# Wetting-Drying Durability of Lateritic Soil Stabilized with One-Part High-Calcium Fly Ash Geopolymer

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## Abstract

This study investigates the durability under wetting and drying conditions of marginal lateritic soil (MLS) stabilized with a one-part high-calcium fly ash geopolymer (OPFAG). The variables include an MLS: fly ash ratio of 70:30, solid sodium hydroxide content ranging from 0 to 40%, and the number of wet-dry cycles. Durability is evaluated by measuring the unconfined compressive strength (UCS) of MLS samples stabilized with OPFAG and MLS samples stabilized with ordinary Portland cement (OPC). The results show that OPFAG improved the engineering properties of MLS. The highest UCS values are achieved at 20% solid sodium hydroxide, achieving a UCS of 1889 kPa for the geopolymer-stabilized MLS and at 5% OPC for OPC-stabilized MLS (1320 kPa). The UCS of both stabilized MLS samples increases with the number of wet-dry cycles up to 6 cycles, after which a decline is observed.

**Keywords:** durability, solid sodium hydroxide, marginal lateritic soil, fly ash

## 1. Introduction

Transport infrastructure (e.g., railways and roads) must be developed to stimulate and support economic growth [1]. Road infrastructure is one transport system that affects the population, urban form, economic status, and environment. Lateritic soil (LS) is popularly used in the subbase layer. However, the LS borrow sites that meet the Department of Highways' standards are often located far from the construction area, leading to increased transportation and overall construction costs. In recent years, numerous researchers have explored methods to enhance the engineering and physical properties of problematic soils, such as expansive soil and marginal lateritic soil (MLS), through both mechanical and chemical techniques [2-8]. Ordinary Portland cement (OPC) is one of the chemical methods used to stabilize problematic soils, namely, soil cement.

Recent research by Pham et al. [3] studied the improvement of LS using cement at different water-to-cement ratios. The findings showed that the strength of LS used for the subbase layer increased from 2441 kPa and 3618 kPa for water-to-cement ratios of 0.5 and 1.25, respectively. However, the OPC manufacturing process results in the depletion of natural resources, environmental degradation, and air pollution. This contributes to global warming through the release of carbon dioxide ($CO_2$) into the atmosphere [9-12]. To mitigate these impacts, alternative materials were being sought to replace some of the OPC, thereby reducing environmental and natural resource damage caused by OPC production. One such alternative is geopolymer material, an innovative and environmentally friendly substitute for traditional OPC [13-20]. Materials rich in aluminosilicates,

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such as fly ash (FA) [13], can be used to produce geopolymerization products. The chemical reaction occurs when the mineral components are amorphous, primarily consisting of silica ($SiO_2$) and alumina ($Al_2O_3$) [13-14]. A highly alkaline solution breaks these down and requires heated temperatures of 40 to 80 °C to accelerate the reaction, which leads to high energy consumption [15].

In recent years, alkaline materials have received significant attention. Research by Ghadir and Ranjbar [21] shows that when comparing geopolymer to Portland cement Type I under the same curing conditions, geopolymer exhibits higher strength. Several studies have used sodium hydroxide (NaOH) or sodium silicate ($Na_2SiO_3$) solutions mixed with $SiO_2$ and $Al_2O_3$ mineral components to synthesize geopolymer. However, the use of geopolymer has been limited due to challenges related to shipping, storage, and preparing large quantities of alkaline solutions. To simplify the geopolymer preparation process, Luukkonen et al. [22] defined a method using a mixture of raw materials with a dry alkaline activator called a “one-part geopolymer”. This method offers lower costs and improved workability for engineering applications. However, the durability of MLS stabilized with one-part high-calcium fly ash geopolymer (OPFAG) has not yet been investigated.

This research aims to examine the durability of OPFAG-stabilized MLS as a pavement subbase material and compare it with OPC-stabilized MLS. The studied ratio of MLS to FA was 70:30. The solid NaOH content varied from 0, 5, 10, 15, 20, 25, 30, 35, and 40% by weight of the optimum water content (OWC). The unconfined compressive strength (UCS) of OPFAG-stabilized MLS and OPC-stabilized MLS samples was tested at various wetting and drying cycles. The findings of this research can be applied to replace OPC with OPFAG as an alternative binder material.

## 2. Materials and Methods

Before exploring the durability of OPFAG-stabilized MLS and OPC-stabilized MLS as pavement subbase materials, it is essential to understand the chemical and physical properties of the materials used, such as MLS, FA, OPC, and NaOH. Additionally, the sample preparation and testing of OPFAG-stabilized MLS and OPC-stabilized MLS are presented in the subsequent sections.

### *2.1. Materials*

MLS characteristics are shown in Fig. 1. The soil had a specific gravity ($G_s$) of 2.71, with a liquid limit (LL) of 34%, a plastic limit (PL) of 19%, and a plasticity index (PI) of 15% according to ASTM D4318-17 [23]. According to the Unified Soil Classification System (USCS), MLS was categorized as clayey sand (SC). Thailand’s Department of Highways suggests a maximum PI of 11% for subbase materials. MLS was not satisfied because the PI was greater than the requirement.

Fig. 1 The characteristics of MLS

FA was sourced from the Mae Moh power plant in Thailand, as shown in Fig. 2. FA had a $G_s$ of 2.37 [24]. The chemical composition of the FA was determined using X-ray fluorescence spectrometry (XRF), as shown in Table 1. The primary components consist of $SiO_2$ + $Al_2O_3$ + ferric oxide ($Fe_2O_3$) at 63.3%, and calcium oxide (CaO) at 31.4%. According to ASTM C618-19 standards [25], this FA is classified as Class C. Fig. 3 indicates the Scanning Electron Microscopy (SEM) of FA with smooth and round surfaces.

Fig. 2 The characteristics of FA

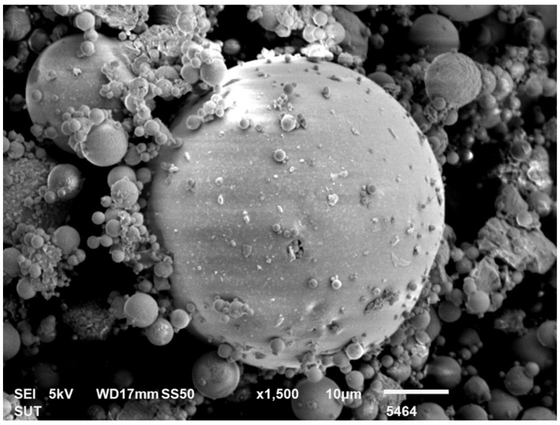

Fig. 3 The SEM of FA

Table 1 Chemical composition of FA and OPC

| Chemical compositions | FA (%) | OPC (%) |
|---|---|---|
| $SiO_2$ | 45.4 | 18.52 |
| $Al_2O_3$ | 10.5 | 3.56 |
| $Fe_2O_3$ | 7.4 | 4.51 |
| CaO | 31.4 | 66.53 |
| MgO | N.D. | 1.35 |
| $SO_3$ | 2.2 | 1.88 |
| $Na_2O$ | N.D. | 0.42 |
| $K_2O$ | 2.2 | 0.11 |
| LOI | 1.0 | 3.12 |

The characteristics of OPC were angular, with a rough surface and an irregular shape, as indicated in Fig. 4. The average particle size ($D_{50}$) of Type I OPC was 0.01575 mm, and its $G_s$ was 3.15, which is by ASTM C188-95 standards [24] in that specify the $G_s$ of general Portland cement is between 3.00 and 3.20. The chemical properties of OPC are presented in Table 1, indicating that the CaO content was 66.53%, $SiO_2$ was 18.52%, $Al_2O_3$ was 3.56%, and $Fe_2O_3$ was 4.51%. Solid NaOH was used in this study, as indicated in Fig. 5. The NaOH concentrations varied from 0 to 40% by weight of OWC, which ranged from 0 to 10 molar.

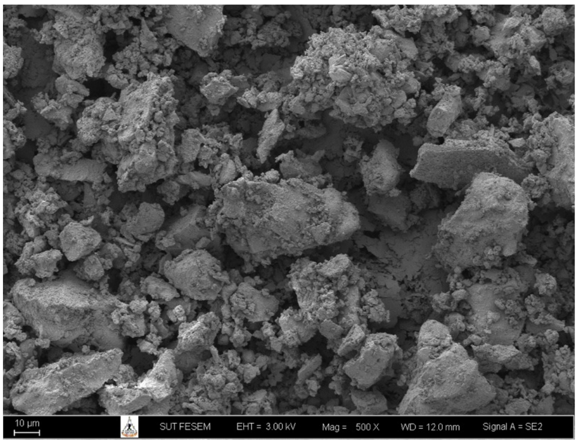

Fig. 4 The SEM of OPC

Fig. 5 The characteristics of NaOH

### 2.2. *Sample preparation*

The OPFAG stabilized MLS samples were created by mixing MLS, FA, NaOH, and water. The ratio of MLS to FA was 70:30. The solid NaOH content varied from 0, 5, 10, 15, 20, 25, 30, 35, and 40% by weight of the OWC. For OPC stabilized MLS, the OPC contents of 1, 3, and 5% by weight of MLS were used in this study. The maximum dry unit weight (MDW) and OWC for samples with MLS: FA ratios of 100:0 and 70:30 were determined, as shown in Fig. 6, using a modified Proctor compaction test following ASTM D1557-12 [26]. The test results indicated that the MDW and OWC at MLS:FA ratios 70:30 were 19.63 kN/m$^3$ and 9.8%, respectively. While the MDW and OWC at MLS:FA ratios of 100:0 were 20.43 kN/m$^3$ and 8.2%, respectively.

Fig. 6 Compaction test

For OPFAG stabilized MLS samples, FA and solid NaOH were mixed for 2 minutes, followed by a 5-minute mixing with MLS until homogeneous. Water was then added and blended for another 5 minutes. For OPC-stabilized MLS samples, MLS and OPC were mixed for 5 minutes, followed by a 5-minute mixing with water until homogeneous. The OPFAG-stabilized MLS and OPC-stabilized MLS samples were formed by static compression into cylindrical molds measuring 50 mm in diameter and 100 mm in height. The samples were wrapped in clear vinyl to prevent moisture loss during curing. The UCS as per ASTM D2166-06 [27] of soaked samples was evaluated after the curing ages of 7 days. For the soaking conditions, the OPFAG-stabilized MLS and OPC-stabilized MLS samples were submerged in water for 2 hours.

For the durability test following ASTM D559 [28], OPFAG-stabilized MLS and OPC-stabilized MLS samples at curing ages of 28 days were exposed to alternating wet and dry conditions. They were soaked in water for 5 hours, then rested for 0.5 hours in a controlled room at 25-29 °C. The samples were then dried in an oven at 110±5 °C for 42 hours, followed by a 0.5-hour rest in the controlled room. Each wet-dry cycle lasted a total of 2 days. The five specimens for each condition were prepared, and the average UCS was measured after 0, 1, 3, 6, 9, and 12 cycles.

## 3. Results and Discussions

Table 2 indicates the UCS values of OPFAG-stabilized MLS at a curing age of 7 days. The results showed that the UCS values of OPFAG-stabilized MLS increased with increasing solid NaOH content. For example, UCS values of OPFAG-stabilized MLS were 455, 1239, 1889, 1413, and 1255 kPa for solid NaOH contents of 0, 10, 20, 30, and 40%, respectively. This is because alkaline activated from NaOH could leach Silicon (Si) and Aluminum (Al) from FA to react with Calcium (Ca), forming calcium aluminosilicate hydrate (C-A-S-H) gels [16]. In addition, the highest UCS values of OPFAG-stabilized MLS were found at a solid NaOH content of 20%. In contrast, the high amount of NaOH content (more than 20%) resulted in a rapid setting time, which caused a reduction of UCS in a sample [15].

The UCS values of OPC-stabilized MLS at a curing age of 7 days are indicated in Table 2. The results indicated that UCS values of OPC-stabilized MLS increased with an increase in OPC. The increase in UCS is because of the hydration reaction from OPC. The highest UCS value of OPFAG-stabilized MLS samples with NaOH content of 20% was higher than that of OPFAG-stabilized MLS with 5% OPC. The UCS values of OPFAG-stabilized MLS for all solid NaOH contents and OPC-stabilized MLS for OPC contents of 3 and 5% were greater than the UCS standard for sub base materials (689 kPa).

Table 2 UCS values of OPFAG stabilized MLS and OPC stabilized MLS

| Sample | 7-day UCS (kPa) |
|---|---|
| 70 MLS:30 FA + 0% NaOH | 455 |
| 70 MLS:30 FA + 5% NaOH | 987 |
| 70 MLS:30 FA + 10% NaOH | 1239 |
| 70 MLS:30 FA + 15% NaOH | 1481 |
| 70 MLS:30 FA + 20% NaOH | 1889 |
| 70 MLS:30 FA + 25% NaOH | 1651 |
| 70 MLS:30 FA + 30% NaOH | 1413 |
| 70 MLS:30 FA + 35% NaOH | 1309 |
| 70 MLS:30 FA + 40% NaOH | 1255 |
| MLS + 1% OPC | 590 |
| MLS + 3% OPC | 979 |
| MLS + 5% OPC | 1320 |

The durability of OPFAG-stabilized MLS with 70 MLS:30 FA and 20% NaOH content and OPC-stabilized MLS with OPC content of 3% is depicted in Fig. 7. Test results indicated that the UCS of OPFAG-stabilized MLS with 70 MLS:30 FA and 20% NaOH content was higher than that of OPC-stabilized MLS with OPC content of 3%. For example, the UCS of OPFAG-stabilized MLS was 1941, 2143, 2316, 2356, 2096, and 1799 for wet-dry cycles values of 0, 1, 3, 6, 9, and 12 cycles, respectively, while the UCS of OPC-stabilized MLS was 1309, 1709, 2130, 1804, 1573, and 1418 for the same wet-dry cycles values. The UCS of the OPFAG-stabilized MLS sample increased as the wet-dry cycles increased. This is because the reaction between FA and NaOH formed C-A-S-H and sodium aluminosilicate hydrate (N-A-S-H) when stimulated at 70 °C during the dry cycle [18-19]. Beyond the wet-dry cycles of 6 cycles, the UCS of OPFAG-stabilized MLS and OPC-stabilized MLS samples decreased because the sample structure may experience shrinking, leading to the formation of microscopic cracks and voids, thus allowing more water penetration [29-30].

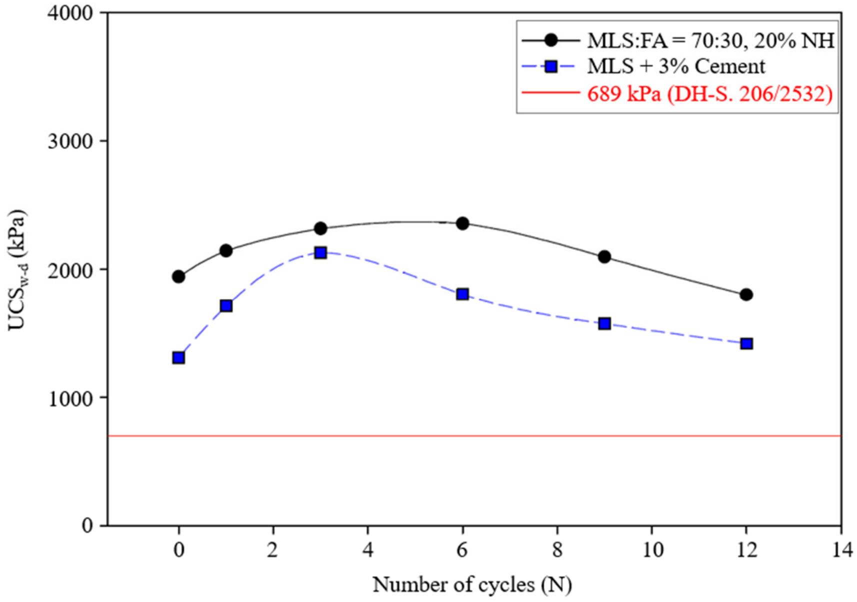

Fig. 7 Durability of OPFAG stabilized MLS and OPC stabilized MLS samples

## 4. Conclusions

The UCS and durability of OPFAG-stabilized MLS and OPC-stabilized MLS samples for pavement subbase applications were investigated in this study. The following conclusions were drawn:

(1) OPFAG can improve the durability of MLS because the solid NaOH leaches Si and Al in FA, which reacts with Ca to form C-A-S-H gels.

(2) The highest UCS values were observed at 20% NaOH content for OPFAG-stabilized MLS (1889 kPa) and 5% OPC content for OPC-stabilized MLS (1320 kPa).

(3) The UCS values of OPFAG-stabilized MLS for all solid NaOH contents, and OPC-stabilized MLS for OPC contents of 3 and 5% exceeded 689 kPa, which meets the requirements for subbase materials.

(4) The UCS of OPFAG-stabilized MLS with 70 MLS:30 FA ratios and 20% NaOH content was higher than that of OPC-stabilized MLS with OPC content of 3%. The UCS of both samples increased as the number of wet-dry cycles increased. The UCS decreased after 6 wet-dry cycles. Microstructural analysis using SEM and energy-dispersive X-ray spectroscopy (EDS) of OPFAG-stabilized MLS is recommended for further study.

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## Conflicts of Interest

The authors declare no conflict of interest.

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