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# Alkaline Activation of Clayey Soil Using Potassium Hydroxide & Fly Ash

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**Abstract:** In this paper the potential of introducing alkali activated fly ash to a clayey soil as stabilizing agent was investigated. As alkaline activator Potassium hydroxide of 12 M was introduced to the soil fly ash mixtures. Unconfined compressive strength tests were carried out. Four different fly ash/solid ratios were proposed to be 10 %, 20 %, 30 % and 40 % at two curing regimes of 7 & 28 days. The highest unconfined compressive strength was of 40 % mixture recorded at 3.68 MPa after 28 days. Alkaline activation of clayey soil using KOH solution as an activator proved to be a feasible alternative for soft soil stabilization.

**Keywords:** Alkaline activation, Potassium hydroxide, Fly ash, Soft soil improvement

## 1. Introduction

Alkaline activation technique was first introduced to the concrete stabilization sector to replace cement in order to reduce the effect of CO2 emission and its unfriendly impact on the environment [1-3]. The process of alkaline activation or so called gepolymesation is comprised of a mix of alkali metals and alkali solution, where OH ions attacks the Si-O-Si and Si -O- Al, Al-O-Al bonds. By this process Si and Al are liberated and dissolved, building monomers, then accumulate into polymers and further turn into a semi crystal framework, which finally forms a firm gel of aluminum silicate hydrate (A-S-H). The alkali metals needed for the alkaline activation are present as an amorphous constitution in waste materials namely fly ash, metakaolinte, ggbs, rise husk ash, etc. [4-6]. An Extraordinary breakthrough has been documented in the last decade. Involving fly ash based geopolymer to the field of soft soil engineering domain. Variety of research works have addressed the feasibility of introducing the aforesaid binder to remediate problematic soils. Their results drawn confirmed high stiffness and durability of treated soft soils [7-15]. Though, the alkaline activator used by the above mentioned trials was either Sodium hydroxide, a mix of Sodium hydroxide and Sodium silicate or a mix of Potassium hydroxide and Potassium silicate. In other words the literature is deprived in investigating the role of a solely Potassium hydroxide to enhance the stiffness of soft soils. Therefore, the present study aims at improving the compressive strength of a clayey soil using Potassium hydroxide as alkaline activator.

## 2. Material

### 2.1 Soil, fly ash & activator

The soil used for the testing program was a clayey soil utilized from the Kaolin Company in Puchong /Kuala Lumpur. Its physical properties were conducted according to [16]. Soil basic properties are summarized in Table 1. In addition, soil & fly ash particle size distribution curves are depicted in Fig. 1. The fly ash used in the existing testing program is a low calcium class F fly ash, which was supplied by the electrical power station in Kapar Selangor. It is chemical compositions along with that of the soil are depicted in Table 2. The alkali activator used in the current investigations is a Potassium hydroxide solution provided by R & M UK in pellets to be later dissolved in water to produce a 12M alkaline solution.

Table. 1 Soil physical index properties

| Basic Soil Properties | Standard | Value |
|---|---|---|
| Liquid limit (LL) | BS 1377-2 | 74 % |
| Plastic limit (PL) | BS 1377-2 | 43 % |
| Plasticity index (PI) | BS 1377-2 | 31 |
| Linear shrinkage | Bs 1377-2 | 5 % |
| Specific gravity | BS 1377-2 | 2.58 |

| | | |
|---|---|---|
| Gs ($g/cm^3$) | | |
| MDD ($g/cm^3$) | BS 1377-4 | 1.30 |
| OMC | BS 1377-4 | 30 % |

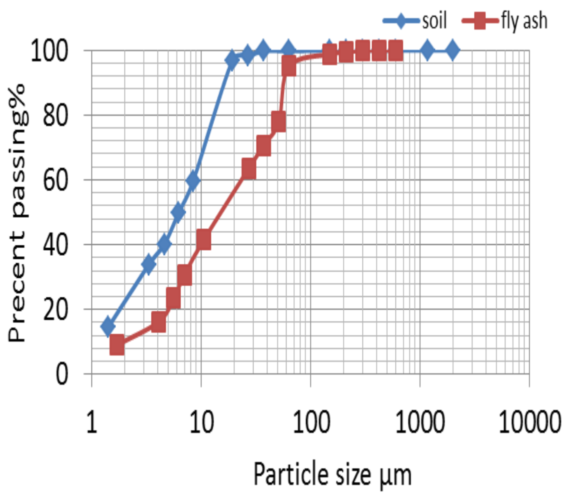



Fig. 1 Soil & fly ash particle size distribution curves

Table 2 Chemical composition of fly ash

| Oxide composition (%) | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | CaO | $K_2O$ |
|---|---|---|---|---|---|
| Fly ash | 42.87 | 16.06 | 20.56 | 8.88 | 3.52 |
| Soil | 38.62 | 28.31 | 26.85 | - | 3.95 |

## 3. Methods

### 3.1 Unconfined Compressive Strength

Soil fly ash mixtures having a fly ash solid ratio of 10%, 20%, 30% and 40% are compacted in a stain steel compaction mold with 50mm diameter and 100mm height at their MDD, OMC to be later examined on unconfined compressive strength [8]. Potassium hydroxide is added to the soil fly ash mixtures at fixed molarity of 12 [17]. After compaction the specimen is extracted than covered with polyethylene folia to prevent moisture loss and stored for two different curing regimes of 7 & 28 days. A day prior to testing the specimens are submerged in water to prevent the positive effect of suction. Three specimens are made for each test for repetition purposes and the average deviation should not exceed 5%. The unconfined compressive test was conducted on natural soil as well as treated soil using Instron testing machine capable of generating 100 KN axial load under an axial strain rate of 1mm per min [18].

### 3.2 Microstructural

Microstructural analysis including SEM, EDS and FTIR are considered of essential benefits in detecting the gel formation mechanism occur by the alkaline activation process. They represent supportive tools along with mechanical testing. In this regard, selected specimens (natural soil (S), fly ash (F) and KOH-Soil-Fly ash (KSF) were analyzed (after submitted to the respective UCS test) using Scanning Electron Microscope (SEM) with OXFORD INCA EDS 300. Only treated specimen was undergoing Fourier transform infrared spectroscopy (FTIR) & EDS analyses. Prior to SEM/EDS analysis, the crushed soil specimens were exposed to Al-stubs with double-sided carbon tabs and then coated with a thin layer of platinum in a sputter coater. In addition to perform the FTIR test, the KBr pellet technique was adopted (3.5 mg of crushed specimens mixed with 800 mg of KBr). Table 3 illustrates various mixture proportions of tested specimens

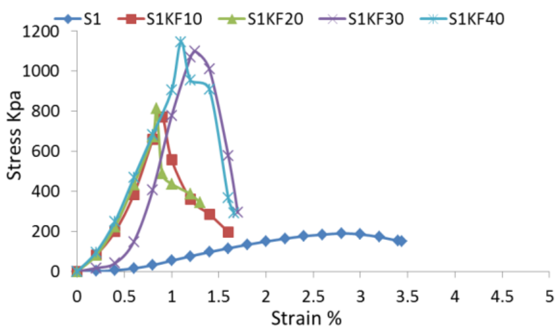
Table 3 Mixture Proportions of Various Series of Test Specimens

| Group series | Samples |
|---|---|
| S | Soil |
| KSF group | KOH12M, Soil,<br>Fly sh10%,20%,30%,40% |

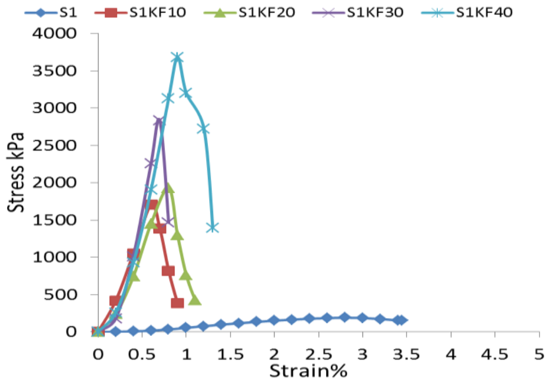
## 4. Results and Discussion

### 4.1 Unconfined Compressive Strength

Fig. 2 (a, b) illustrate the compressive strength of alkaline activated soil & fly ash with KOH solution (KSF) over two curing regimes namely 7 and 28 days. As can be seen, the compressive strength has increased up to 6 times comparing with that of host soil during the first 7 days. The KSF30 & KSF40 showed to attain the highest UCS value at 1100 kPa and 1145 kPa respectively, whereas the KSF10,20 delivered less UCS values at 770 kPa and 815 kPa respectively. A strength increment rate of 1900% for specimen cured for 28 days was observed attaining a strength value of 3680 kPa for KSF40 followed by KSF30 with a UCS value at 2830 kPa, while the KSF10, KSF20 were exhibiting less UCS values at 1705 kPa, 1929 kPa respectively. This finding is in a line with results drawn by compressive testes carried out by many researches [15-18] who reached a conclusion that a proportional coloration between fly ash content and compressive strength values was recorded, which was attributed to the vitreous silica and alumina present in the precursor.




(a)

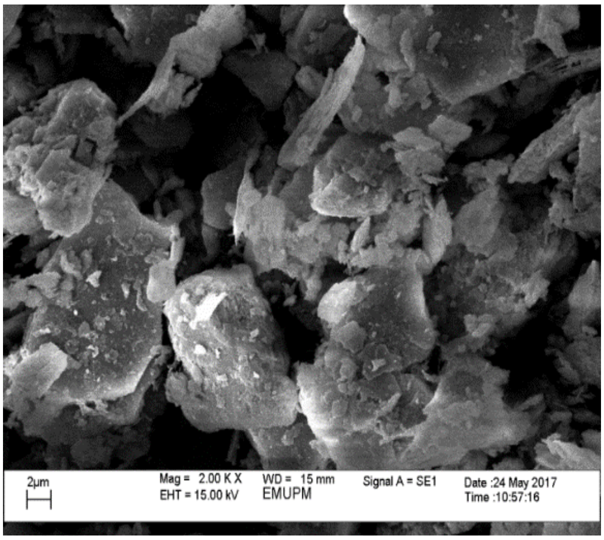



(b)

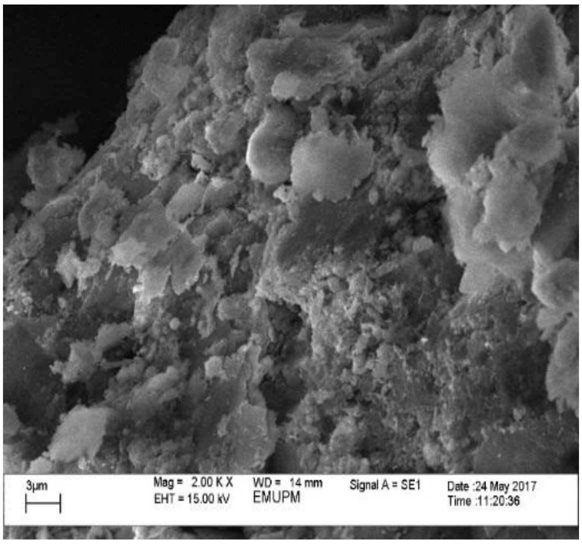
Fig. 2 Results for unconfined compressive strength for KSF (a) 7 days, (b) 28 days

## 4.2 Microstructural Analyses

As illustrated in Fig. 3. (a) The natural soil indicated a more open, discontinuous texture and clearly existing voids between its particles. SEM for natural soil and treated soil were taken at magnifications of 2000 to allow for clear and comparable imaging. The effect of alkaline activation is evident in Fig. (3b), in which the geopolymer gel is obviously depicted in the matrix as a result product induced by fly ash activation due to the alkaline solution (KOH 12 M). In addition, the structure of the matrix is denser than that of natural soil due to uptake, re-condensation of dissolved particles and the presence of glassy phase.




(a)




(b)

Fig. 3 SEM Imaging for (a) natural soil, (b) treated soil

As for EDS analyses the rate of geopolymerizetion is indicated by the ratio Si/Al in the gel matrix Fig. 4 and Fig.5. Based on the measurements taken by EDS analyses it can be stated that along the five spectrums the value of Si/Al did not exceed a value of 1.3, which pointed out only a partial activation of the glassy phase present in fly ash. Although a Si/Al ratio above 2 was reported to indicate an optimum compressive strength gain [10], the rate of strength evolution over 28 days is substantial. The reason behind might be the increasing fly ash content present in the matrix, that contributed to a drastic increase in the compressive strength of the treated soil [8-14].

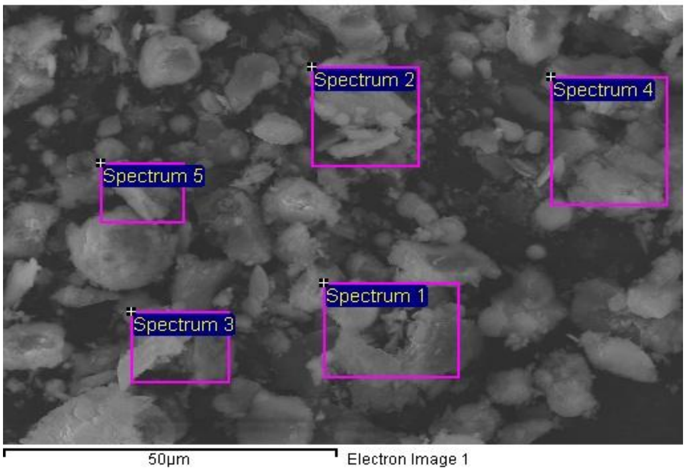



Fig. 4 Different EDS spectrums for KSF

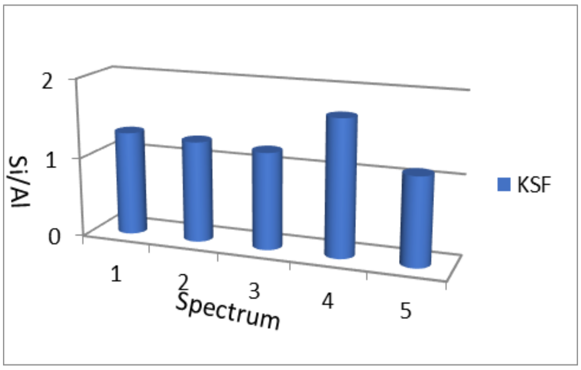



Fig 5. Si/Al versus spectrum of KSF

Fourier transform infrared spectroscopy (FTIR) was conducted to characterize the different bonds with short-range structural order for KSF as depicted in fig. 6. As can be observed from Fig. 6 the first peak observed is a broad peak with a low intensity between wave numbers between 630 $cm^{-1}$ and 721 $cm^{-1}$ centered at approximately 690 $cm^{-1}$, which may refer to the symmetric stretching vibrations of Si-O-Si and Al-O-Si. The second peak was recorded at wave numbers between 721 $cm^{-1}$ and 770 $cm^{1}$, centered at approximately 752 $cm^{-1}$, and at wave numbers 721$cm^{-1}$ and 821$cm^{-1}$ centered at 794 $cm^{-1}$ which may refer to the $CO3^{-}$ vibrations in CaCO3 with intensity at 35%. The third peak appeared between 929 $cm^{-1}$ and 1199 $cm^{-1}$ at 1006 $cm^{-1}$, which exemplify the asymmetric stretching vibration band of Si–O–T (T = Al, Si) indicating a sharp peak and high intensity at 88%. This peak might be more promoted by Si–O–Si as Al was only traced in small amounts as described in EDS results. Another Si-O links are inspected between wave numbers 1199 $cm^{-1}$ and 1442 $cm^{-1}$ at 1408 $cm^{-1}$ with very low intensity at only 5%. At between higher wave numbers of 1600 $cm^{-1}$,1751 $cm^{-1}$ and 2762 $cm^{-1}$, 4000 $cm^{-1}$ for both of S1F and S1FR two main broad peaks of 1651 $cm^{-1}$ and 3622 $cm^{-1}$ with low intensities of 2% were observed indicating stretching and deformation vibrations of OH and H–O–H groups from the weakly bound water molecules, which were adsorbed on the surface or trapped in the cavities between the framework bonds of the activated specimen. These observations were similar to those reported by plenty of researchers [7-17].

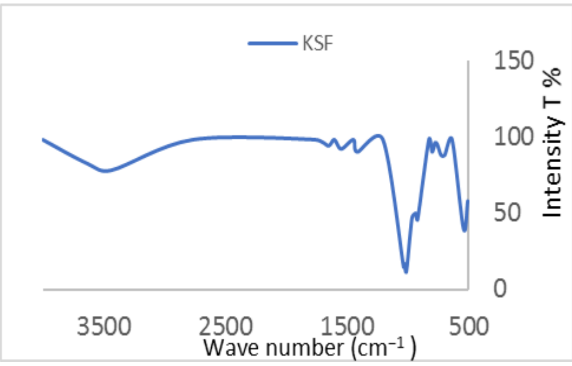



Fig. 6 FTIR of KSF

A remarkable improvement in terms of unconfined compressive strength has been observed by means of alkaline activation process using KOH solution and fly ash class F. This major increase is accounted for the immediate dissolution and uptake of vitreous alumina, occurring on the fly ash particle surface, upon exposure to Potassium hydroxide solution. The phenomenon is best explained by the gradual increase in strength of about six times after seven days induced by weak Al bonds. However, due to the presence of Si species in the internal entity of fly ash and its accompanied low dissolution rate the greatest strength evolution rate is only apparent after around 28 days. The reason behind is that Si bonds more govern the strength increment, which was recorded to be nineteen times greater than that seen by the host soil.

These findings are in a line with conclusion drawn by Abdullah et al. [21], who ascertained the rate of strength increment to be depended upon Si condensations. Moreover, SEM imaging showed a denser structure represented by the gel formation induced by alkaline activated fly ash particles. Vitreous alumina and silica have been able to be taken up in the KOH solution, thus enabling for monomers to gather, which further turn into polymers to form a gradually hardening three-dimensional frame network of Si-O-Si or Al-O-Si. However, based on the EDS analyses the reason for the achieved high degree of strength might be attributed to the threshold value of clay content present in the natural soil rather to the Si/Al values. The low S/Al is consistent with results drawn by FTIR analyses, by which a considerable amount of water molecules was detected to reside between the cemented cluster and soil particles, thus the median of reaction represented by water was not sufficient to help in dissolution reactions.

Furthermore Si-O-Si bonds were detected at various wave numbers confirming the gel formation seen in the SEM imaging.In general, the compressive strength result achieved by the KSF 40, which stands for the clayey soil containing 40% activated fly ash, is higher than that recorded by Pourakbar et al. [22], who have used Sodium hydroxide in their study. They reported a compressive strength value of around 1250 kPa after 28 days curing regime recording an increment rate of about 1150% when comparing with that of host clayey soil.

Moreover, the results concluded by the present study are better than that reached by Abdullah et al. [14], who have used a mix of Sodium hydroxide and Sodium silicate to enhance the strength of a Kaolin clay. The addition of KOH and $Na_2SiO_3$ to a mix of fly ash, GGBS and Kaolin clay contributed to a strength value of 2100 kPa post to 28 days curing regime. In short, based on the results derived by the present study and trials conducted by previous researches it is recommended to use Potassium hydroxide as alkaline activator to achieve higher strength values .when considering longer curing regime more than 28 days.

## 5. Summary

In this paper the potential of alkaline activation technique using Potassium hydroxide and fly ash class F was investigated. In this regard different fly ash solid ratios were proposed to improve the unconfined compressive strength of a clayey soil. From the laboratory tests the following can be summarized:

(i) The results derived from the tests confirmed that the introduction of fly ash and Potassium hydroxide solution of 12M to the clayey soil brought about a drastic increase in terms of compressive strength regardless of fly ash content. The effective fly ash content was that of 40%, which delivered a strength increment rate of 1900% after 28 days pointing out a value of 3680 kPa when comparing with that strength value of the host soil.

(ii) Through SEM imaging a cementious cluster could be clearly detected seemingly cover the existing voids between the soil skeleton of KSF. This is in a line with the mechanical test results. Moreover, the mineral content measurement provided by EDS confirms the compatibility of the former with those glassy minerals present in fly ash. Despite providing low Si/Al strength increase was essential. In addition, The FTIR analyses supports the finding reached by the mechanical testing by ascertaining of Si-O-Si and Si-O-Al bonds at several wave numbers.

(iii) The alkaline activation of problematic soil using fly ash and a 12 M Potassium hydroxide solution proved to be a feasible method in soft soil stabilization.

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