



## Research Paper

# High calcium fly ash geopolymer stabilized lateritic soil and granulated blast furnace slag blends as a pavement base material



Itthikorn Phummiphan<sup>a</sup>, Suksun Horpibulsuk<sup>b,\*</sup>, Runglawan Rachan<sup>c</sup>, Arul Arulrajah<sup>d</sup>, Shui-Long Shen<sup>e</sup>, Prinya Chindaprasirt<sup>f</sup>

<sup>a</sup> Graduate Program in Construction and Infrastructure Management, Suranaree University of Technology, 111 University Avenue, Muang District, Nakhon Ratchasima 30000, Thailand

<sup>b</sup> School of Civil Engineering, Center of Excellence in Innovation for Sustainable Infrastructure Development, Suranaree University of Technology, Thailand

<sup>c</sup> Department of Civil Engineering, Mahanakorn University of Technology, Nong Chok District, Bangkok 10530, Thailand

<sup>d</sup> Department of Civil and Construction Engineering, Swinburne University of Technology, Melbourne, Australia

<sup>e</sup> Department of Civil Engineering, Shanghai Jiao Tong University and State Key Laboratory of Ocean Engineering, 800 Dong Chuan Road, Minhang District, Shanghai 200240, China

<sup>f</sup> Sustainable Infrastructure Research and Development Center, Department of Civil Engineering, Khon Kaen University, Khon Kaen, Thailand

## HIGHLIGHTS

- Evaluation of Fly Ash (FA) based geopolymer stabilized lateritic soil/GBFS blend.
- Role of L, NaOH/Na<sub>2</sub>SiO<sub>3</sub>, GBFS content, and curing time were investigated.
- Microstructural development was examined via XRD and SEM analyses.
- UCS of FA geopolymer stabilized blends was compared with road authorities requirements.

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## ABSTRACT

Granulated Blast Furnace Slag (GBFS) was used as a replacement material in marginal lateritic soil (LS) while class C Fly Ash (FA) was used as a precursor for the geopolymerization process to develop a low-carbon pavement base material at ambient temperature. Unconfined Compression Strength (UCS) tests were performed to investigate the strength development of geopolymer stabilized LS/GBFS blends. Scanning Electron Microscopy and X-ray Diffraction analysis were undertaken to examine the role of the various influencing factors on UCS development. The influencing factors studied included GBFS content, Na<sub>2</sub>SiO<sub>3</sub>:NaOH ratio (NS:NH) and curing time. The 7-day soaked UCS of FA geopolymer stabilized LS/GBFS blends at various NS:NH ratios tested was found to satisfy the specifications of the Thailand national road authorities. The GBFS replacement was found to be insignificant for the improvement of the UCS of FA geopolymer stabilized LS/GBFS blends at low NS:NH ratio of 50:50. Microstructural analysis indicated the coexistence of Calcium Silicate Hydrate (CSH) and Sodium Alumino Silicate Hydrate products in FA geopolymer stabilized LS/GBFS blends. This research enables GBFS, which is traditionally considered as a waste material, to be used as a replacement and partially reactive material in FA geopolymer pavement applications.

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\* Corresponding author at: School of Civil Engineering, Suranaree University of Technology, 111 University Avenue, Muang District, Nakhon Ratchasima 30000, Thailand.

E-mail addresses: [suksun@g.sut.ac.th](mailto:suksun@g.sut.ac.th) (S. Horpibulsuk), [runglawa@mut.ac.th](mailto:runglawa@mut.ac.th) (R. Rachan), [arulrajah@swin.edu.au](mailto:arulrajah@swin.edu.au) (A. Arulrajah), [slshen@sjtu.edu.cn](mailto:slshen@sjtu.edu.cn) (S.-L. Shen), [prinya@kku.ac.th](mailto:prinya@kku.ac.th) (P. Chindaprasirt).

## 1. Introduction

Ordinary Portland Cement (OPC) is the most widely used cementing agent in civil engineering infrastructure projects. The production of OPC, however, emits a large amount of greenhouse gases, notably CO<sub>2</sub> into the atmosphere. Cement production worldwide discharges up to 4.0 billion tons of CO<sub>2</sub> annually [1–3]. The production of just 1 ton of OPC releases about 1 ton of CO<sub>2</sub> [4].

Pollution and global warming coupled with growing public environmental awareness has been increasing rapidly in many

developed and developing countries. Environmentally friendly alternative construction materials are increasingly being sought [2]. Geopolymer, a novel green cementing agent manufactured from various industrial waste by-products, is considered as an alternative materials to OPC. Geopolymer is an inorganic aluminosilicate material synthesized by mixing source materials rich in silica ( $\text{SiO}_2$ ) and alumina ( $\text{Al}_2\text{O}_3$ ) such as Fly Ash (FA), metakaolin, Granulated Blast Furnace Slag (GBFS) and Silica Fume (SF) with alkali activators [5].

The engineering properties of geopolymers that are sought for civil engineering applications include: high compressive strength [6–8], rapid controllable setting and hardening [9], fire resistance [10–12], acid and salt solution resistance [13], lack of deleterious alkali–aggregate reactions and low shrinkage [14].

The commonly used activators for geopolymerization include alkaline metal and alkaline earth metal compounds [15]. Generally, the most effective activator providing the best performance for high strength and other advantageous properties is a mixture combining sodium hydroxide (NaOH) and sodium silicate ( $\text{Na}_2\text{SiO}_3$ ) [16]. The use of large quantities of sodium silicate is not recommended for the environment, as it imparts a high carbon footprint alkali. The emission factors are 1.514 kg  $\text{CO}_2\text{-e/ton}$  [17] and 0.86 kg  $\text{CO}_2\text{-e/ton}$  [18] for sodium silicate and cement production, respectively.

Both class F and class C Fly Ash (FA) as precursors have been extensively used for the development of geopolymers [19–21]. The class C FA contains high calcium oxide (CaO) and is designated as a self-cementing FA. The Class C Fly ash has been used for making concrete and soil stabilization without cement [22–24]. The reaction between class C FA and the liquid alkaline activator therefore forms Calcium Silicate Hydrate (CSH) and Calcium Alumino Hydrate (CAH), which co-exists with geopolymerization products. Mechanical properties and microstructure of class F FA geopolymer at ambient temperature were found to be improved by including very fine GBFS as an additive [25,26]. This is as the FA–GBFS geopolymer system will form aluminium-modified calcium silicate hydrate (CASH) gel which coexists with sodium aluminosilicate hydrate (NASH) gel [27,28]. The coexistence of CASH and NASH was also evident for other FA and calcium-rich additive based geopolymers [29,30].

Several researchers have used geopolymers in concrete applications. However, only in recent years research has been undertaken on geopolymer improved demolition waste materials and soft soils [31–38]. Phummiphan et al. [35] have first introduced the usage of high calcium FA-based geopolymer to stabilized marginal lateritic soil to develop a green pavement base in Thailand. The early strength of the geopolymer stabilized marginal lateritic soil was found to be enhanced by using a waste Calcium Carbide Residue (CCR) as an additive [36]. The CCR was small-sized and was proven to be a binder, which reacted with silica and alumina from soil and FA, to form Calcium Silicate Hydrate (CSH) [39]. Phetchuay et al. [40] first introduced a FA geopolymer to stabilize soft marine clay in Australia and reported that the CCR not only improved the strength of geopolymer stabilized clay but also provided low carbon-emission when compared to cement stabilization.

Similarly, fine sized GBFS as an additive has been demonstrated to enhance the engineering properties of class F FA geopolymer stabilized recycled demolition aggregate [41,33] and FA geopolymer stabilized spent coffee grounds [42] for pavement base/subbase and subgrade applications, respectively. The very fine GBFS particles can react rapidly with a liquid alkaline activator and improve the early strength of FA geopolymer stabilized materials. However, crushing of GBFS to very fine particles is a costly and energy-intensive process. A cost-effective and environmental-friendly means is to reuse medium-sized GBFS as a replacement as well as a partially reactive material for geopolymer stabilization.

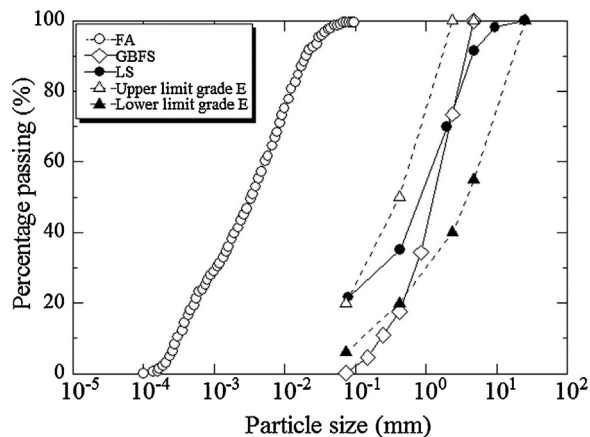


Fig. 1. Particle size distribution of LS, FA and GBFS.

The study on the usage of medium-sized GBFS as a partial replacement of lateritic soil in class C FA geopolymer stabilization for sustainable pavement application is to date limited and is the focus of this research. The usage of by-products (class C FA and GBFS) and liquid alkaline activator without Portland cement to stabilize marginal lateritic soil is novel and significant in terms of engineering, economic and environmental perspectives. Unconfined Compression Strength (UCS) was used to evaluate the strength development of the FA geopolymers stabilized soil/GBFS blends. Scanning Electron Microscopy (SEM) and X-ray Diffraction (XRD) analysis were undertaken to investigate the effect of various influencing factors on the strength development. The factors studied included GBFS content,  $\text{Na}_2\text{SiO}_3\text{:NaOH}$  (NS:NH) ratio and curing time. The outcome of this study will enable GBFS, an industrial by-product, to be used as a replacement and partial reactive material in FA geopolymer pavement applications.

## 2. Materials and properties

### 2.1. Soil sample

Lateritic Soil (LS) samples were obtained from a quarry in the city of Rayong, Thailand. The Liquid Limit (LL), Plastic Limit (PL), and Plasticity Index (PI) in accordance with ASTM D4318 [43] were 27.72%, 21.65%, and 6.07%, respectively while the specific gravity ( $G_s$ ) was 2.58. The natural water content of LS was 10%. The grain size distribution was determined by sieve analysis [44] as shown in Fig. 1 and was compared to that specified for base/subbase materials by AASHTO and Department of Highways, Thailand [45,46]. The gradation of LS was within the specified limits. The LS was a silty clayey sand (SC-SM) and A-2-4(0) according to the Unified Soil Classification System (USCS) [47] and the AASHTO [48], respectively. The optimum moisture content (OMC) and maximum dry unit weight ( $\gamma_{d,\text{max}}$ ) of LS under modified Proctor energy [49] were 8.0% and 20.85  $\text{kn/m}^3$ , respectively. California Bearing Ratio (CBR) value at 95% of  $\gamma_{d,\text{max}}$  was 14.7%. Los Angeles (LA) abrasion in accordance with ASTM C131 [50] and ASTM C535 [51] was 52.9%.

When comparing the CBR and LA abrasion results to the specification of Department of Highways for subbase and engineering fill materials (DOH 1989) (Table 1), LS did not meet the specified subbase requirement but met the requirements of an engineering fill material. In remote construction sites, located far away from high quality quarry materials, chemical stabilized LS can potentially be used as pavement construction materials. The chemical stabilization of LS will lead to savings in haulage costs and will furthermore minimize negative environmental impacts. Chemical composition of LS obtained from X-ray Fluorescence (XRF) analy-

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