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Soil Stabilization using Cementless Geopolymer

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Abstract: *Soil stabilization is essential for the development of resilient infrastructure on soft and collapsible ground. Conventional stabilization relies heavily on ordinary Portland cement (OPC), a material with a high carbon footprint and limited durability in aggressive environments. This study investigates the feasibility of a cementless geopolymer binder—derived from industrial by-products such as fly ash, ground granulated blast furnace slag (GGBS), and alkaline activators to stabilize sandy soils. This study examined how varying levels of cementless geopolymer addition influence the soil's mechanical characteristics. A sandy-clayey soil, locally available in Korea, was utilized in this study with a 0%, 10%, 20%, 30%, and 40% replacement with cementless geopolymer binder. Water content was fixed at 30% for this testing. After 5-days of curing, specimens were checked for Unconfined Compressive Strength (UCS) to check the impact of cementless geopolymer on soil stabilization. Optimal mix designs, with 30~40% replacement with cementless geopolymer, achieved considerably higher UCS values after 5-days of curing at ambient temperatures, surpassing the performance of OPC stabilized specimens while reducing CO_2 emissions. The results demonstrate that cement less geopolymer binders can serve as sustainable, high performance alternatives for soil stabilization, offering both environmental benefits and enhanced durability in chemically aggressive settings.*

Keywords: Cementless, Geopolymer, Unconfined Compressive Strength, Construction Materials, Soil Stabilization

1. INTRODUCTION[1]

Constructing durable infrastructure on weak or collapsible soils poses a persistent challenge for road and geotechnical engineers. In many parts of the world, sandy and loose soils exhibit low shear strength, high compressibility, and poor bearing capacity. To enhance the engineering performance of such soils, stabilization using chemical binders has become a widely adopted practice. Among these binders, Ordinary Portland Cement (OPC) and lime have traditionally been favored because of their effectiveness in improving the strength and stiffness of problematic soils [1]. However, the production of these binders is energy-intensive and is known to be a major contributor to greenhouse gas emissions, accounting for nearly 8–10% of the global anthropogenic CO_2 output [2,3]. The environmental impact associated with cement production has prompted the engineering community to explore low-carbon alternatives for soil improvement [4].

Given the global drive toward carbon-neutral and sustainable construction materials, researchers have increasingly turned to cementless alternatives. Among the various sustainable options proposed, cementless geopolymer binders have emerged as a promising replacement for cement-based materials.

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Geopolymers [5] are inorganic aluminosilicate binders synthesized through the alkali activation of industrial by-products such as fly ash and ground granulated blast furnace slag (GGBS), free of traditional cement, thereby supporting waste utilization and reducing carbon emissions [6,7]. Common industrial by-products such as fly ash, slag, industrial sodium carbonate, and hydrated lime can be used as precursor materials, transforming waste streams into value-added construction binders.

In recent years, several researchers have examined the application of geopolymer technology in soil stabilization. Studies have shown that the addition of geopolymer binders enhances the unconfined compressive strength (UCS), stiffness, and water resistance of various soil types. Bui et al. [8] utilized 20-40% fly ash and 10% GGBS-based geopolymer to check the mechanical strength improvement of laterite soil. Their results showed that geopolymer mixes containing more than 30% fly ash demonstrated substantially greater compressive and tensile strengths than cement-stabilized soils. Mugula et al. [9] investigated the effect of 0-50% steel slag and 0-1% unhydrolyzed cellulose on stabilization of silica sand. Their findings established that 30% steel slag could enhance the UCS strength by 99%. Onyelowe et al. [10] used the geopolymer binders produced from quarry dust and metallurgical slag, activated by alkaline silicate solutions. The results showed that with increasing proportion of geopolymer, the UCS strength was increased.

Despite these advantages, the application of geopolymer binders in soil stabilization is still relatively new compared to conventional cement or lime treatments. Furthermore, the utilization of industrial residues such as fly ash and GGBS in geopolymer systems supports waste valorization and circular-economy principles by diverting large volumes of by-products from landfills and reducing the overall environmental impact of construction [11].

The current research aims to address these gaps by investigating the stabilization of sandy-clayey soil using two different compositions (KC-1 and CGC) of cementless geopolymer powder in varying percentages. The study evaluates the influence of geopolymer content and powder ingredients on the mechanical behavior of the treated soil. The overarching goal is to assess the feasibility of geopolymers as a sustainable and environmentally responsible alternative for soil stabilization, reducing dependence on traditional cement-based methods while maintaining desirable engineering performance.

2. METHODOLOGY

2.1 Raw Materials

Cementless geopolymer powder was prepared using appropriate percentages of slag, fly ash and other constituents as presented in Table 1. Granulated Blast Furnace Slag (GGBS) was obtained from StarMaterials Co. Ltd, while fly ash was obtained from KC GreenMaterials. The locally available sandy-clayey soil was obtained from Goyang city of South Korea.

Table 1. Cementless geopolymer composition

Powder constituents	KC-1 (%)	CGC (%)
Slag	55	76
Fly Ash (PC-FA)	20	15
CaO	-	6
$CaCl_2$	-	3
Na_2CO_3	10	-
Slaked Lime	15	-
Anhydrite (additive)	-	5

Slag = Granulated blast furnace slag; PC-FA = Pulverized Coal Fly Ash; CaO = Calcium Oxide; $CaCl_2$ = Calcium Chloride; Na_2CO_3 = Sodium Carbonate



Fig. 1. Sieved sandy-clayey soil & Cementless geopolymer

2.2 Sample Fabrication

Cylindrical specimens (50 mm dia, 100 mm height) were prepared using 0%, 10%, 20%, 30% and 40% cementless geopolymer with a 30% water content by weight of total mix. At least two replicates for each percentage and type of geopolymer powder were prepared.

The soil was dried in oven at 60ºC for at least 24hrs to remove any moisture and sieved. Soil passing through 4.75mm sieve was then mixed with different percentages of cementless geopolymer in dry state. Water was then added and thoroughly mixed until a homogeneous mass was obtained.



Fig. 2. Dry mixing of soil and cementless geopolymer

The prepared mixture was then filled in the UCS molds in 3 layers. Each Layer was compacted with 25 blows of standard proctor rammer. Specimens were then extracted from the molds and cured for 5-days in moisture-controlled oven at 23℃.



Fig. 3. Compacted UCS specimens

2.3 Testing Protocol

The uniaxial compressive strength test was conducted at 5th day, using Universal Testing Machine (UTM) with a constant loading speed of 1 mm/min as per ASTM D2166 [12]. At least two replicates were tested for each percentage of cementless geopolymer. Specimens were loaded until failure and peak loads were measured. Uniaxial compressive strength was then calculated using the area under loading and peak loads.

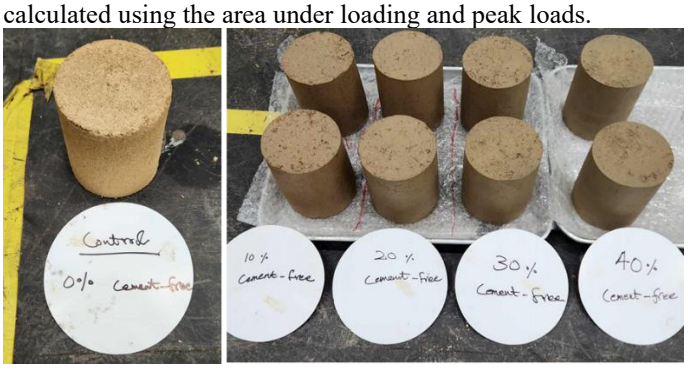


Fig. 4. Extracted and cured specimens

Figure 5 illustrates the variation in unconfined compressive strength (UCS) of sandy-clayey soil stabilized with two types of cementless geopolymer powders (KC-1 and CGC) at different replacement levels (0%, 10%, 20%, 30%, and 40%). Both geopolymer compositions significantly enhanced the strength of the soil compared to the untreated soil. The UCS values exhibited a consistent increase with increasing powder content up to 40%, demonstrating the progressive formation of geopolymeric gels and improved particle bonding within the soil matrix.

For both binder types, the increase in UCS after five days of ambient curing was substantial. The control specimen (0% binder) showed minimal strength, primarily due to weak particle cohesion in the untreated soil. At 10% replacement, both KC-1 and CGC mixtures achieved a noticeable strength improvement, suggesting early geopolymeric reactions between the alkaline activators and aluminosilicate precursors. With increasing geopolymer content, UCS values rose sharply; the 30 % and 40% mixes demonstrated the highest strength gains. This can be attributed to the enhanced availability of reactive silica and alumina species that participated in geopolymerization, producing a denser microstructure and stronger interparticle bonds [13-14].

Between the two binder formulations, the CGC-stabilized soil consistently exhibited higher UCS values than KC-1 at equivalent replacement levels. This difference is likely due to the higher slag content (76%) and inclusion of calcium oxide (CaO) and calcium chloride ($CaCl_2$) in CGC, which promote rapid calcium–aluminosilicate-hydrate (C-A-S-H) gel formation alongside geopolymeric N-A-S-H structures. These hybrid gels accelerate early strength development and reduce porosity in the stabilized soil. The presence of anhydrite in CGC may also contribute to sulfate activation, enhancing the solidification process. In contrast, KC-1 contained a higher proportion of fly ash (20%) and sodium carbonate, leading to slower geopolymerization kinetics and slightly lower short-term strength, though still far superior to untreated soil.

3. RESULTS AND DISCUSSION

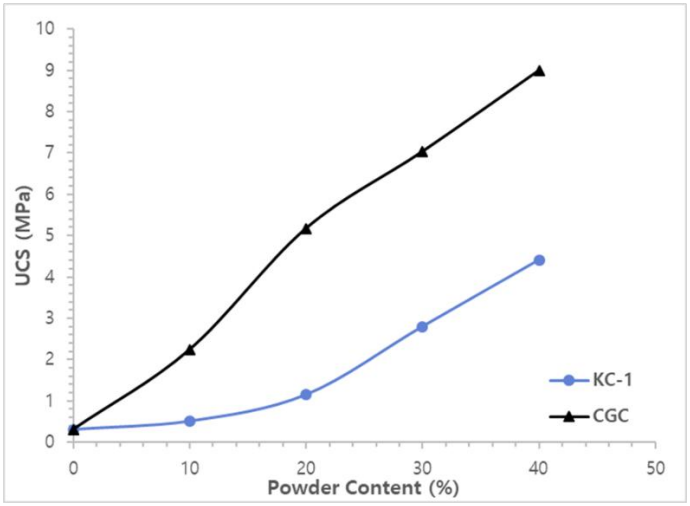


Fig. 5. Comparison of unconfined compressive strength for cementless geopolymer powders type and content

The failure patterns presented in Fig. 6 and Fig. 7 indicate a transition from brittle to more ductile behavior with increasing cementless geopolymer content. Specimens containing lower powder proportions (0% and 10%) failed under smaller axial loads, displaying early strain localization and minimal deformation beyond the peak stress, reflecting weak particle bonding and insufficient cohesion. Conversely, mixtures with higher powder contents (30% and 40%) developed distinct peak strengths followed by gradual strain softening, implying enhanced load-carrying capacity.

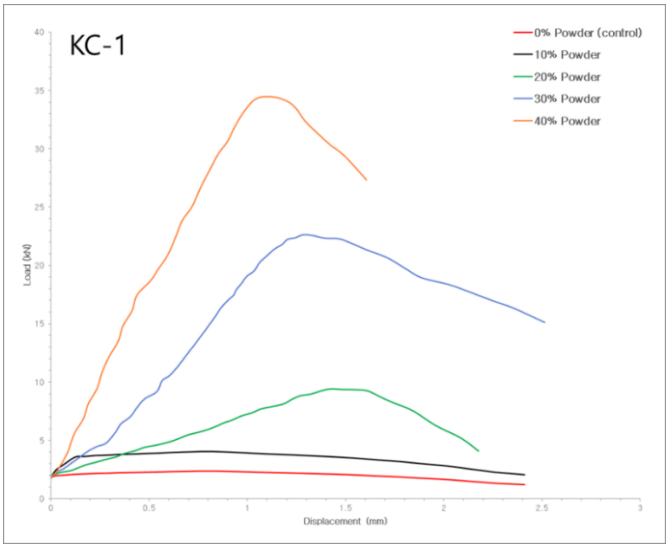


Fig. 6. Comparison of failure pattern of 5-day cured specimens for KC-1 powder

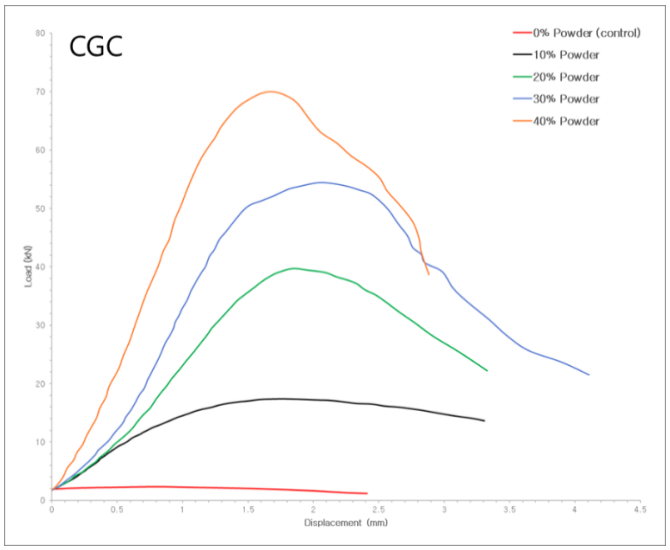


Fig. 7. Comparison of failure pattern of 5-day cured specimens for CGC powder

The performance of cementless geopolymers in this study surpasses that typically observed for OPC-stabilized soils under similar curing conditions, but normally OPC content is used at 8~20% [15]. The maximum UCS values obtained for both KC-1 and CGC (at 30–40% replacement) were significantly higher than those reported for OPC-treated specimens after comparable curing durations. Additionally, the geopolymer-treated soils demonstrated greater structural integrity and less brittle failure, suggesting improved ductility and resistance to crack propagation. These findings confirm the potential of cementless geopolymers as sustainable and high-performance alternatives for soil stabilization, capable of reducing CO_2 emissions and utilizing industrial by-products effectively.

4. CONCLUSIONS

In this study, the soil stabilization effect of two cementless geopolymer powders was discussed. Based on the results obtained, following conclusions can be drawn;

UCS increased consistently with geopolymer content for both KC-1 and CGC, with optimum performance observed at 30–40% replacement levels.

CGC outperformed KC-1 due to its higher calcium and anhydrite contents, which accelerated gel formation and early strength gain.

Failure modes transitioned from brittle to cohesive as geopolymer content increased, indicating enhanced bonding and reduced porosity.

The results demonstrate that cementless geopolymer binders can effectively replace OPC for stabilizing sandy-clayey soils, offering both mechanical and environmental advantages.

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