

# Mechanical properties of geopolymer stabilized laterite soils

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**ABSTRACT:** Lateritic soils are weathered soil, which is available around the tropical regions in the world. However, the application of this soil as a construction material is limited due to the complexity of its properties. In general, for the improvement of the mechanical properties of soil, cement is used as a common method. However, the use of cement results in the emission of carbon dioxide. Recently, geopolymer is a green binder, which is successfully applied in concrete and mortar. For the stabilization of laterite soil, few studies used geopolymer to treat this soil. The results from some previous studies indicated that geopolymer can be used as a new green binder to stabilize laterite soil for sub-base and sub-grade of pavement, in which the compressive strengths at both early and later ages satisfied the strength requirement by some countries. This implies that geopolymer can be applied as a potential binder to reinforce laterite soil for sustainable development.

**KEYWORDS:** Laterite soil, geopolymer, compressive strength, CBR, C-S-H.

## 1. INTRODUCTION

To stabilize soils (including soft soil), there are many methods including material replacement method, vertical drain method and reinforcement soil using chemical stabilization. The use of chemical binders such as cement is one of the most popular approaches to treating soils. It is reported that the production of 1 ton of cement discharges 1 ton of CO<sub>2</sub>, resulting in approximately 4.0 billion tons of CO<sub>2</sub> every year [1]. Besides, due to rapid urbanization as well as fast population growth, pollution and climate change have been increasing rapidly in both developed and developing countries. Thus, it is urgent to find an eco-friendly material to replace cement as a binder to stabilize soils.

Geopolymer, a novel binding agent, which is produced from various by-products associated with an alkaline solution, is known as a substitute material for cement. Geopolymer is synthesized by supplementary cementitious materials (SCMs) containing high reactive silica (SiO<sub>2</sub>) and alumina (Al<sub>2</sub>O<sub>3</sub>) such as fly ash (FA), Granulated Blast Furnace Slag (GBFS), metakaolin, silica fume with alkali activator [2]. Previous studies indicated the outstanding of

geopolymer, including high compressive strength, rapid setting and hardening, high fire resistance, acid and salt resistance and low shrinkage [3]. The common activator used for geopolymer synthesis includes sodium hydroxide (NaOH "NH") and sodium silicate (Na<sub>2</sub>SiO<sub>3</sub> "NS").

FA and GBFS are extensively used as precursors for developing geopolymers [4]. The reaction between FA and GBFS with an alkaline activator produces Calcium Alumino Hydrate (CAH), Calcium Silicate Hydrate (CSH), calcium silicate hydrate (CASH) and sodium aluminosilicate hydrate (NASH) gel [5]. Previous studies indicated that the addition of fine GBFS into FA class F-geopolymer improves both mechanical and microstructural properties [5]. In recent years, some studies have applied geopolymer to improve the properties of soft soil and demolition waste materials [6]. A previous study concluded that FA-based geopolymer can be utilized for stabilizing black cotton soil for the sub-base and sub-grade of highway pavement. Furthermore, another study used FA-GBFS-based geopolymer to stabilize marine clay, the result of this study indicated that this geopolymer significantly enhanced the compressive strength of marine clay. They also suggested that FA-GBFS base geopolymer should be used to substitute cement in soft ground improvement in the future.

Laterite soil is a soft soil with complex properties, this soil is mostly located in the tropical region of the world. In general, without treatment, this soil cannot be used as a construction material for subgrade or sub-base of pavement. Recently, few studies focused on the stabilization of this soil using FA-base geopolymer or FA-GBFS-based geopolymer with an alkaline activator solution of NaOH and/or Na<sub>2</sub>SiO<sub>3</sub> [7]. These primary studies on this soil using geopolymer indicated that geopolymer can be a potential approach for improving the mechanical properties of this soil. Thus, to have an overview, and understanding, as well as give a direction for future studies on the application of geopolymer in soil stabilization, particularly in laterite soil, this paper will review existing papers related to laterite soil stabilized by geopolymer.

## 2. PROPERTIES OF LATERITE SOIL AND OVERVIEW OF GEOPOLYMERIZATION

### 2.1. Properties of laterite soil

#### 2.1.1. Geotechnical properties of laterite soil

The distribution of laterite soils is shown in *Figure 2.1*, it can be seen that this soil is mainly located in tropical areas such as Africa, India, Australia, Southeast Asia, and South

America. Generally, laterite soils are found in tropical climate regions with a long dry season. The formation of laterite soils is affected by many factors such as parent rock, time, topography, vegetation and climate. The color of laterite soil is mainly red, yellow, or varies from liver brown to rusty red, which is governed by alumina (Al<sub>2</sub>O<sub>3</sub>) and hematite (Fe<sub>2</sub>O<sub>3</sub>).

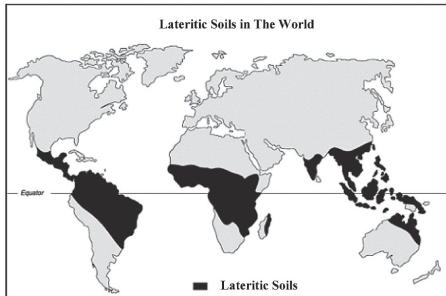


Figure 2.1: Map of lateritic soil over the world adopted from the literature [8]

In general, laterite soil is easy to compact and this soil has cementitious characteristics. Indeed, there are many physical types of laterite soil, including pisolitic, vesicular, cellular, concretionary, and vermicular. The properties of laterite soil are mostly dependent on the particle size, thus laterite soils contain both cohesionless and cohesive soil. Cohesive soil includes clay and silt, while non-cohesive soil is known as sand. The characteristic of laterite soil is shown in Figure 2.2. From the figure, it can be observed that there is a big variation in geotechnical characteristics regarding plasticity index, specific gravity, bulk density, and optimum moisture content regardless of sources. It is known that the depth of quarried soil in exploitation strongly affects the physicommechanical properties. It was reported that friction angle and suction are two main factors affecting the shear strength of compacted laterite soil. It was reported that the particle size of laterite soil ranged from 4.75 mm to 150 μm, which resulted in an increase in water absorption of laterite soil. Laterite soil has a particle size in a range of sand (from 4.75 mm to 150 μm), however, this soil takes more time to complete saturation in comparison with conventional sand. A previous study indicated that compressive strength, specific gravity and hardness of laterite soil were reduced with an increase in the depth of the soil profile, while clay content and water absorption were increased with the rising of the depth of the soil profile. Finally, it is indicated that the geotechnical features of laterite soil varied significantly with parent rock, climate and laterisation process.

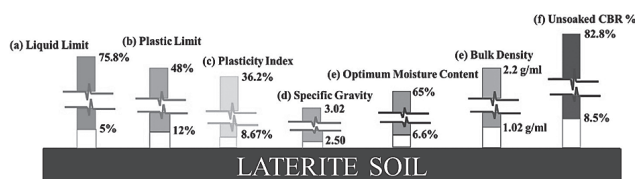


Figure 2.2: Geotechnical characteristics of laterite soil

2.1.2. Chemical properties

Laterite soils are known as the matrices of Fe<sub>2</sub>O<sub>3</sub>(FeO)-Al<sub>2</sub>O<sub>3</sub>-SiO<sub>2</sub>-H<sub>2</sub>O, caused by the transformation of kaolinite, where a high percentage of aluminum (Al<sup>3+</sup>) is substituted

by iron atoms (Fe<sup>2+</sup> or Fe<sup>3+</sup>) from goethite, ilmenite and hematite, etc. This replacement influences the microstructure of laterite, resulting in a less crystalline structure (i.e more amorphous structures). Due to this less crystalline structure, previous studies indicate that this soil possibly owns high reactivity when it exposes to chemical activators. Generally, the chemical and mineralogical compositions of laterite are two main factors that used to determine the reactivity of laterite soils. For instance, due to a higher content of iron minerals, raw iron-rich laterite possesses a greater reactivity of geopolymerization than clay-rich laterite, this is because raw iron-rich laterite has less crystallinity as well as higher dissolution in the alkaline solution. This implies that there is a possible reactive phase in iron-rich lateritic soil and this phase could react with the alkaline solution. The different behaviors of two types of laterite (clay-rich and iron-rich laterites) are associated with the lateralization degree, which relates to the particle size distribution and iron content. Table 2.1 shows the chemical composition of various lateritic soils distributed all over the world. From the table, it can be observed that lateritic soils mostly contain SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub> and Fe<sub>2</sub>O<sub>3</sub>, with the sum of these oxides ranging from 70 to 90%, which indicated that these laterites are suitable materials used in the synthesis of geopolymer.

Table 2.1. Chemical compositions of different lateritic soils in some regions taken from literature [9]

Location	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	K <sub>2</sub> O	Na <sub>2</sub> O	MgO	TiO <sub>2</sub>	MnO	LOI*
Cameroon	46.2	27.2	23.4	0.2	0.24	0.02	1.84	-	13.0
Indonesia	40.12	26.53	19.66	1.61	2.10	1.90	2.26	0.20	-
Burkina Faso	47.43	18.90	22.26	0.01	0.05		0.7	0.01	10.34
Europe	32.75	28.29	22.02	0.02	0.03	0.63	2.65	0.43	11.67
India	40.98	34.20	10.86	0.04	0.08	0.60	0.92	-	11.37
Thailand	77.81	4.42	10.93	2.33	1.36	1.13	1.33	0.55	

2.2. Overview of geopolymerization

The mechanism of polymerization is different from the mechanism of cement hydration between Portland cement. The reaction that happened in the geopolymer process is essentially based on the inherent properties of the precursors and conditions of synthesis. In an alkaline environment, the geopolymerization mechanism consists of three steps as follows: (i) the first step is dissolution, (ii) the second step is condensation and (iii) the final step is polymerization. In the first step, Si-O-Si and Si-O-Al bonds in the aluminosilicate material (such as fly ash, slag, metakaolin, and volcanic ash) are broken into distinct silica and alumina ions with alkali ions OH<sup>-</sup> from the alkaline solution. It was reported that the progress of the first steps is affected by many factors such as the reactivity content of the aluminosilicate material used, curing temperature, the pH value of the alkaline solution and the grain size of the precursor. For the second step, the individual silica and alumina ions from the first one tend to transform into monomers of silica and alumina, creating polymer and dimers. In the final step, the monomers of silica and alumina polymerize and establish a 3D structure including a long chain of Si-O-Al-O- bonds. Indeed, the three steps are explained as above, but it is quite difficult to separate each step of the geopolymerization reaction due to those steps can be overlapped.

**3. MECHANICAL PROPERTIES OF LATERITE SOIL STABILIZED BY GEOPOLYMER**

**3.1. compaction properties of laterite soil stabilized by geopolymer**

The laterite soil (LS) is stabilized by supplementary cementitious materials (SCMs) based geopolymer with an alkaline activator. The SCMs include fly ash (FA), ground granulated blast furnace slag (GBFS), rice hush ash, metakaolin, etc., while the alkaline activation mostly consists of NaOH (NH) and Na<sub>2</sub>SiO<sub>3</sub> (NS). A previous study conducted by Phummiphan et al., 2016 [9] on LS-FA geopolymer (a fixed LS:FA of 70:30) with different NS:NH ratios (100:0, 90:10, 80:20, and 50:50). The relationships between dry unit weight ( $\gamma_d$ ) and activator content (solution of NH and NS) with different NS:NH ratios of LS-FA geopolymer is shown in Figure 3.1. It can be observed that the compacted curved are varied with different NS:NH ratios. The dry unit weight increases with activator content until achieving maximum dry unit weight  $\gamma_{d,max}$ . After that, the dry unit weight reduces with an increase in activator content. This feature of LS-FA geopolymer is similar to the compaction behaviour of conventional soils. From Figure 3.1, it can be observed that the maximum dry unit weight ranges from 19 kN/m<sup>3</sup> to around 20.3 kN/m<sup>3</sup>. The LS-FA geopolymer mixtures with NS:NH of 50:50 and NS:NH of 90:10 obtained almost the same value of  $\gamma_{d,max}$  in which activator content varies from approximately 15 to 20%.

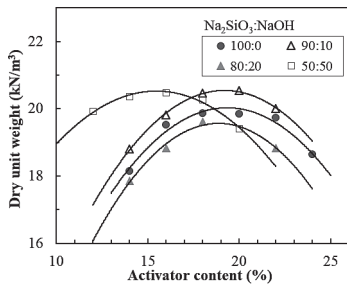


Figure 3.1: Relationship between dry unit weight and activator content of LS-FA geopolymer stabilized laterite soils at different ratios of NS:NH [7]

Another study was conducted to investigate the compaction characteristics of the mixture of LS-FA-GBFS geopolymer with different LS:FA:GBFS and NS:NH ratios [6]. The compaction curves of different LS-FA-GBFS geopolymers are shown in Figure 3.2. It was reported that  $\gamma_{d,max}$  of LS-FA-GBFS geopolymer was higher than that of untreated laterite soil, this is because GBFS particle is finer than that of laterite soil [6]. The values of  $\gamma_{d,max}$  range from 20 to 22 kN/m<sup>3</sup>, these values are greater than those observed in Figure 3.1, due to the addition of GBFS. Besides, from Figure 3.2, it can be observed that compaction curves are strongly affected by NS:NH ratio and GBFS content. In addition, the  $\gamma_{d,max}$  increases with an increase in GBFS content regardless of NS:NH ratios, due to finer particles.  $\gamma_{d,max}$  increases with a decrease in the NS content for mixtures with 20% and 30% GBFS, while the 10% GBFS sample produced an opposite tendency. Based on the results shown in Figure 3.2, the mixtures with NS:NH of 40:60 and NS:NH of 50:50 give the highest  $\gamma_{d,max}$ .

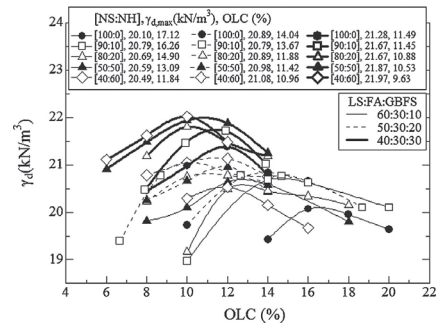


Figure 3.2: Relationship between dry unit weight and activator content of FA-GBFS geopolymer treated laterite soils with different ratios [6]

**3.2. Unconfined compressive strength of laterite soil stabilized by geopolymer**

LS was partially replaced by GBFS up to 25% in an LS-GBFS geopolymer, and then the sample of this mixture was cured at room temperature and high temperatures (100 and 250°C). The results of their study showed that the unconfined compressive strength (UCS) was between 0.5 - 4.9 MPa and 0.68 - 7.84 MPa for a curing period from 14 to 40 days. In a similar way, Phummiphan et al. [9] conducted a study to stabilize laterite soil using FA with an activator solution of NS and NH. The NH in the activator solution has a concentration of 5 mol/L, the NS:NH ratios were 100:0, 90:10, 80:20 and 50:50 and all LS-FA geopolymer mixture was cured under room temperature for a period from 7 to 90 days. It is known that the UCS of geopolymer is mostly produced by the reaction between alumina and silica in the alkaline environment [6]. Figure 3.3 shows the UCS development of different mixtures of LS-FA geopolymer. It is clear that the UCS for all mixtures increases with the curing period. At an early age, all mixtures achieved the UCS greater than the requirement specified by Thailand authorities (UCS > 1724 and 2413 kPa for light and heavy traffic, respectively). The improvement of the UCS at the early age of a mixture of with NH and without NH was attributed to the formation of C-S-H + N-A-S-H and C-S-H, respectively. For later age (after 60 days), the mixture with NS:NS of 50:50 achieved the highest UCS due to the higher formation of both C-S-H and N-A-S-H [7]. Based on the compressive strength result, it is noticed that the mixture of LS-FA geopolymer with NH:NS of 50:50 is the most suitable mixture for stabilizing laterite soil in terms of technical and economical features.

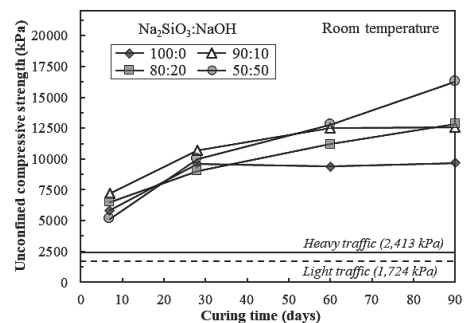


Figure 3.3: The compressive strength development of LS-FA geopolymer with different NS:NH ratios [7]

Another study by Phummiphan et al. [6] on the laterite soil stabilized by FA-GBFS geopolymer with the activator solution NS and NH. Four ratios of NS:NH (100:0, 90:10, 80:20 and 50:50) were used and three rates of LS:FA:GBFS (60:30:10, 50:30:20 and 40:30:30) were employed. The results shown in Figure 3.4 indicate that all mixtures achieved a compressive strength larger than the requirement specified by Thailand authorities (UCS > 1724 and 2413 kPa for light and heavy traffic, respectively) and by the Australia road authority (>3.5 MPa). In terms of technical and economical features, it is noticed that the mixture with NS:NH of 50:50 is the optimal mixture for treating laterite soil.

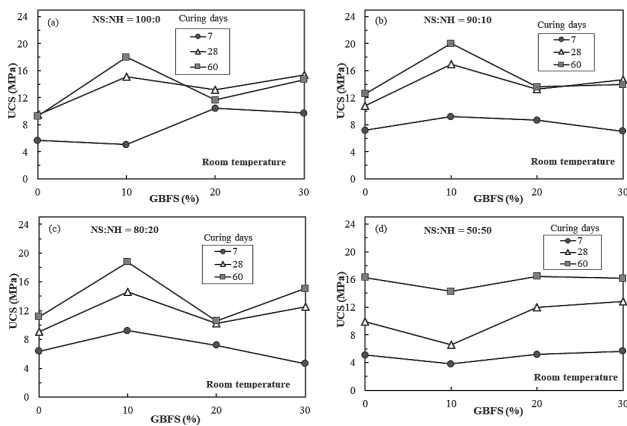


Figure 3.4: The USC development of LS-FA-GBFS for different ratios of NS:NH ratios (a) 100:0, (b) 90:10, (c) 80:20 and (d) 50:50 [6]

A previous study on the stabilization of laterite soil by geopolymer with hydrated lime, where the stabilized specimens were cured under air conditions, water curing, and a wet/drying cycle. The results showed that the compressive strength was in ranges of 4.05 to 5.55 MPa, 3.13 to 4.62 MPa and 3.57 to 4.11 MPa for air curing, water curing and wet/drying cycle, respectively. The improvement in strength development was attributed to the formation of CSH and NASH gel. In summary, it can be concluded that the stabilization of laterite soil by FA and/or GBFS in the synthesis of geopolymer permitted the formation of geopolymerization products in the alkaline environment favorable for an improvement of LS stabilized by geopolymer.

#### 4. CONCLUSION

Laterite soil can be treated by geopolymer in order to improve its properties regarding both mechanical properties and durability. Up to date there are limited studies on laterite stabilization using geopolymer with a solution of NaOH and Na<sub>2</sub>SiO<sub>3</sub>. The results from some previous studies indicated that geopolymer can be used as a new green binder to stabilize laterite soil for sub-base and sub-grade of pavement, in which the compressive strengths at both early and later ages satisfied the requirement by Thai Land and Australian authorities. However, the previous studies mostly focused on the mechanical properties, more further studies should investigate the durability of this

type of material in acid conditions. In addition, previous studies only examined some mix proportions, thus more mix proportions should be investigated to understand the universal behavior as well as to obtain an optimal mixture for this material. Finally, more different SCMs materials should be examined.

**Funding:** This study was supported by the Ministry of Transport (MOT), under grant number DT223007, with principal investigator: Dr. Dao Phuc Lam

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Receipt date: 04/02/2023

Acceptance date for posting: 25/3/2023

Reviewer: Dr. Bui Van Duc

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