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The Effect of HCWA-PFA Hybrid Geopolymer Modification on the Properties of Soil

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Abstract. This study investigated the performance of the properties of foamed concrete when replacing volumes of cement of 10%, 15% and 20% by weight. A control unit of foamed concrete mixture made with Ordinary Portland Cement (OPC) as well as samples containing 10%, 15% and 20% silica fume were prepared. Three mechanical property parameters of foamed concrete containing different percentages of silica fume were studied: compressive strength, flexural strength and splitting tensile strength. Silica fume is commonly used to increase the mechanical properties of concrete materials as well as for economic concerns. The foamed concrete in this study was cured at a relative humidity of 70% and a temperature of ±28°C. Improvements in the mechanical properties of foamed concrete were due to a significant densification in the microstructure of the cement paste matrix in the presence of silica fume hybrid supplementary binder as observed from micrographs obtained in the study. The overall results showed that silica fume has great potential to be utilized in foamed concrete as there was a noticeable enhancement in thermal and mechanical properties with the addition of silica fume.

1 Introduction

The study of soils is essential in the field of civil engineering. When either soft or highly compressible soils are present at a construction site, it will likely lead to some geotechnical problems such as landslides, slope failure and soil deformation, or failure of engineering structures. The reason for such failures is related to a lack of shear soil strength needed to support substantial loading either during construction or throughout the service life of a civil engineering structure. Engineering structures constructed on clay soils tend to undergo settlement deformation when exposed to any additional surcharge load. This type of soil deformation may cause a significant failure to the foundation and, subsequently, the super structures [2]. Many problems concerning foundations are related to the consolidation of clay layers as found in different studies of cases such as deformed road embankment [25,28] and multi-story buildings [28]. These cases show that most of the problems occur due to the compression of clay layers, causing the foundation to collapse. Due to this matter, many researchers [citation] have studied various soil stabilization techniques to improve the geotechnical characteristics of clay soil in order to maintain the vertical alignment of road pavement, prevent civil engineering structures from collapsing, control foundation settlements and evade any associated soil failure [2].

The use of geopolymer materials as soils stabilizers has been widely studied and results of such past studies indicate that geopolymers could be used as an effective soil stabilizer. The inorganic types

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of stabilizing agents which have been popularly applied for the purpose of slope stabilization are cement [3,6], lime [4,16,22], fly ash [8], organic polymers [14] and their mixtures [19,20,24]. These inorganic stabilizing agents are mainly used in non-ecological soil stabilization. Though they have been found to improve the engineering properties of soils significantly, such inorganic materials do inhibit plant growth as they cannot meet the requirements for slope ecological stabilization [23]. Geopolymer binders used in this study are High Calcium Wood Ash (HCWA) and Pulverised Fuel Ash (PFA). These materials were chosen for this study due to their abundance in Malaysia [10]. It has been stated that, geopolymers have a low shrinkage potential and excellent adhesion to aggregates as well as acting as effective soil stabilizers. Recent research has investigated the effectiveness of both low-calcium and high-calcium fly ash based geopolymers in the improvement of deep soft soil [7,16].

This study attempts to apply the geopolymer stabilizer technique from a chemical point of view with geotechnical considerations in order to study the effect of the geopolymers on the engineering characteristics of lateritic soil. In this study, the unconfined compressive strength and shear strength of stabilized soil was investigated. The main aim of this research study was to utilize hybrid geopolymer materials to improve the geotechnical properties of soil based on the modification of soil strength properties.

2 Materials

2.1 Soil Samples

The lateritic soil samples were extracted from a depth of 2m to 3m near the location of the laboratory. The initial geotechnical data of engineering properties of the extracted soil was tested according to ASTM specifications. All the laboratory tests were conducted according to the experiment manual which was prepared by the Committee of Soil Laboratory USM and updated in 2010. The initial physical and mechanical properties of the soils were analysed as presented in Table 1.

Table 1. Mechanical properties of base soil sample

Property	Value
Specific Gravity	2.67
Particle Size Distribution(mm)	0.60
Liquid Limit(%)	77
Plastic Limit(%)	34
Linear Shrinkage(%)	9.40
Organic Matter Content(%)	4.33
pH Value	5.9

2.2 Geopolymers

The geopolymers of ceramic class are characterized by advanced technological properties as well as low manufacturing energy consumption for construction purposes and engineering applications [11]. Geopolymers are usually obtained through inexpensive and eco-friendly synthetic procedures with low waste gas emission [9,12,13,21]. For these reasons they are considered “green materials” [11].

Table 2. Density of materials

Materials	Density (kg/m^3)
Lateritic Soil	2670
HCWA	2632
PFA	2800
H_2O	1000

The geopolymer stabilizers used in this study were selected due to their abundance in Malaysia. They were formed from the hybridization of HCWA-PFA. Recent research has also provided great supporting evidence of the high performance of these materials, the characteristics of which will be described briefly in its section below. In general, mineral content (geopolymer) with a higher extent of dissolution will result in higher compressive strength after the process of polycondensation is complete [7]. The mixed fabrication sample is determined through the calculation of Equation 1 below:

$$\frac{x(\text{Soil})\% + x\left(\text{HCWA} + \text{PFA}\right)\% + 21\%\,H_2O + 4\%\ \text{porosity}}{\text{soil density} \quad \text{HCWA density} \quad \text{PFA density} \quad H_2O\ \text{density}} = 1 \qquad \text{Eq. 1}$$

The geopolymer stabilizing admixture had a mass ratio of 60:40 for high-calcium wood ash (HCWA) and pulverized fuel ash (PFA), respectively. The percentage of the stabilizer was varied between 0% up to 30 % by soil mass. Table 3 can be referred to for an overview of the proportions of mixed materials in this study. The tests performed on the control soil sample were to determine moisture content, liquid limit, plastic limit, linear shrinkage, specific gravity of soil, particle size distribution, organic matter content and pH value. All of these tests were conducted in order to define basic soil properties. The results of the mentioned properties are presented in Table 1.

Table 3. Proportion of Mixed Materials

Lateritic Soil %	Geopolymer Stabilizer %	Proportion of Hybrid Binder Geopolymer Stabilizer		Water, H_2O %	Porosity %
		60	40		
100	0	0	0	21	4
95	5	0.05	0.02	21	4
90	10	0.06	0.04	21	4
80	20	0.12	0.08	21	4
70	30	0.18	0.12	21	4

2.2.1 High-calcium Wood Ash

High-calcium wood ash (HCWA), or wood ash, is a by-product of combustion from wood-fired boilers at typical paper mills and other wood burning facilities. Findings by a recent study have indicated that wood waste ash can be effectively used as a cement replacement material for the production of structural concrete of acceptable performance in terms of strength and durability [5]. Despite its great performance as a cement replacement material, wood ash has another significant potential use as a soil stabilizer or for site remediation. In terms of fineness, the average amounts of wood fly ash passing through sieve #200 (75μm) and retained by sieve #325 (45 μm) were 50% and 31% respectively. The bulk density of wood fly ash was determined to be relatively low at 490 kg/m^3 with a specific gravity value of 2.48. Wood fly ash was found to have a low average autoclaved expansion value of 0.2% [17]. A study which evaluated the physical properties of wood ashes from five different sources concluded that wood ash samples have varying values of unit weight ranging from 162 kg/m^3 to a maximum of 1376 kg/m^3. The specific gravity of wood waste ash samples investigated ranged between 2.26 and 2.60. A higher degree in the variation of wood ash fineness was observed, whereby the percentage of wood ash retained on a 45 μm sieve varied between 23% and 90% [18]. Other research has reported similar results, whereby the specific gravity and the bulk density of wood waste ash were found to be 2.13 and 760 kg/m^3, respectively [1].

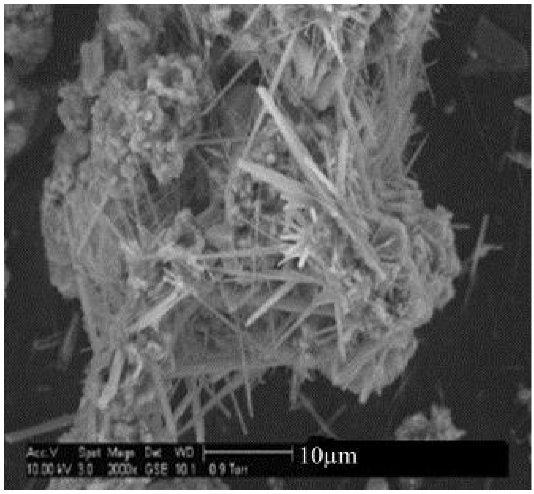

Figure 1. Particle morphology of wood fly ash (Wang et al., 2008)

2.2.2 Pulverised Fuel Ash

Pulverised fuel ash (PFA), or fly ash, refers to part of the non-combustible residues of combustion. Fly ash is obtained from the combustion of coal, consisting of the inorganic matter that did not burn during the process [7]. Since fly ash has already undergone thermal treatment, together with the fact that it is an abundant waste material with few applications, this makes it an ideal source of silica and alumina for alkaline activation. However, the percentage of calcium in fly ash is an important, and sometimes neglected, consideration [10]. This type of ash has self-cementing properties, meaning that, in theory, water is the only additive needed to hydrate this material and form cementitious products similar to those created from Portland cement. Findings from a study on the reaction of a geopolymer (fly ash + sodium) with the addition of sodium-based alkaline activators suggested that low calcium fly ash is a better source for long term soft soil stabilization with alkaline activation than high calcium fly ash [7]. In general, (geopolymer) mineral content with a higher extent of dissolution will result in higher compressive strength after the process of polycondensation is complete. Another previous study investigated the effectiveness and performances of both low-calcium and high-calcium fly ash based geopolymers in deep soft soil improvement and the results were very positive [7]. Table 4 displays the chemical composition of ground fly ash.

Table 4 Chemical composition of ground fly ash

Composition	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_3	LOI
% by weight	31.2	18.9	16.5	20.8	1.86	1.53	2.8	4.1	1.8

3 Experimental Set-up

3.1 Preparation of Specimens

The soil samples were first dried for 48 hours within an average temperature of 80-100°C. The studied soil specimens were synthesized in the laboratory by mixing the oven dried soil with stabilizer materials at different percentages of admixture at 0%, 5%, 10%, 20% and 30% respectively. Data from the samples was obtained by calculating the equation above to get a standard and constant volume of mixed fabrication sample procedure. Accordingly, an optimum water content of 21% of unstabilized soil was used to prepare all the soil specimens in the study for consistency and practical considerations. The formation of soil specimens was conducted using a circular mould with a diameter of 38mm and a height of 76mm. The samples were compacted in the mould in 3 layers with each layer undergoing 10 rounds of tamping compaction. Data collection for this study was based on two separate tests, namely, Unconfined Compressive Strength (UCS) and Triaxial Compressive Strength. These tests were used to determine the Shear Strength, Young's Modulus and Maximum Strain at failure. The tests were conducted on soil specimens subjected to 7 days of air curing upon completion of fabrication. The specimens used for these tests were five (5) remoulded cylindrical specimens for each mix design and testing age. Three (3) remoulded specimens were used for the UCS test and the remaining two (2) specimens were used for the triaxial test. The curing time for this test was 7 days.

Figure 2. Sample Fabrication

Figure 3. Fabricated Specimens

3.2 Unconfined Compressive Strength

Three (3) specimens were examined throughout the test for each mixed design. In the unconfined compressive test, a cylindrical specimen of cohesive soil was subjected to steadily increasing axial compression until failure occurred. Axial force was the only force applied to the specimens. In this particular research, the specimens were uniformly sized 38mm in diameter and with a height of 76mm. The test provided an immediate approximate value of the compressive strength of each remoulded, unconfined and unconsolidated soil sample. It was carried out within a short enough time to ensure that no drainage of water was permitted into or out of the specimens. In every plastic soil in which the axial stress did not readily reach maximum value, an axial strain of 20% was used as the criterion for failure.

Figure 4. Apparatus for UCS test

Figure 5. Placement of specimen

Figure 6. Reading being recorded

Figure 7. Specimen condition before and after the test

3.3 Triaxial Compressive Strength

The two (2) specimens were examined in this test for every mixed design and curing process. This test method covered the determination of the undrained strength of a specimen of cohesive soil when it was subjected to a constant confining pressure and to strain-controlled axial loading, where no change in total moisture content was allowed. The tests were carried out on a set of similar specimens which were subjected to different confining pressures. The strain controlled axial loadings used for this particular test were 41kPa and 20kPa for each specimen respectively. The test was carried out using a triaxial scanner apparatus on specimens in the form of right cylinders with a height approximately equal to twice that of the diameter, or more specifically, 36mm diameter and 76mm in height. The aim of the triaxial scanner apparatus tests was to help determine the shear strength of the applied load transferred to the soil sample.

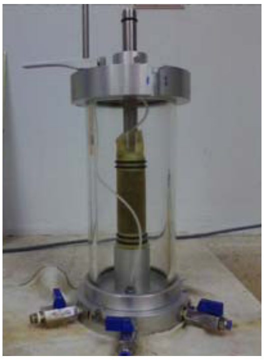

Figure 8. Set-up

Figure 9. Testing in progress

Figure 10. Specimen condition before and after test

4 Results and Discussion

4.1 Geopolymer Samples

Through a trial mixing procedure, it was established that the wood ash had the ability to absorb more water. Therefore, the higher percentage of admixture will have a greater value in terms of the moisture content as compared to the control soil specimen. Moisture content is one the most useful and important soil parameters as the amount of water in soil influences the mechanical behaviour of the soil itself. From the figure below, it can be seen how the moisture content of stabilized soil increased with the addition of the stabilizer admixture. The zero additive soil sample was used as a control for data in the study and was found to have about 15% moisture. On the other hand, the soil samples with a higher percentage of soil stabilizer admixture had a greater value of moisture content at 18% in order to achieve consistency similar to that of the control soil sample.

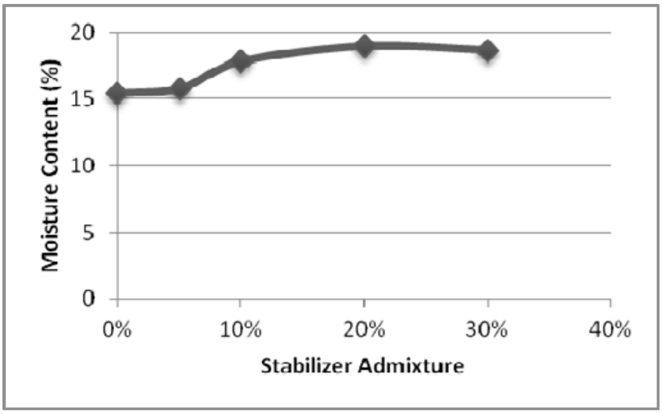

Figure 11. Moisture Content of Sample Fabrication

4.2 Unconfined Compressive Strength (UCS)

Figure 5 below shows the unconfined compressive strength (UCS) of soil samples including the control soil and the soil samples activated with the hybrid admixture. The mixture with 10% stabilizer additive showed the lowest strength after 7 days of curing (0.17 N/mm^2) compared to the control subject containing zero stabilizer content. The highest compressive strength was obtained by the soil sample with 20% stabilizer content. However, after exceeding 20% stabilizer additive, the compressive strength began to decrease. The geopolymer specimens of 20% that were cured for 7 days achieved the highest compressive strength of 0.28 N/mm^2. The compressive strength of the 30% stabilizer additive was found to be 0.26 N/mm^2 which was lower than those containing 20% stabilizer.

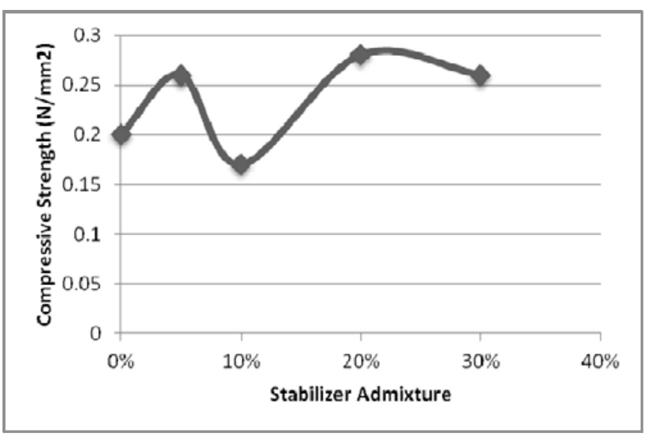

Figure 12. Unconfined Compressive Strength of Stabilized Soil Sample

4.3 Shear Strength

The data for shear strength of the soil samples was obtained from triaxial shear strength test instrumentation. The two specimens were tested using different confining pressures of 41kPa and 20kPa, respectively. Based on the test results in Figure 3, the addition of 20% stabilizer gave a higher shear strength at both confining pressures as compared to the original lateritic soil sample. In addition, the lowest shear strength was exhibited by the soil sample containing 10% stabilizer. This could be due to the effect of the test specimen's higher moisture content which was more dominant than the stabilizing effect of the low percentage of added stabilizer. For the 41kPa confining pressure, as the geoplymer content of the composite mixture was incrementally increased, the shear strength was observed at 20% stabilizer content (208kPa). At the 20kPa confining pressure, soil specimens with the same stabilizer content also achieved the highest shear strength (175kPa) among the various soil specimens examined. When geopolymer content exceeded 30% by mass of soil, the shear strength decreased to 150kPa and 112kPa at confining pressures of 40kPa and 20kPa, respectively. At 10% stabilizer content, the examined soil samples exhibited similar shear strengths (74kPa and 68kPa) even though the confining pressure was halved from 41kPa to 20kPa. However, the pure lateritic soil samples without any additive also exhibited similar strengths for both confining pressures. The shear strengths of the soil with 0% stabilizer content were 90kPa and 83kPa for confining pressures of 40kPa and 20kPa, respectively.

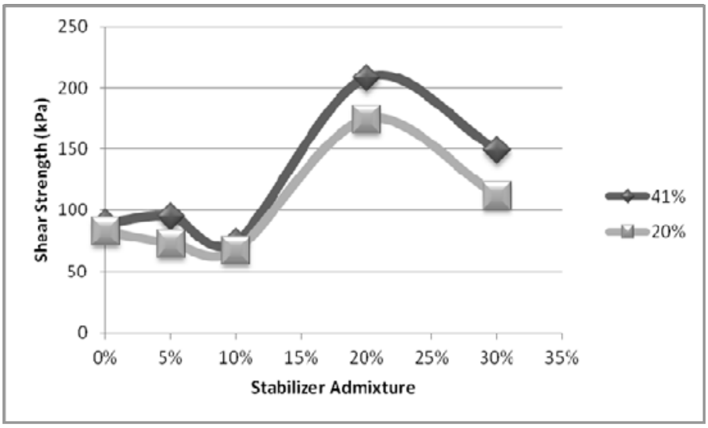

Figure 13. Shear Strength of Stabilized Soil Sample

5 Conclusion

Based on the data obtained in this research, the hybridization of High Calcium Wood Ash (HCWA) and Pulverised Fuel Ash (PFA) geopolymer for use as a soil stabilizer improved both the shear strength and unconfined compressive strength of lateritic soil. Implicitly, the use of this hybrid geopolymer as a soil stabilizer may improve the load bearing performance and slip failure resistance of soil slope. The soil sample containing 20% stabilizer content was found to have unconfined compressive strength at 0.28 N/mm^2 and shear strength of 208kPa which is significantly higher compared to pure lateritic soil. The utilization of a wood ash and fly ash geopolymer as a soil stabilization material offers a viable solution for the disposal of ash materials while, at the same time, helping to enhance soil stability.

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