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Using Alkali-Activated Binders to Improve UAE Dune Sand

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Abstract **-** Soil improvement is a technique that improves the soil engineering properties. Several chemical and mechanical techniques have been developed over the last decades to alter or improve poor soil conditions. Many of these chemical techniques use either cement or lime. These traditional techniques have proven efficiency and durability over many years of use despite environmental concerns. Alkali-activated binders (AABs) have shown potential for low energy, low cost and high strength alternative to these traditional cementitious materials. A preliminary study was conducted on the feasibility of using alkali activated mixture of fly ash and Ground-granulated blast-furnace slag (GGBFS) to stabilize local dune-sands. Several micro- and macro-characterization techniques are used to examine the suitability of these binders to improve these local soils. Two different precursors are employed as activators in this investigation namely sodium silicate solution (Na_2SiO_3) and sodium hydroxide (NaOH). The factors studied for the geopolymerization process were Na_2SiO_3/NaOH ratio, total ratio of activator solids by sand weight, and finally ratio of fly ash to GGBFS. The tested specimens were cured temperature of 45 degree Celsius for 24 hours to replicate UAE environmental condition. A maximum strength of 3.68 MPa was attained after 14 days of curing for mixture with a ratio of Na_2SiO_3/NaOH equal to 1 and 40%:60% of fly ash to GGBFS. The total binder to soil ratio for this mixture was 15% by weight.

Keywords**:** Soil improvement; alkali activated; dune sand; fly ash, GGBFS.

1. Background
1.1. Introduction
Unfavourable soil conditions affects structures and pavement performance adversely during their service life. Sand dunes soil formation is by far the most soil encountered in the UAE. Those soil formations are fine to medium, non-plastic, wind-blown sand deposits at shallow depths. These loose sand soil deposits is characterized by its low bearing capacity and may experience excessive settlement and or differential settlement under loading. Over the past decade, many types of chemicals have been used as additives to enhance loose sand deposits mechanical properties, such as cement, lime, and petroleum emulsions. Cement, widely used treatment method for dune sand deposits, is believed to generate around 7% of artificial CO_2 emissions during manufacturing [1]. This consequently encourages the researchers to find sustainable alternative soil additives. In recent years, non-traditional stabilization methods using novel materials such as natural biopolymer, Alkali-activated binders and nanomaterials to enhance mechanical properties of the weak soils have been proposed.

Alkali-activated binders (AABs) can constitute an option as sustainable alternative of traditional cementitious binders (i.e. cement and lime) in geotechnical projects since calcination is not essential in the production of AABs. Essentially, the synthesis of alkali-activated binders, which are formed by the reaction of any amorphous Si–Al primary material, such as (fly ash and slag) with alkali liquid to form a three-dimensional, essentially amorphous, binder gel. Throughout the curing time, water is gradually consumed, originating a well-structured aluminium silicate cementitious material. The use of AABs in geotechnical applications has great potential to reduce the environmental burden on the construction industry in general and the cement industry in particular. Using a series of experimental testing, this study will examine preliminary the feasibility of treating local loose fine sand soils with alkali-activated binders. This study focuses on geotechnical engineering design parameters specifically, compressive strength.

Despite the advantages, there are several challenges that need to be overcome for AAMs to be used as a geotechnical improvement. One such challenge is the dependency of the properties of these binders on the pre-cursor source and the activation system. Several studies on the mechanical behaviour of heat cured AAM are available in the literature [2-12]. However, ambient cured AAM is preferable especially for soil improvement techniques. For heat cured AAMs the mechanical properties and microstructure of the matrix is highly influenced by the mixing conditions, rest period, curing time and temperature, and the concentration of the activating solutions. However, a binder needing heat curing has limited geotechnical applications. Therefore, more recently focus has shifted to ambient cured alkali activated materials with some success. Since AAB uses industrial by-products as binder paste and is therefore cheap, its application to stabilizing problematic soils has great potential. Unlike OPC where the only controlling ratio is water/binder, AABs can be engineered by varying the composition of the precursor material, the type and ratio of activator solution and the ratio of activator solution to the precursor material. Also, the presence of natural chemicals in the soil like salts in saline soils will have a very different influence on the properties of the stabilized soils if AABs are used instead of OPC.

1.2. Previous studies on soil treated with Alkali-activated binder

Alkali-activated binder is an inorganic polymeric material formed through polycondensation of tetrahedral silica (SiO_4) or alumina (AlO_4), which are linked alternatingly by sharing all the oxygen atoms [2]. The geopolymerization is a two-step process to form the alkali-activated binder. First, amorphous aluminosilicate materials (such as fly ash or slag) are dissolved by alkali hydroxide solution and/or alkaline silicate solution to form reactive silica and alumina. In the second step, the dissolved solution then polycondense into amorphous or semi-crystalline oligomers which further polymerize and harden into synthetic aluminosilicate materials. This process of polarization needs a temperature range of 25- 80^o C depending on the type of the binder [2].

Zhang et al. [3] conducted an experimental study to examine the feasibility of using Alkali activated metakaolin binder to treat a lean clay [14]. The researchers treated the soil with different levels of alkali-activated binders and compared the results to cement treated samples. These researchers concluded that the compressive strength values of geopolymer stabilized soils are much higher than the bare control soil, and higher than 5% PC stabilized soil when Alkali activated metakaolin binder concentration is higher than 11%. However, Zhang noticed a minor strength growth from 7-day curing to 28-day and attributed this to the quick reactions of Alkali activated metakaolin binder [14]. Also, compressive strength results showed that the treated soils have more ductile behaviour compared to bare soil samples which is preferred behaviour especially for flexible pavement applications.

Liu et al. [4] conducted experimental study using fly ash–based Alkali-activated binder for the loess soil stabilization. In this study, the investigators used a Class F fly ash as the raw material for the synthesis of AAB with two types of alkaline activators (i.e., potassium hydroxide and sodium hydroxide). The researchers showed that a compact and stable microstructure has developed in the stabilized loess by the synthesis of AAB. The unconfined compression test on soil treated with different concentration of AAB showed that hydroxide activated AAB treated soils renders a higher compressive strength value, higher failure strain, and higher Young's modulus than sodium hydroxide activated geopolymer treated soils with the same fly ash/loess ratio [15]. However, the increasing fly ash/loess ratio showed higher strength for stabilized soils with lower failure strain (more brittle behaviour). Liu et al. [4] attributed this to the inadequacy of precursor in the mixture with a high portion of fly ash.

Cristelo et. al. [5] investigated the stabilisation of residual granitic soils by alkaline activation of fly ash. In this study, a low calcium content fly ash (type F) was used, and a solution of sodium silicate and sodium hydroxide was used as activator. The researchers investigated the effect of maximum soil particle size, liquid:solid ratio, activator concentration, Na_2O:ash ratio. The study showed substantial increase of compressive strength in the range of 3 MPa to 23 MPa (when cured for periods between 1 and 7 days at 60 °C) even with low fly ash content (lowest content used in the study was 15%). This means that the content of geopolymeric binder can be further decreased in order to promote higher sustainability and lower cost of this stabilisation solution in SRE construction. In conclusion, Cristelo et al. [5] emphasized the strong dependency between the activator/ash ratio and mechanical strength of the treated soil.

Rios et al. [6] studied silty sand stabilised with an AAB from low calcium fly ash activated by alkaline solution mixture of sodium silicate and sodium hydroxide. In this research, ambient curing were used for the treated soils up to

360 days. The investigators studied the effect of fly ash content, sodium hydroxide concentration and sodium silicate to sodium hydroxide ratio. Interestingly, the researchers have not noticed a direct correlation between the sodium hydroxide concentration and sodium silicate to sodium hydroxide ratio versus the UCS of the treated soil. However, the UCS of the the treated soil generally increased with the increase of the fly ash content. The strength results show continuing increase beyond the 28th curing day with reasonable short term strength (within the range of 1 MPa to 2 MPa after 28 days).

The use of AAB in soil improvement is rather limited as seen from the literature review. Moreover, the investigators were unable to find any published work on the use of AABs to improve dune soils in the UAE.

2. Materials

2.1. Fly Ash and Ground-granulated Blast-Furnace Slag (GGBFS)

Fly ash is an industrial by-product from the combustion industries like coal combustion industry used to generate electricity. Fly ash usually contains silica, alumina and calcium minerals. Fly ash is the main source of aluminosilicate in the Alkali -Activated binder. GGBFS is a by-product from the blast furnaces in the iron industry and consists mainly of silicates and aluminosilicates of calcium. Commercially available Class F fly ash and GGBFS were used in this work and their composition as found using X-ray fluorescence (XRF) are shown in Table 1.

Table 1: Fly ash and GGBFS Constituents Based on XRF Test Results.

Constituent	Fly Ash % by weight	GGBFS % by weight
$\mathbf{CaO}$	5.9	46.6
$\mathbf{SiO_2}$	51.2	30.9
$\mathbf{Al_2O_3}$	16.2	10.8
$\mathbf{Fe_2O_3}$	17.2	1.1
$\mathbf{MgO}$	3.8	5.4
$\mathbf{K_2O}$	2.1	0.3
$\mathbf{SO_3}$	1.4	3.3
$\mathbf{TiO_2}$	1.4	1.1
$\mathbf{MnO_2}$	0.2	0.7
$\mathbf{SrO}$	0.2	0.1

2.2. Alkaline Solutions (NaOH and Na_2SiO_3)

Sodium silicate and sodium hydroxide solutions were used as alkaline activators. Sodium silicate solution (Na_2SiO_3) with density between 1.296 and 1.396 g/ml produced by Merck, KGaA, Germany and procured from ESTS, UAE was used. Sodium Hydroxide solutions (8M) were made from 98% purity flakes supplied by ESTS, UAE.

2.5. Dune sand

Natural fine dune sand used in this study was collected from Sharjah Desert in UAE near Al-Zaid Area. Figure 1 shows a gradation curve for the sand used in the study. The soil classified as fine poorly graded sand.

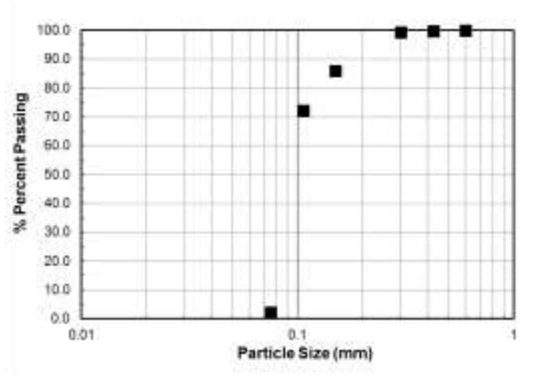

Fig. 1: Dune sand gradation curve.

3. Testing Program

3.1. Geopolymer soil mixing

Two precursor materials, fly ash and GGBFS, are used in different ratios varied from 100:0 to 0:100. For all mixes, 8M concentration of sodium hydroxide was used. The activators, sodium hydroxide (SH) and sodium silicate (SS), were used in three varying proportions (SH/SS ratio = 0.5, 1.0 and 1.5). Two replicates were prepared for each mix to ensure repeatability. To identify the specimens, labelling scheme was used to differentiate soil specimens. The specimen labels are distinguished by giving the fly ash percentage letter F and the GGBFS percentage letter G, then number for SH/SS ratio was assigned and finally percentage of alkali activated binder to soil ratio was added. Thus, F20-G80-1.5-10% is for a specimen contains fly ash to GGBFS ratio of 20 to 80 and SH/SS ratio of 1.5, while the total binder to soil percentage is 10% by weight.

3.2. Sample preparation

The soil samples for Unconfined Compression Strength (UCS) test were prepared inside PVC tubes with an inner diameter of 50 mm and a height/diameter ratio of 2.0 for reducing the end effects during UCS testing. After preparing the ingredients by mass, dry dune sand was mixed with fly ash and GGBFS for 2 minutes. The sodium silicate solution was added to the dry mix and mixed for 3 minutes. Then sodium hydroxide solution was added and mixed for 2 minutes as per the procedure laid out by Junaid et al [7].

The inner surface of PVC tubes were coated with oil to ease the extraction process. The tubes were then filled with treated soil mixture in 3 layers in consistent approach (Fig. 2). Each layer was compacted 25 times using a 10 mm dimeter rod and then the layer was scratched and excess soil was removed before compacting the next layer. A metal tray was used as the base of the PVC tube during casting to prevent any water absorption by the wood table. In the end soil surface was smoothed and excess soil was removed by a spatula. Four specimens were prepared for each mixture 2 for each curing period (7 and 14 days). The samples were cured for a 24 hour period in the oven at 40^{o} Celsius. The extruded samples were left to cure in the room temperature (about 25^{o} Celsius) till time of testing.

3.3. Unconfined Compression Strength Test

The UCS was performed in accordance with ASTM D 2166 (ASTM 2013) and the load was applied at a constant rate of 0.5 mm /minute. The specimens then were placed in the compression testing machine, and the compression load was applied till the sample failed.

Fig. 2: Samples after casting inside the plastic tubes.

3.4. Scanning Electron Microscope (SEM)

SEM/EDX (Tescan VEGA XM variable pressure SEM/ Oxford Instruments X-Max 50 EDS detector). The specimens used for the SEM analysis were coated with a thin layer of gold for charge dissipation using Sputter Coating System (Quorum Technology Mini Sputter Coater, SC7620).

4. Results

4.1. Unconfined Compressive Strength (UCS) Results

As mentioned earlier the testing program included testing soils with different binders percentages by weight (10 % & 15 %). Moreover, the effect of the change of the geopolymer binder constitutions is examined. Table 2 shows the compressive strength of samples with binder/sand percentage by weight of 10% at 7 and 14 days. Table 3 shows the strength of samples with binder/sand percentage by weight of 15% at 7 and 14 days. Some samples were not intact after extrusion from the plastic tubes (referred to as W in the summary tables) and did not have enough strength to be tested. While other samples were damaged during the extraction process (referred to as D in the summary tables). The Damaged samples are not necessary weak but due to lack of grease was damaged due to bonding between the tube walls and the sample.

Generally the treated specimen with binder/sand percentage equal to 15% have higher strength compared to 10% treated samples. Also, treated specimens with binder/sand percentage equal to15% show increase in UCS strength with the increase in the GGBFS content.

Table 2: Summary UCS peak strength of treated sand specimens with treated with 10 % binder by weight.

Fly ash to GGBFS Ratio	F100-G0		F80-G20		F60-G40		F50-G50		F20-G80		F0-G100	
Curing time (days)	7	14	7	14	7	14	7	14	7	14	7	14
Na_2SiO_3/NaOH ratio	UCS strength (MPa)											
0.5	W	W	W	W	0.78	0.96	1.08	1.20	0.81	D	0.683	0.874
1	W	W	W	W	0.04	0.05	0.34	0.42	0.30	0.31	D	0.04
1.5	W	W	W	W	D	D	0.16	D	0.02	D	0.55	D

4.2. SEM Results

SEM pictures shown in Fig. 3 shows the sand particle coated the soil surface and at soil/soil contact points. The SEM picture then was analysed using element mapping technique to show the spatial distribution of chemical elements. The untreated soil particles are defined by the silicon as shown in Fig. 3(a), while treated soil have shown introduction of Ca, Al, Fe, Na and Mg as shown in Fig. 3(b). The SEM imagery clearly shows the difference between the treated and untreated samples, with the latter being disconnected and loose while the earlier showing good contact and substantial geopolymeric compounds. These compounds are seen covering the sand grains while additional compounds are formed elsewhere. This resulted in the increased compressive strength of the samples. The EDS results confirm the presence of new elements (CA, Na and Al in addition to Si) which attributed to the formation of NASH and CASH gels; typical products of alkali activation of FA and GGBFS.

Table 3: Summary UCS peak strength of treated sand specimens with treated with 15 % binder by weight.

Fly ash to GGBFS Ratio	F100-G0		F80-G20		F60-G40		F50-G50		F40-G60		F20-G80		F0-G100	
Curing time (days)	7	14	7	14	7	14	7	14	7	14	7	14	7	14
Na_2SiO_3/NaOH ratio	UCS strength (MPa)													
0.5	W	W	0.08	0.15	W	W	2.31	1.52	0.96	2.75	0.97	1.97	2.07	2.51
1	W	W	W	W	0.36	0.37	0.64	0.95	2.57	3.69	1.07	D	D	D
1.5	0.07	W	W	W	W	W	D	D	D	D	0.27	0.56	0.56	0.68

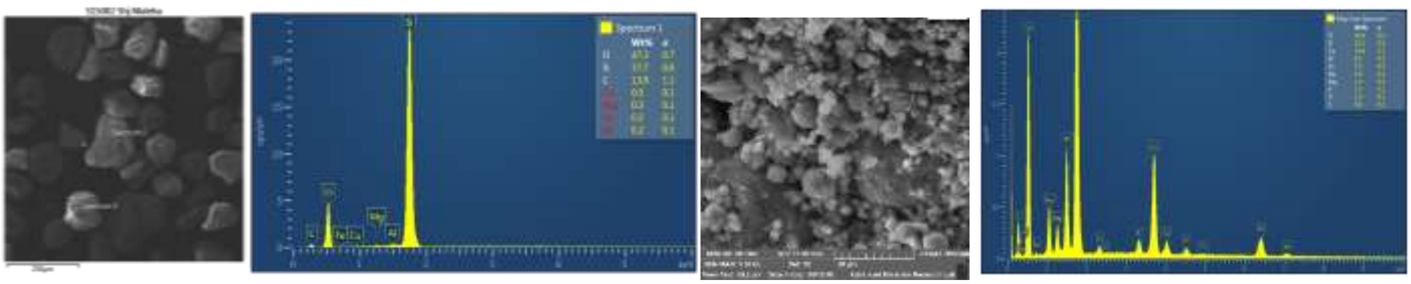

Fig. 3: (a) SEM picture of untreated soil sample with EDS; (b) SEM of treated soil sample (F40-G60-1-15% cured for 14 days) along with the EDS chemical mapping.

5. Discussion

5.1. Effect of binder percentage by weight.

Two percentages of binder to sand were tested; 10% and 15%. As expected, with increased binder content the strength of the samples also increased. As the percentage of the precursor material was increased, the alkali activators were able to react with these resulting in higher quantity of geopolymeric paste. This increase in paste covered the sand grains as shown in the SEM results. Any additional paste formed geopolymeric compounds in the voids available. As the past volume was increased, the additional paste more effectively filled the voids in the sand mass, thereby increasing the strength and decreasing the porosity of the material. These observations are reflected when comparing the graphs presented in Figures 4 and 5. The maximum compressive strength for 10% binder ratio was 1.2 MPa while that for 15% binder ratio was 3.6 MPa.

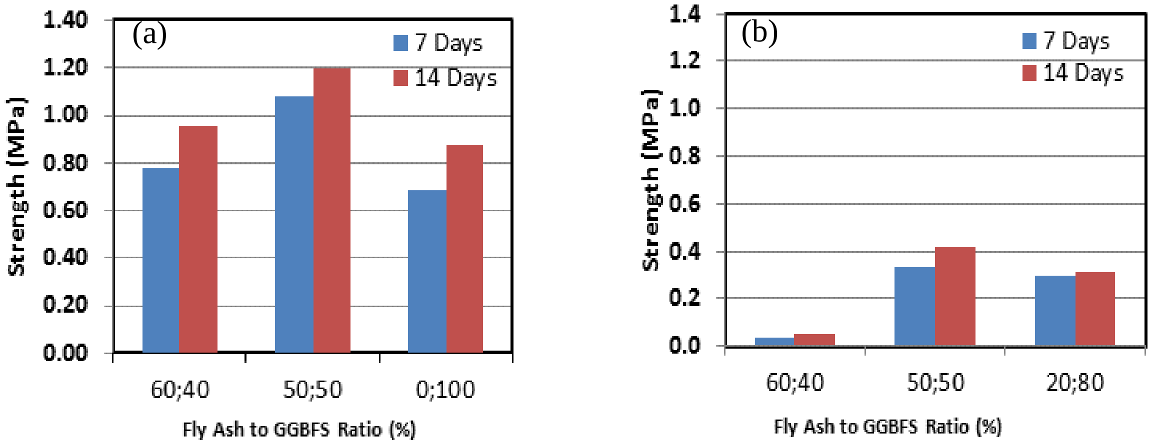

Fig. 4 : Strength at 7 days and 14 days of Samples with a) Na2SiO3/ NaOH= 0.5 b) Na2SiO3/ NaOH= 1.0 & 10% binder by weight.

5.2. Effect of Silicates to Hydroxides Ratio

It can be easily identified that with the increase in the ratio strength increases only if the binder percentage by sand weight also increases. At low binder content the activator solutions do not have enough binder to react fully with, thus only adding to the liquid content of the mix. This increase results in lower strength as seen in Fig. 5 (a) and (b). However, as the binder content is increased from 10 to 15% the increase in Silicate to Hydroxide ratio has a very different effect on the behaviour of the treated samples. At 15% binder content, the additional liquid is utilized to react with the precursor material resulting in increased paste quantities. This in turn provides better contact between the sand grains as well as filling any additional voids that might remain in the treated sand mass.

5.3. Effect of Fly ash to GGBFS Ratio

The results indicate that for an effective system presence of both GGBFS and Fly Ash is important. Mixes with higher GGBFS content exhibited a higher strength than those with high fly ash content. However, without fly ash the mix will set too fast and will not allow for reasonable setting time. This may illustrate the equal strength for the 40:60 mix compared to the 20:80 mix after 7 days of curing. The most optimal ratio of FA to GGBFS found out during this study from a strength point of view is 40:60 which returned maximum strength values of 2.5 MPa and 3.6 MPa at 7 and 14 days respectively.

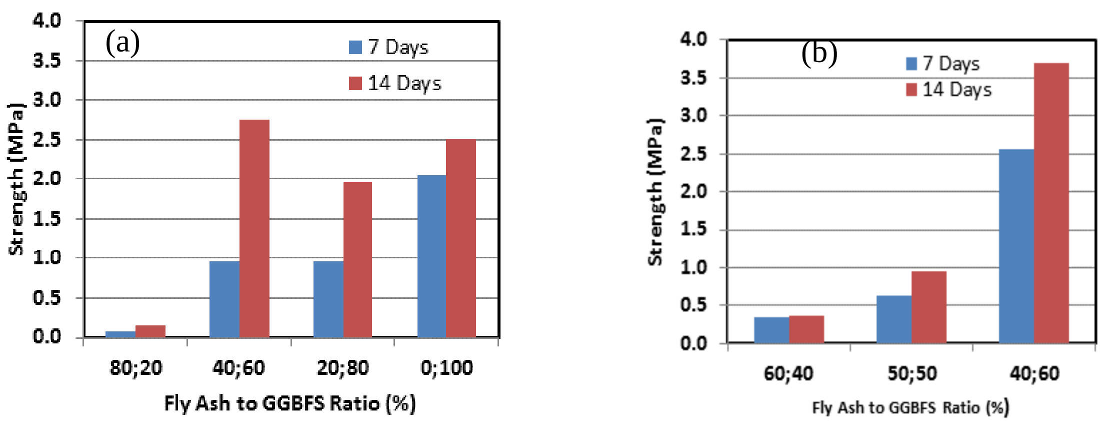

Fig. 5 : Strength at 7 days and 14 days of Samples with a) Na_2SiO_3/ NaOH= 0.5 b) Na_2SiO_3/ NaOH= 1.0 & 15% binder by weight.

6. Conclusion

This experimental study investigated the use of alkali activated material as an alternate to loose soil stabilization in middle east region. Different precursor materials, binder content, and activator ratios were studied to test the compressive strength of treated soils as a measure of soil improvement. SEM and EDS were also used to investigate the micro of the treated soils. Based on the results the following conclusions may be drawn:

1. Alkali Activated Binders may be used as an alternate to OPC to improve strength properties of loose soil. Such an alternate binder can be tailored to suit the strength requirement of the soil in question and may provide a more sustainable alternate to OPC.
2. In general, increasing the binder content results in increase in the strength of the treated soil. Moreover, curing time also plays an important part in strength development with samples gaining more strength with age.
3. Increasing the SS to SH ratio has an adverse effect on the strength of samples containing low percentage of precursor material. However, once the precursor material is increased, the SS to SH ratio has a positive effect on the treated soil samples. A ratio of FA to GGBFS of 40:60 provided the highest strength which was attained for a binder content of 15% and an SS to SH ratio of 1.0

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