution which is the combination of NaOH solution and water glass exhibited a highly porous microstructure after exposure to 950 °C. In addition, it was found that geopolymer materials performed better heat resistance in terms of phase stability and retained compressive strength than OPC paste.

Chapter 5 discusses the effect of silica fume on efflorescence formation and the alkali leaching behavior of AAS paste. The study on efflorescence is of large practical importance since it is one of the main issues limiting the application of AAMs in the civil engineering field. Unlike OPC materials in which efflorescence is considered harmless, efflorescence in AAMs can be structurally harmless. Although this study did not provide the measurement of mechanical strength, the information considered to be crucial in reducing the efflorescence formation is provided. The results show that the inclusion of silica fume could reduce the alkali leaching rate, resulting in lower efflorescence formation. Since efflorescence is strongly related to the free alkali, the reduction in efflorescence formation could be due to the fact that the additional silica from silica fume reduces the Na/Si ratio in the AAS system; thus, less sodium will remain unreacted in the matrix. In addition, the inclusion of silica fume generated micropores. Although some previous studies have suggested that porosity has a strong correlation to alkali loss, this study did not find such a correlation. In this study, specimens without silica fume present lower porosity but faster alkali leaching, and rapid efflorescence formation compared to specimens containing silica fume.

Chapter 6 provides the experimental results of the investigation on the alkali leaching and mechanical performances of fly ash/GGBS-based geopolymer reinforced by bisphenol F type epoxy resin. In this study, the effect of curing conditions on the alkali leaching and mechanical strengths was also investigated. It was found that the addition of epoxy resin up to 2.5% could reduce the alkali leaching rate and total alkali leaching of ambient-cured geopolymer. The compressive strength and flexural strength were up to maximum value while doping 1% epoxy resin. Despite reducing the alkali leaching, the inclusion of 2.5% epoxy resin was found to reduce the homogeneity of the matrix. Interestingly, although geopolymers cured in water leached significant amounts of alkalis, their compressive strength was higher than that of geopolymers cured at ambient conditions, proving that alkali leaching did not negatively influence the compressive strength.

Chapter 7 stated the conclusions of this study and some recommendations for future research related to this study.