Effects of basic Oxygen steel slag (BOS) on strength and durability of kaolinite

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Abstract

The use of various slags as by-products of steel industry is well established in civil engineering applications. However, the use of BOS slag in the area of soil stabilization has not been fully researched and developed despite having similar chemical composition and mineralogy to that of Portland cement. This paper reports on efforts to extend the use of BOS slag to soil stabilization by determining possible beneficial effects it may have on compressive strength and durability. Results of laboratory tests conducted on kaolinite samples stabilized with lime and treated with various percentages of BOS slag are presented. Tests determined strength development of compacted cylinders, moist cured in a humid environment at 35° C and durability by freezing and thawing method. Results showed that additions of BOS slag to kaolinite samples singularly or in combination with lime increased unconfined compressive strength and durability. These characteristics were significantly enhanced by the concurrent use of lime and BOS slag for stabilization of kaolinite.

Key words: BOS slag, Kaolinite, Lime, Durability, Strength, Freezing, Thawing

1. Introduction

The rapid industrialization has resulted in generation of large quantities of wastes. Most of which do not find any effective use and create environmental and ecological problems apart from occupying large tracts of valuable land. At the same time, disposal of industrial waste or by-products has become more difficult and expensive because of the increasing stringent environmental regulations and shortages of suitable nearby disposal sites. It has been observed that some of these wastes have high potential and can be gainfully utilized as raw mix/blending ingredient in cement manufacturing or other industries. To use industrial wastes will not only help in solving the environmental pollution problems associated with their disposal but also help in conservation of natural resources such as limestone and aggregates.

Iron and steel slag are produced as the nonmetallic co-product of iron and steel production which comprise mostly of silica and alumina from the original iron ore with calcium and magnesium oxides from the added flux (lime)[14]. Once slag cools and solidifies, the metallic part is removed and fed back into the steel mill and the nonmetallic slag is sized by crushing to fractions that range from about 1 to 10 inch. [22].

Steel slag aggregates show an inclination to expand because of the presence of free lime and magnesium oxides that have not reacted with the silicate. They can hydrate and expand in humid environments. Steel slag intended for use as aggregate should be stockpiled outdoors for several months to expose the material to moisture from rain or application of water by spraying. The purpose of such storage (ageing) is to allow potentially destructive hydration and its associated expansion to take place before using the material. Processed steel slag has favourable mechanical properties for aggregate use, including good abrasion resistance, good soundness characteristics, and high bearing strength. Steel slag aggregate has long been used as granular base, in embankments, highway shoulders, hot mix asphalt pavements, railway ballast and hydraulic structures. More recently slag uses have been expanded to include use as a cement additive and landfill cover material [21].

The chemical composition and mineralogy of steel slag is similar to that of Portland cement. It is considered a weak Portland cement because of its low tricalcium silicate (C_3S) content [12, 18, 26, 27]. According to Wu et al. [31], Shi and Quin [27], and Altun and Yilmaz [3], the reactivity or hydraulic properties of BOS slag is dependent on its chemical composition, mineral phase, and alkalinity. It has been

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reported the higher the alkalinity, the greater the reactivity or hydraulic properties of the steel slag. Steel slag produced from BOS has higher alkalinity than slag produced from EAF process.

Wild et al. [32] examined the effects of partial substitution of lime with ground granulated blast furnace slag (GGBS) on the strength properties of lime stabilized sulphate-bearing clay soils. In their laboratory investigation they used lime-stabilized kaolinite containing different levels of added gypsum and lime stabilized gypsum bearing Kimmeridge clay to which lime was progressively substituted with GGBS. They used cylindrical specimen cured in a humid environment at 30° C. Their results showed that substitution of lime with GGBS in stabilizing gypsum containing clays produces significant improvements in strength development. Poh et al. [23] conducted a laboratory investigation of using three BOS slag fines from different steel production sites in United Kingdom for stabilizing English China Clay (ECC) and Mercia Mudstone (MM). Results showed that using mixtures of BOS slag fines produces improvements in strength and durability (soaked UCS/unsoaked UCS) as well as reducing expansion.

2. Scope of research

Considering that steel slag has similar chemical composition and mineralogy to Portland cement, there might be potential for furthering its use in soil stabilization. Based on the literature review, the use of BOS slag in soil stabilization has not been extensively examined so far. This research will examine the potential use of Basic Oxygen Steel slag singularly or in combination with lime for improving strength and durability of fine-grained soils.

3. Materials and experimental program

3.1. Materials

Kaolinite was used as the clay soil in this investigation to reduce the effects of material variability in tests results. Index characteristics of kaolinite determined according to appropriate ASTM standards are summarized in Table 1. According to Unified Soil classification System, kaolinite is classified as CL. The lime used for the investigation was hydrated lime with particles passing No. 200 sieve having specific gravity of 2.3. Basic Oxygen Steel (BOS) slag aggregates passing sieve No. 4 (i.e. 420 μm) with a specific

Table 1. Kaolinite index characteristics

Characteristic	Value
Particle size distribution (% by mass)	
<0.075mm	100(%)
Specific gravity	2.6
Plastic limit (%)	26
Liquid limit (%)	45
Plasticity index (%)	19
Max. dry density (Mg/m³)	1.69
Optimum moisture content (%)	21

gravity of 3.32 were used. Considering the size of the samples this was necessary to separate the coarse particles and promote possible chemical reactions by increasing specific surface. Grain size distribution curves for the clay and the BOS slag are shown in Figure 1. The chemical and mineralogical composition of the materials determined by the National Geological Organization using XRF and XRD analysis are presented in Table 2.
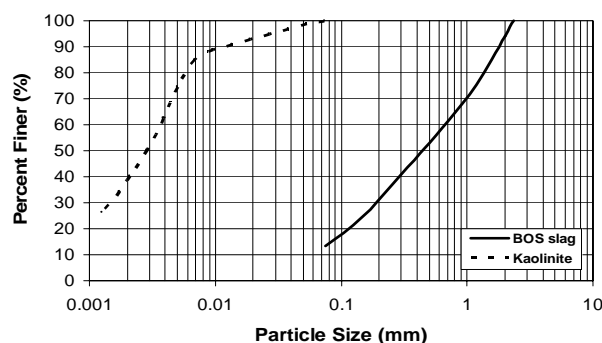

Fig. 1. Particle size distribution curves for kaolinite and BOS slag

3.2. Mixtures

Mixtures studied together with their respective maximum dry density (MDD) and optimum moisture content (OMC) is presented in Table 3. Results show that lime addition resulted in slightly reducing MDD and increasing OMC of the soil, whereas BOS slag addition had exactly the opposite effect. Kaolinite treated with a particular percentage of lime and various amounts of BOS slag also showed slight increase in MDD and reduction in OMC. The decrease in dry density of lime treated kaolinite samples is attributed to the immediate formation of cementitious products at particle contact points. These products reduce compactibility and thus density of the treated soil. The air within the macro-pores formed is easily expelled to be replaced by water without increasing the

Table 2. Chemical and mineralogical composition of kaolinite, lime and BOS slag

	Kaolinite	Lime	BOS Slag
L.O.I.	2.46	30.76	12.52
Na_2O	0.07	0.10	0.17
MgO	0.40	0.32	4.75
Al_2O_3	26.33	0.63	2.33
SiO_2	67.51	0.39	10.07
P_2O_5	0.09	0.02	1.38
SO_3	0.09	0.16	0.87
K_2O	0.44	0.02	0.05
CaO	1.89	66.3	45.77
TiO_2	0.03	<0.03	0.92
V_2O_5	<0.10	<0.01	1.41
Cr_2O_3	<0.10	<0.03	0.22
MnO	0.01	0.01	4.40
Fe_2O_3	0.49	0.10	-
Fe_3O_4	-	-	14.92

Minerals					
Kaolinite	$(Al_2Si_2O_5(OH)_4)$	Calcite	$(CaCO_3)$	Portlandite	$(Ca(OH)_2)$
Quartz	(SiO_2)	Portlandite	$(Ca(OH)_2)$	Calcite	$(CaCO_3)$
Orthoclase	$(KAlSi_3O_8)$	Larnite	$(CaSiO_4)$	Periclase	(MgO)
Illite	$(KAl_2Si_3AlO_{10}(OH)_2)$	-	-	Larnite	$(CaSiO_4)$
Montmori-llonite	$(Al_2O_3.4SiO_2.xH_2O)$	-	-	Magnetite	(Fe_3O_4)
Calcite	$(CaCO_3)$	-	-	-	-

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Table 3. Compaction characteristics of mixtures

Mixtures	Max. dry density (Mg/m^3)	Optimum Moisture (%)	Mixtures	Max. dry density (Mg/m^3)	Optimum Moisture (%)
K	1.69	21	K+1%L+15%B	1.77	19.5
K+1%L	1.68	21.4	K+1%L+20%B	1.81	18.5
K+3%L	1.67	22	K+3%L+10%B	1.73	20.5
K+5%L	1.65	23	K+3%L+15%B	1.76	19.7
K+10%B	1.74	19.7	K+3%L+20%B	1.79	19
K+15%B	1.77	19	K+5%L+10%B	1.70	21
K+20%B	1.81	18	K+5%L+15%B	1.73	20.5
K+1%L+10%B	1.74	20	K+5%L+20%B	1.76	19.7

Notations: **K**= kaolinite, **L**=lime, **B**=BOS Slag

volume, thus causing the increase in optimum moisture content [1, 4]. The slight increase in MDD and the reduction in OMC of BOS slag treated kaolinite are attributed to the coarser slag particles promoting better compaction.

3.3. Sample Preparation

Cylindrical test specimens with 38mm diameter and 76mm height were prepared with MDD and OMC values shown in Table 3. After mixing and compaction of the samples, they were labeled and wrapped in several layers of cling film and placed in airtight plastic containers. They were then transferred to a controlled chamber set at 35° C and approximately 100% relative humidity and cured for 1, 7, 28 and 90 days. To ensure repeatability in sample preparation, preliminary investigations were conducted on two of the mix compositions. A maximum variation of 7% was observed in UCS result which was considered satisfactory. For the main tests, results that varied more than 5% were discarded.

4. Testing

Tests were conducted on both treated and untreated kaolinite samples to determine the changes in compressive strength and durability by resistance to freezing and thawing (F/T). X-ray fluorescence (XRF) and X-ray diffraction (XRD) analysis were also carried out on kaolinite, lime and BOS slag to determine their chemical and mineralogical compositions (see Table 2).

4.1. Unconfined compression tests

To determine the effects of lime and BOS slag addition on strength of kaolinite, unconfined compressive strength (UCS) tests were performed in accordance to ASTM D: 2166-87. After completion of UCS tests, samples were collected for moisture content determination to ensure that moisture loss was not significant and uniformity was achieved with samples prepared using the same procedure.

4.2. Durability Tests

Durability of untreated and treated soil samples were examined by conducting freeze / thaw (F/T) tests in accordance to ASTM D 560. At the designated curing periods, samples were taken out of the curing chamber, cooled, weighted and then stood on carriers and placed in a freezer.

On removal after 24 hours of freezing, the specimens were transferred to a humidity chamber and kept for a further 24hr. Each cycle of freezing / thawing lasted 48 hours to complete. Because of the variety of mix compositions, number of samples as well as time limitations, a maximum of 4 cycles of F/T were used. On completion of designated F/T cycles, samples were subjected to UCS tests. Brushing of samples after F/T was not carried out as it is conducted manually and could be affected by the consistency of the technician. In this regard, Shibata and Baghdadi [28] reported a good correlation between F/T durability as measured by mass loss (i.e. brushed) and residual strength (i.e. unbrushed) for soil - cement specimens. Baghdadi and Shibata [5] also reported that replacing brushing by measuring the compressive strength of specimens after they are subjected to cycles of wet - dry or freeze - thaw provides a more consistent and convenient measure of the deterioration of the material. Durability in terms of residual strength after freezing and thawing as well as being based on the calculated index of "UCS after F/T / UCS before F/T" has been determined. This index, denoted by "Di" is a measure of the resistance of a specimen to the deteriorating effect of freezing and thawing on its strength. Poh et al. [23] used the "soaked UCS / unsoaked UCS" as the index for determining the durability of stabilized soils.

5. Results

5.1. Unconfined compression tests

5.1.1. Lime stabilized samples
Compressive strength development of untreated and stabilized kaolinite samples with 1, 3 and 5% lime is shown in Figure 2. As expected, untreated samples do not show any
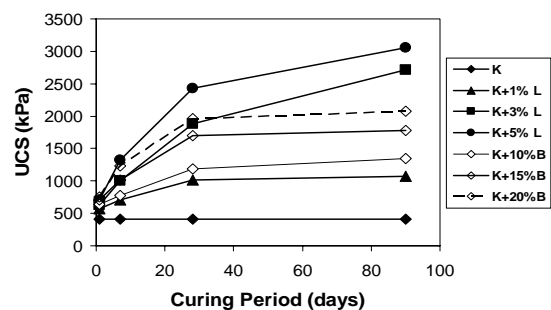

Fig. 2. UCS versus curing period for lime and, BOS slag treated kaolinite

strength development with curing time. Lime addition enhanced strength development which increased with increasing lime content. Strength development is very significant between 7 and 28 days of curing with the trend continuing up to 90 days but at a reduced rate. Samples stabilized with 1% lime, showed no gain in strength after 28 days whereas those stabilized with 3 and 5% lime, show continued strength development even after 90 days of curing. Kaolinite samples stabilized with 3% lime in particular show a substantial increase in strength. Increasing lime content from 3% to 5%, although resulted in higher compressive strengths, but the changes are not substantial. Considering the results, it can be concluded that 1% lime was not sufficient to produce enough pozzolanic compounds needed for significant strength development and 5% is the optimum lime content for the kaolinite studied. Strength development showed to be dependent on the lime content as well as the curing time. The observations made are in agreement with the results reported by Abdi [1], Arabi [4] and Thompson [30]. Taking strength of untreated kaolinite as the base, addition of 1, 3 and 5% lime respectively resulted in 160, 558 and 642% improvement after 90 days of curing (see Table 4).

5.1.2. BOS slag treated samples

Compressive strength of BOS slag treated kaolinite samples are also shown in Figure 2. It can be observed that by the addition of 10, 15 and 20% BOS slag to kaolinite, strength enhancement is achieved. The most significant increase in strength is displayed by samples treated with 10% BOS slag and further increases (i.e. 3 and 5%) although resulted in higher compressive strengths, but the changes are not substantial. Strength gain by all samples mainly occurred during the first 28 days of curing and remained almost constant from 28 to 90 days. Considering the results, 20% BOS slag seem to be the optimum content for the kaolinite examined. The changes observed in this investigation are slightly different to the results reported by Poh et al. [23]. Although they also reported increase in strength by adding BOS slag fines to English China Clay and Mercia Mudstone, it was stated that strength gain showed continuing even after 90 days of curing. The difference in observations are attributed to the fact that Poh et al. [23] used ground BOS slags with particles finer than 63 μm and 425 μm compared to 420 minor particles used in this investigation. The finer slag particles probably promoted more extensive chemical reactions, taking longer to complete. Addition of 10, 15 and 20% BOS slag respectively resulted in 227, 331 and 404% improvement in strength after 90 days curing (see Table 4).

Table 4. UCS and the percentage increase after 90 days curing

Mixture	UCS (kN/m^2)	% Increase	Mixture	UCS (kN/m^2)	% Increase
K	412	0	K+1%L+15%B	2112	413
K+10%B	1347	227	K+1%L+20%B	2586	528
K+15%B	1776	331	K+3%L+10%B	3091	650
K+20%B	2077	404	K+3%L+15%B	3480	744
K+1%L	1074	160	K+3%L+20%B	3606	775
K+3%L	2713	558	K+5%L+10%B	4130	902
K+5%L	3061	642	K+5%L+15%B	4714	1044
K+1%L+10%B	1872	354	K+5%L+20%B	4861	1080

Notations: **K**= kaolinite, **L**=lime, **B**=BOS Slag

5.1.3. Lime/BOS slag treated samples

Figures 3(a), (b) and (c) respectively show the effects of 10, 15 and 20% BOS slag addition on strength development of lime stabilized kaolinite samples. Concurrent addition of lime and BOS slag to kaolinite samples resulted in enhanced UCS compared to UCS of samples treated with only lime or BOS slag. Lime acts as an activator increasing the hydration of BOS slag which can be distinguished by comparing their UCS with the UCS of lime only treated samples. Kaolinite samples treated with higher percentages of lime and BOS slag, displayed substantially higher UCS. Figures 3(b) and (c) show that even after 90 days of curing the gain in UCS of samples treated with 3 and 5% lime is still continuing. The UCS and the associated percentage increases after 90 days of curing compared with untreated kaolinite are presented in Table 4. Poh et al. [23] reported greater improvements in UCS development by using quicklime. In the current investigation greater UCS enhancement might have been reached if CaO instead of Ca(OH)$_2$ and BOS slag in powder form were used.

5.2. Durability

5.2.1. Lime addition

Figures 4(a), (b), (c) and (d) show the UCS of untreated and lime stabilized kaolinite samples after undergoing freezing and thawing. The untreated kaolinite samples could not withstand a single cycle of freezing and thawing even after 90 days curing (Figure 4(d)). Samples treated with 1% lime and cured for 1 and 7 days, disintegrated after the first cycle of F/T. Prolonging the curing period to 28 and 90 days, enabled these samples to resist two cycles of F/T. Further increasing the lime content to 3 and 5%, enabled even the 1-day cured samples to withstand 4 cycles of F/T. Samples cured for 7, 28 and 90 days, although showed decrease in UCS, but displayed good resistance to F/T. Generally, samples with higher initial compressive strengths, displayed higher residual strengths after undergoing 4 cycles of freezing and thawing. The observations made are compatible
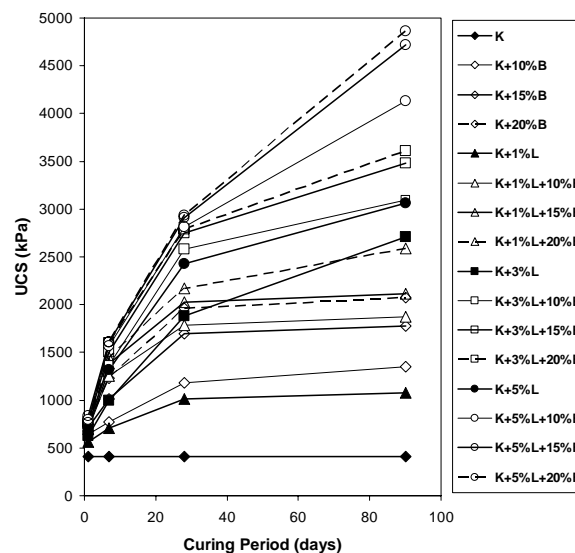

Fig. 3. UCS versus curing period for untreated , lime , BOS slag and lime + BOS slag treated kaolinite
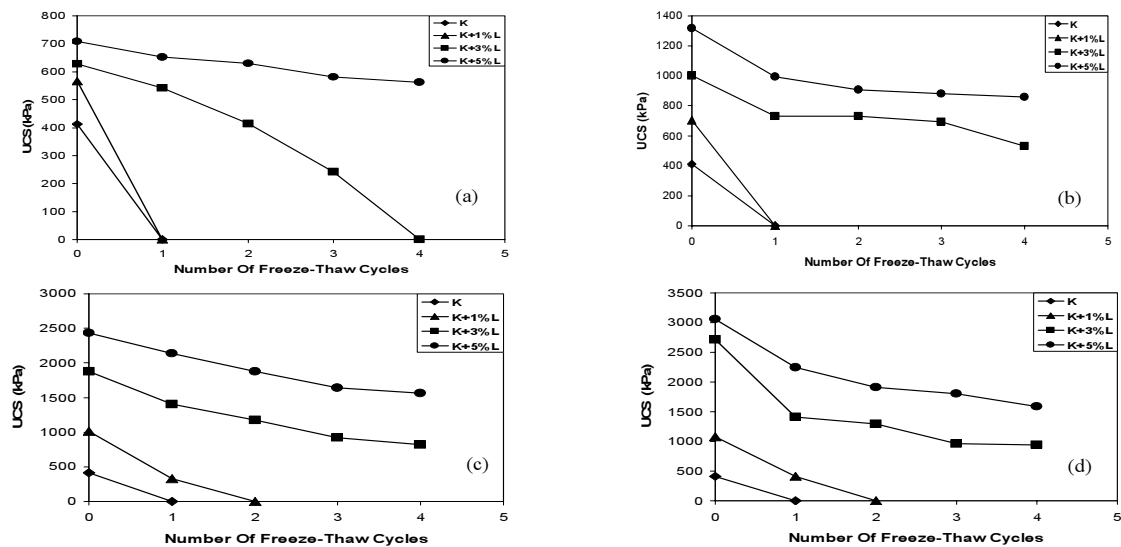
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Fig. 4. UCS versus Number of freeze - thaw cycles for lime treated kaolinite cured for (a) 1-day, (b) 7-days, (c) 28-days, (d) 90-days

with the results reported by other researchers about the decrease in strength with increasing number of F/T cycles [2, 10, 25]. The decrease in strength is a consequence of the rupturing of the bonds between particles because of ice formation in the voids.

5.2.2. BOS slag addition

The changes in the UCS of kaolinite samples treated with various percentages of BOS slag and subjected to cycles of F/T are presented in Figures 5(a), (b), (c) and (d). Addition of BOS slag resulted in increasing the resistance of kaolinite to freezing and thawing. As before, untreated samples of kaolinite even after 90 days curing broke up after the first cycle of F/T. Samples treated with 10, 15 and 20% BOS slag, showed resistance to 4 cycles of F/T after only 1-day of curing. Results show that the longer the curing period, the higher the

residual compressive strengths after completion of 4 cycles of freezing and thawing. Irrespective of the curing period, the highest reductions in UCS were caused during the first cycle of F/T and later cycles were not as effective. Results show that samples treated with 20% BOS slag consistently displayed the greatest resistance to F/T at any particular period of curing. It is concluded that durability of treated kaolinite samples is dependent on both the curing period and the percentage of BOS slag.

The resistance to freezing and thawing displayed by both lime and BOS slag treated samples show the same trend but of different magnitudes of residual strength. This is because the initial UCS of lime stabilized kaolinite samples was also consistently higher than the BOS slag treated samples. It can be concluded that lime proved more effective compared to BOS slag in improving durability of kaolinite.
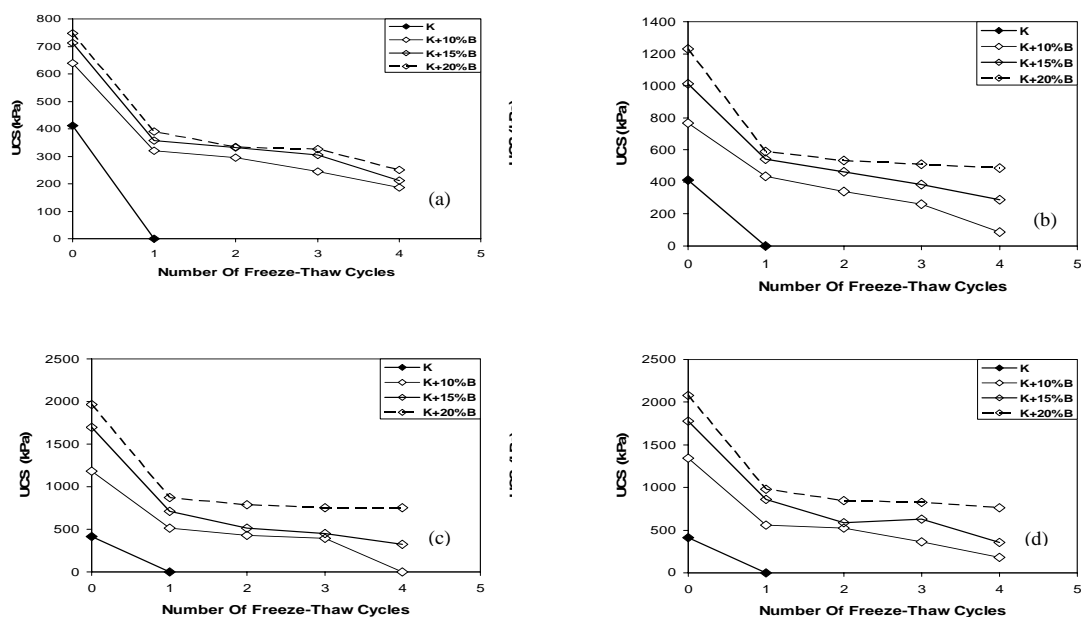

Fig. 5. UCS versus Number of freeze - thaw cycles for BOS slag treated kaolinite cured for (a) 1-day, (b) 7-days, (c) 28-days, (d) 90-days

5.2.3. Lime/BOS slag addition

Effects of concurrent addition of lime and BOS slag on durability of kaolinite are presented in Figures 6(a), (b), (c) and (d). Each figure shows the results for a particular curing period (i.e. 1, 7, 28 and 90 days). Figure 6(a) shows that apart from the sample stabilized with only 1% lime, all other samples showed good resistance to 4 cycles of F/T even after 1-day of curing. All lime/BOS slag treated samples cured for only 1-day showed approximately the same residual strengths with the difference becoming greater at longer curing periods. The positive effects of lime/BOS slag addition on durability of kaolinite became intensified at longer curing periods (i.e. Fig. 6(b), (c) and (d)). Generally the higher the initial UCS, the higher the residual strengths after F/T which is a function of both lime and BOS slag content as well as the curing period.
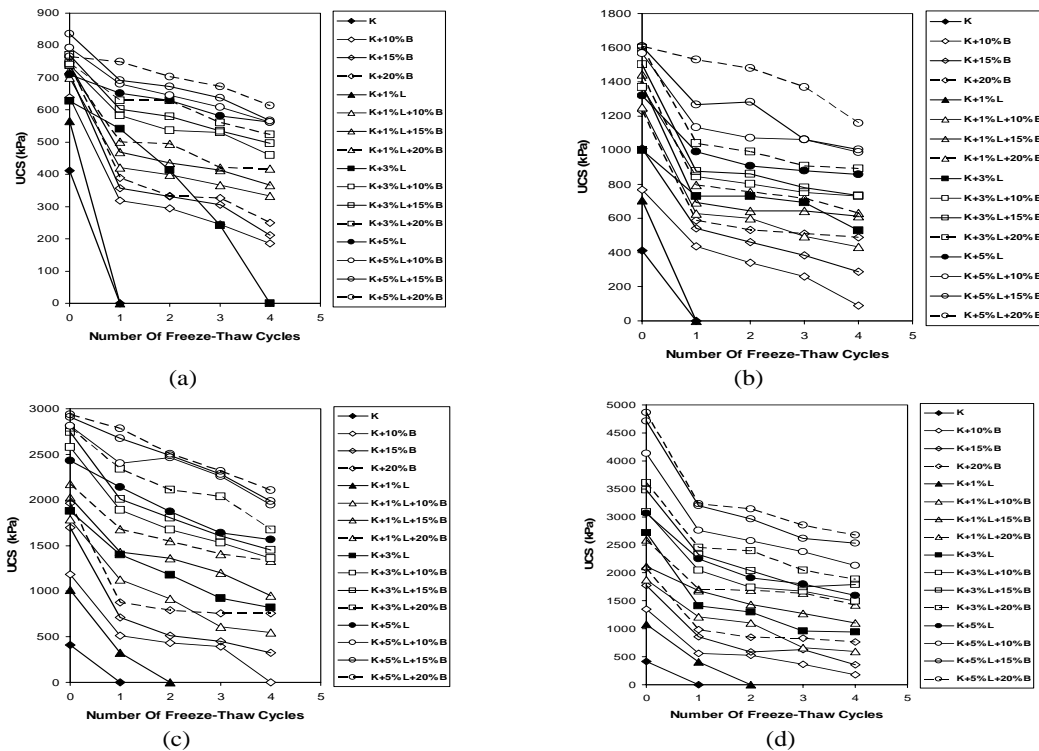
Samples stabilized with 3 and 5% lime and treated with 10, 15 and 20 % BOS slag showed the same trend of changes as mentioned above but of different magnitude. Using higher lime contents combined with BOS slag significantly improves kaolinite resistance to freezing and thawing which is attributed to the formation of more extensive cementitious reaction products. These products not only change the nature of clay particles through modification but also bind the particles promoting greater resistance to deteriorating effects of ice formation.

Summary of the UCS results determined before and after conducting freeze/thaw tests with durability index (i.e. Di) are presented in Table 5. It can be seen that for kaolinite samples treated with a certain percentage of BOS slag, increasing lime content resulted in enhancing the durability index, "Di". For

Fig. 6. UCS versus Number of freeze - thaw cycles for untreated, lime treated, BOS slag treated and BOS slag/lime treated kaolinite cured for (a) 1-day, (b) 7-days, (c) 28-days, (d) 90-days

Table 5. UCS of 90 day cured samples before and after freezing with durability index, Di

C/P (days)	IUCS (kPa)	FUCS (kPa)	Di	IUCS (kPa)	FUCS (kPa)	Di	IUCS (kPa)	FUCS (kPa)	Di
	K+1%L+10%B			**K+3%L+10%B**			**K+5%L+10%B**		
1	700	333	**0.48**	740	459	**0.60**	792	561	**0.71**
7	1252	432	**0.36**	1368	729	**0.53**	1569	989	**0.63**
28	1785	543	**0.30**	2579	1361	**0.53**	2810	1949	**0.69**
90	1872	591	**0.32**	3091	1496	**0.48**	4130	2131	**0.52**
	K+1%L+15%B			**K+3%L+15%B**			**K+5%L+15%B**		
1	740	366	**0.49**	770	496	**0.64**	836	566	**0.68**
7	1384	613	**0.44**	1504	733	**0.49**	1608	1002	**0.62**
28	2029	951	**0.47**	2746	1451	**0.53**	2909	1986	**0.68**
90	2112	1101	**0.52**	3480	1790	**0.51**	4714	2529	**0.54**
	K+1%L+20%B			**K+3%L+20%B**			**K+5%L+20%B**		
1	723	417	**0.58**	744	522	**0.70**	766	613	**0.80**
7	1444	631	**0.44**	1600	891	**0.56**	1608	1157	**0.72**
28	2172	1333	**0.61**	2790	1674	**0.60**	2937	2107	**0.72**
90	2586	1428	**0.55**	3606	1883	**0.52**	4861	2671	**0.55**

Note: **C/P**= Curing Period, **IUCS**=Initial UCS, **FUCS**=Final UCS, **Di**=Durability index

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example, for the K+10%B mixture stabilized with 1, 3 and 5% lime and cured for 1-day, durability indices of 0.48, 0.60 and 0.71 were respectively determined. The higher the durability index, the greater the resistance of a sample to the deteriorating effects of F/T. Considering that the durability index for untreated kaolinite is "zero", the overall conclusion drawn is that the addition of lime and BOS slag to kaolinite either singularly or in combination significantly increases its durability. The durability enhancement is a function of lime and BOS slag content as well as curing period. Poh et al. [23] also reported that durability index in terms of "soaked UCS / unsoaked UCS" for ECC and MM to increase when treated with BOS slag. The amount of improvement was stated to be function of the slag type.

6. Discussion

6.1. Unconfined compressive strength

Results of current investigation showed that both lime and BOS slag have positive effects as stabilizers of kaolinite with lime being slightly more effective in enhancing strength. Following the initial rapid reactions which modify the plastic characteristics of kaolinite, continued chemical reactions occur slowly. The clay constituents, mainly silica and alumina are involved in these reactions. As a result, there is development and growth of cementitious products within and between the clay particles. The cementitious compounds bind the particles together which increases strength and a durable material is obtained [1, 4]. Two mechanisms are generally recognized which are: (**a**) a through solution mechanism and (**b**) a solid-state reaction mechanism. In the former it is thought that in high pH solutions, the solubilities of silica and alumina are increased and that of calcium decreased. As a result silicate and aluminate ions leave the clay particles and enter the lime saturated solution. At a critical concentration, precipitation of calcium and aluminate hydrate phases occurs. The latter "solid-state reaction" involves the diffusion of calcium ions onto the active clay particle surfaces and into the clay layers. There, they react and combine with silicate and aluminate species to produce calcium silicate and aluminate hydrates (i.e. C-S-H, C-A-H, C-A-S-H) [1, 4, 6, 9, 11, 15,16].

Poh et al.[23] reported that the rate of hydration and strength development of BOS slag treated samples occur at a slow rate which could not be substantiated in the current investigation. They suggested that the hydration of BOS slag maybe restricted by the encapsulation of its particles by kaolinite. This hypothesis is based on the restriction of the hydration of cement grains because of the encapsulation of its grains by the hydrophilic and finer-grained kaolinite. Kaolinite forms an impermeable envelop around cement grains thus slowing or perhaps almost stopping the cement hydration [20]. As reported by Poh et al. [23], results of this investigation also showed 20% BOS slag to be most effective in increasing compressive strength and generally the higher the BOS slag content, the greater the strength improvement.

To assess the possibility of BOS slag having some of the cementitious properties of Ordinary Portland Cement (OPC), X-Ray Diffraction analysis (XRD) was carried out. XRD Patterns obtained for BOS slag and OPC are shown in Figure 7. From the comparison of the XRD patterns for OPC and BOS slag, the exhibition of several distinct mineral peaks for both materials are indicative that they have an extensively crystalline structure regardless of the amorphous phases between 2θ angles of 14 and $26°$. The similar mineral phases and crystalline structure of both OPC and BOS slag suggest that the main stabilizing mechanism of BOS slag on the soil is the hydraulic reaction and does not necessarily require the use of an alkaline activator. This means that the increase in strength for soil treated with BOS slag was likely to be due to the self-hydration of the BOS slag, which sets and hardens by reacting with water. The main mineral phases of particular relevance for hydraulic activity of OPC are C_3S, C_2S, C_3A and C_4AF. Shi and Qian [27] and Poh et al. [23] reported the presence of these minerals in BOS slag, supporting its cementitious properties. X-ray diffraction (XRD) analysis of the BOS slag used in the current study and those studied by Poh et al. [23] showed C_2S to be the predominant mineral. This mineral exhibits cementitious properties under normal temperature conditions. According to Lea [17] and Shi [26] C_2S exists in four well-established polymorphs (i.e. α, α', β and γ). Emery [12] and Murphy et al. [19] reported that $\beta–C_2S$ is usually the formation found in BOS slag. Poh et al. [23] also reported the presence of in BOS slag which is shown to be an inert mineral under normal hydration conditions by Lea [17], Taylor [28] and Shi [26]. They stated the potential cementitious property of both $\beta–C_2S$ and $\gamma–C_2S$ can be significantly increased by chemical activators under normal room temperature curing conditions.

Concurrent addition of lime and BOS slag significantly enhanced strength development. This was probably caused by additional modification and pozzolanic reactions between the unconsumed lime from the slag, the added lime and the clay minerals rather than the activating effects of lime on the hydration of BOS slag particles. The alkaline environment promotes the formation of more compounds possessing cementitious properties, which bind the soil particles together (Wild et al. [32]). Poh et al. [23] stated the highly alkaline environment created by dissolution of calcium hydroxide might also break the initial Si-O and Al-O layers which form around the surface of the BOS slag. These layers inhibit water penetration to the slag particle and further dissolution of ions
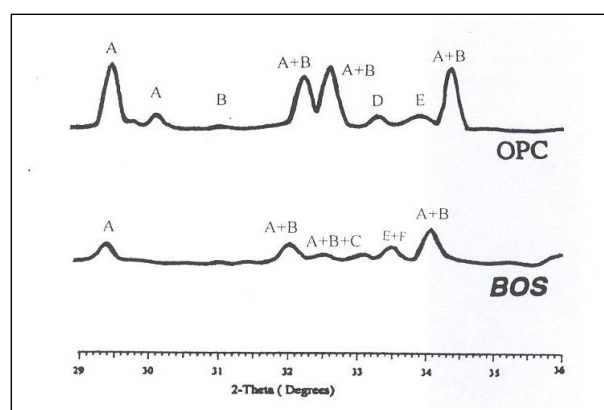

Fig. 7. XRD pattern for OPC and BOS slag (2θ angles, 29-36°): A=C_3S, B=β -C_2S, C= -C_2S, D=C_3A, E=C_2F, F=C_4AF

from the slag to form cementitious products such as C-S-H, C-A-H and C-A-S-H. Therefore, the addition of lime might accelerate the dissolution of the Si and Al ions by breaking the Si-O and Al-O layers so as to allow the continuation of the hydration process.

6.2. Durability

The reaction between clay particles and lime or BOS slag and the formation and growth of cementitious products affect not only strength but also porosity and pore-size distribution which in turn affect permeability and frost resistance. When samples are initially compacted and subsequently cured, their average void size would be smallest. By placing samples in contact with water, they absorbed water mainly through capillary action filling the voids. Freezing causes the water to transform into ice which with lower density would require a greater space to occupy. As ice forms, the particles surrounding the voids would be subjected to expansive pressures (i.e. tensile forces) and thus pushed outwards. This result in reducing effective stresses and an overall increase in the total volume of the soil called "heave". During the heave process, soil particles are displaced from their original positions and the structure of the material is modified. As porosity and pore radii increase, clearly the particles will not reoccupy exactly their original positions when thawing is complete [7, 13]. On thawing the average void size increases and the effect of capillary action on re-wetting and subsequently the amount of water absorbed would be reduced. Therefore, on later freezing and thawing cycle smaller increases in volume and lower decreases in strength would be observed. Results showed that the first freeze-thaw cycle consistently caused the highest deterioration and the reduction in UCS and subsequent cycles proved less effective also reported by Esmer et al. [13]. They concluded that freezing and thawing opens up the pores, reducing the damaging effects of later freeze/thaw cycles.

Considering the results, it is concluded that the improvement in frost resistance of treated kaolinite with lime or BOS slag either singularly or combined is not principally a function of changes in porosity and permeability. It is due predominantly to the development of inter-particle bonding influenced by the amount of reaction products which is a function of the amount of lime, BOS slag, and the silica and the alumina present in the mixture as well as curing period.

7. Conclusions

Results of the investigation showed that using lime and BOS slag either singularly or concurrently for stabilizing kaolinite improves soil properties in terms of increased UCS and durability by resistance to freezing and thawing. The improvements are shown to be dependent on the lime and the BOS slag contents as well as the curing period. Use of these additives for stabilizing kaolinite initiated short term "modification" (i.e. reduced plasticity) and long term "pozzolanic" (i.e. increased strength) reactions which occur concurrently.

In general, lime proved to be a more effective additive in stabilizing kaolinite compared to BOS slag. Their concurrent addition significantly enhanced strength development and resistance to freezing and thawing. These improvements are mainly attributed to the additional modification and pozzolanic reactions between the CaO content of lime and BOS slag and the clay minerals. Breakup of the Si-O and Al-O layers as suggested by Poh et al. [23] may also contribute to the changes. Reactions between the silica and the alumina present in the clay particles and lime or BOS slag cause the formation and growth of cementitious products such as calcium silicate and aluminate hydrates (i.e. C-S-H, C-A-H and C-A-S-H). These compounds affect not only strength development but also permeability and subsequently resistance to F/T. The improvement in frost resistance of kaolinite when treated with lime or BOS slag is not principally a function of changes in porosity but is predominantly due to the development of inter-particle bonding and strength. Particle bonding is influenced by the amount of reaction products which is a function of the lime and the BOS slag contents, the amount of silica and alumina present in the mixture as well as the curing period. XRD analysis of BOS slag showed the presence of mineral phases C_3S, C_2S, C_4AF, and C_2F which also comprise OPC. These indicate that BOS slag possesses some of the cementitious properties of OPC.

Considering the overall results, there is potential for using BOS slag as a stabilizer for fine-grained soils. Whenever an improvement in strength and frost resistance of road materials such as sub-grade or sub-base is required, BOS slag stabilization should be considered as an appropriate alternative. It would be more effective as a stabilizer if used in conjunction with lime.

Acknowledgements

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