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Effects of using silica fume and lime in the treatment of kaolin soft clay

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Abstract. Soil stabilization can make the soils becoming more stable by using an admixture to the soil. Lime stabilization enhances the engineering properties of soil, which includes reducing soil plasticity, increasing optimum moisture content, decreasing maximum dry density and improving soil compaction. Silica fume is utilized as a pozzolanic material in the application of soil stabilization. Silica fume was once considered non-environmental friendly. In this paper, the materials required are kaolin grade S300, lime and silica fume. The focus of the study is on the determination of the physical properties of the soils tested and the consolidation of kaolin mixed with 6% silica fume and different percentages (3%, 5%, 7% and 9%) of lime. Consolidation test is carried out on the kaolin and the mixtures of soil-lime-silica fume to investigate the effect of lime stabilization with silica fume additives on the consolidation of the mixtures. Based on the results obtained, all soil samples are indicated as soils with medium plasticity. For mixtures with 0% to 9% of lime with 6% SF, the decrease in the maximum dry density is about 15.9% and the increase in the optimum moisture content is about 23.5%. Decreases in the coefficient of permeability of the mixtures occur if compared to the coefficient of permeability of kaolin soft clay itself reduce the compression index (Cc) more than L- SF soil mix due to pozzolanic reaction between lime and silica fume and the optimum percent of lime-silica fume was found to be (5%+6%) mix. The average coefficient of volume compressibility decreases with increasing the stabilizer content due to pozzolanic reaction happening within the soil which results in changes in the soil matrix. Lime content +6% silica fume mix can reduce the coefficient of consolidation from at 3%L+6%SF, thereafter there is an increase from 9%L+6%SF mix. The optimal percentage of lime silica fume combination is attained at 5.0% lime and 6.0% silica fume in order to improve the shear strength of kaolin soft clay. Microstructural development took place in the stabilized soil due to increase in lime content of tertiary clay stabilized with 7% lime and 4% silica fume together.

Keywords: soft clay, stabilization, lime, silica fume, consolidation

1. Introduction

There is a long history of adding stabilizers to soils to improve their use for construction purposes. In 1904, the first tests involving soil stabilization were conducted in the USA. Soil stabilization methods caused an increase in road construction which was extensively put to use during the Second World War for roads and runway construction (Bell, 1996). In Malaysia, with the increasing number of national road networks, areas underlain with very soft soils are used for building constructions. The soft soil has become a threat to the construction industry, especially in road construction. As we know, a soft soil is highly compressible and has low shear strength and permeability. Usual construction issues in this area include unsatisfactory bearing capacity, extra post construction settlement and instability during soil removal and embankment forming. In order to construct geotechnical buildings like embankments, structure and roadwork, engineers have to study the soil's properties, cost-effective and environmental aspects (Abdullah and Chandra 1987, Ting *et al.* 1988, Shamshuddin and Anda 2008).

In geotechnical engineering projects, satisfactory soil engineering characteristics play a major part. If a soil does not have sufficient properties, engineers have to find ways to fix the mechanical and chemical problems of local soil. In order to counter issues in geotechnical construction, engineers have to study the engineering properties of the soft clay. A variety of methods like displacement, replacement, reinforcement, and stabilization are the approaches practiced for enhancing the properties of the weak soils (Amiralian *et al.* 2012). In Malaysia, the typical practice ground treatment methods are surface reinforcement, sand or stone column, preloading, prefabricated vertical drains, use of piles and chemical stabilization.

Fattah *et al.* (2015a) reported soil stabilization by which a soil material becomes more stable. This method is applying admixture on the soil. Chemical stabilization methods are adopted in order to provide the soil strength improvement, total and differential settlements and permeability reduction. Soil stabilization is an economical and environmental method implemented to accustom the

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soils' mechanical and chemical characteristics by the pozzolanic reaction (Cuisinier *et al.* 2011).

Soft clay is common occurrence in geotechnical engineering practice. Geotechnical engineers find soft clay really challenging, especially in metropolitan areas, because of its low strength and high compressibility. The use of ground improvement techniques to prepare soft soils for construction has become much more common with cost increases in waste disposal, transport and material procurement. Kaolinite is one of the most commonly found forms of clay mineral in sedimentary and residual soils. A unit sheet of kaolinite, which is approximately 0.7 nm thick, is composed of one aluminum octahedral layer and one silicon tetrahedral layer, joined together by shared oxygen's. A typical particle of kaolinite consists of a stack of sheets forming a stiff hexagonal plate with flat-faced edges. It is about 100 nm in thickness with a breadth/ thickness of about 5 to 10, and a specific surface of 5-15 m^2/g (Terzaghi *et al.* 1996). The chemical composition of kaolinite clay is $Al_2Si_2O_5(OH)_4$. Kaolinite is made up of individual particles that cannot be divided without difficulty and is a layered mineral of silicate. The layered silicate mineral has one tetrahedral sheet linked through oxygen atoms to one octahedral sheet of alumina octahedral. Rocks that are rich in kaolinite are china clay or kaolin. It has low shrink-swell and cation exchange capacity. This white mineral is produced by the chemical weathering of aluminum silicate minerals like feldspar (Budhu 2008).

Lime is often used in soil stabilization in an attempt to increase the shear strength of soils. It has long been used to improve the handling and mechanical characteristics of soils for engineering purposes (Kassim 2009). There are two types of lime which is CaO (quicklime or burnt lime) and $Ca(OH)_2$ (slake or hydrated lime). The use of lime, as chemical additives, is to improve the soil properties as to make it dry, modified and stabilized. It is a well-established construction technique. The reaction between lime and clay minerals is key to the stabilizing effects. Lime stabilization enhance engineering properties of soil, including improved strength, improved resistance to fracture, fatigue and permanent deformation resistance, reduce swelling, and resistance to the damaging moisture effect (Obaid and Hadi 2013). Lime stabilization effects include reduction on soil plasticity, increase in optimum moisture content, decrease in maximum dry density, improvement in compaction of soil, reduction of the soil capacity to swell and shrink and improvement in the CBR value of the soil (Obaid and Hadi 2013).

Past studies examined the effect of lime silica fume stabilizers on the engineering properties of clayey soils. The outcome of these researches was concluded that the plasticity index and swell potential were reduced and California Bearing Ratio value rose notably (Negi *et al.*, 2013). The effect of adding silica fume to silty clayey soils was studied and the investigations indicated that silica fume had great effect on the swelling pressure and compressive strength when silica fume was mixed with the composite samples. There was an increase in the permeability of soil with increase in silica fume content. It was discovered that the development of cracks on the surface of compacted clay samples were reduced by adding silica fume. The addition of silica fume in clay samples reduced the cracks width by 75% (Al-Azzawi *et al.* 2012).

The silica fume can be used as an additive in order to improve the chemical properties of lime treated fine-grained soils. By adding the silica fume into the soil, the reactivity of the mixtures of lime and soil can be improved. Also, the concentration of aqueous aluminium can be reduced in the mixture of silica fume and lime treated soil. This shows that the addition of silica fume is a productive for the control of formation of deleterious products in sulphate bearing soils stabilized with lime or calcium based stabilizers. Lime reacts with any fine pozzolanic components to create calcium-silicate cement with soil particles. This reaction is not soluble in water. The cementing agents are about similar for ordinary Portland cement. The soil attributes were investigated with silica fume as the soil stabilizer. The results obtained were compared with the other stabilizers like fly ash, blast furnace slags and many more. The laboratory studies showed that soil samples acquiring low strength could be treated with silica fume comprising of 5% or 20% of the weight of the dry soil. The treated soil samples indicated great improvement in the strength characteristics (Negi *et al.* 2013). Soil waste disposal has been used because this disposal is cost saving and effective method in order to improve the engineering characteristics of kaolin soil (Negi *et al.* 2013). Chemical stabilizer can adjust the soil properties by the means of solid or liquid additive (Ingles and Metcalf 1972). The salt additives act as catalyzer to reduce the time to improve the engineering properties of soils as well as assist lime to increase the strength of soils. There are two types of salts ordinarily adopted: sodium chloride (NaCl) and calcium chloride ($CaCl_2$). These salts will accelerate the reaction between the lime and organic clay. This is because lime has minor effect in high organic soils (Ingles and Metcalf 1972).

Fattah *et al.* (2015b) used lime (L), silica fume (SF), and lime-silica fume (L-SF) mixes for stabilizing and for considering their effects on the soft clay soil. Their improved technique included improving the behavior of a square footing over the soft clay through grouting the clay with slurry of lime-silica fume before and after installation of the footing. Three different compositions were used for lime (2%, 4% and 6%) and three were used for silica fume (2.5%, 5%, and 10%) and the optimum percentage of silica fume was mixed with the percentages of lime. Several tests were made to test the soil behavior after the addition of lime and silica fume. A 60 ml needle was used as a liquid tank of the lime-silica fume mix for grouting of the soft clay underneath and around the footing. The mass of slurried silica fume typically contains 40 to 60% silica fume. Four categories were studied to stabilize the soft clay before and after the footing construction and for each category, the effectiveness of the grouting was investigated; the effect of the injection hole spacing and depth of grout were investigated too. It was found that there was an increase in the bearing capacity, in the range of 6.58 to 88%, when the soft clay underneath or around the footing was injected with a slurry of lime-silica fume. Due to the increase in the L-SF grout, the depth of the grouting holes around the footing will also increase causing the footing bearing capacity to increase too. The grouting near the footing with a distance of 0.5 B is more effective than grouting with a distance of 1.0 B due to the shape of the shear failure of soft clay around the footing.

The objective of the present study is to use lime and silica fume for stabilization of kaolin clayey soil. It is intended to determine the optimum percentages of these materials to improve the compressibility characteristics of soil.

Table 1 Physical properties of Kaolin used in the study

Test	Value	Specifications
Consistency Limits: •Liquid limit, L.L, % •Plastic limit, P.L, % •Plasticity index, P.I, %	 40 28 12	 BS 1377:1975, Test 2(A) BS 1377:1975 Test 3
Specific gravity	2.64	BS 1377:1975, Test 6 (B)
Soil Compaction: •OMC (Optimum Moisture Content), •MDD (Maximum Dry Density), G/cm³	20% 1.63	BS 1377:1975, Test12
Classification According to Unified Classification System	ML	

Table 2 Chemical composition of Kaolin

No.	Parameter	Results	Unit	No	Parameter	Results	Unit
1	Sio2	66.11	%	10	BaO	0.04	%
2	$Al2O_3$	19.25	%	11	SO3	0.03	%
3	K2O	2.85	%	12	Rb2O	0.01	%
4	MgO	1.23	%	13	ZnO	49	ppm
5	$Fe2O_3$	0.73	%	14	$Y2O_3$	34	ppm
6	TiO_2	0.61	%	15	CuO	29	ppm
7	$P2O_5$	0.41	%	16	NiO	24	ppm
8	ZrO_2	0.09	%	17	$Nb2O_5$	22	ppm
9	CaO	0.08	%	18	$Ga2O_3$	16	ppm

Table 3 Chemical composition of silica fume

No.	Parameter	Results	Unit	No.	Parameter	Results	Unit
1	SiO_2	74.02	%	11	Cl	0.15	%
2	K_2O	4.27	%	12	MnO	0.13	%
3	MgO	3.73	%	13	PbO	0.07	%
4	Na_2O	0.89	%	14	Rb_2O	0.02	%
5	SO_3	0.87	%	15	CuO	93	ppm
6	CaO	0.83	%	17	Ga_2O_3	53	ppm
7	Fe_2O_3	0.71	%	18	NiO	22	ppm
8	Al_2O_3	0.45	%	19	GeO_2	22	ppm
9	ZnO	0.39	%	20	ZrO_2	2	ppm
10	P_2O_5	0.37	%	21	Moisture	1.26	%

Table 4 Chemical composition of lime

No.	Parameter	Results	Unit	No.	Parameter	Results	Unit
1	CaO	75.77%	%	9	SrO	0.03%	%
2	MgO	3.70%	%	10	MnO	0.03%	%
3	SiO_2	0.31%	%	11	SO_3	0.02%	%
4	P_2O_5	0.20%	%	12	TiO_2	0.01%	%
5	Fe_2O_3	0.16%	%	13	ZnO	95	ppm
6	Al_2O_3	0.12%	%	14	CuO	46	ppm

Table 4 Continued

No.	Parameter	Results	Unit	No.	Parameter	Results	Unit
7	Cl	0.04%	%	15	ZrO_2	3	ppm
8	K_2O	0.03%	%	16	Moisture	0.33	%

2. Experimental work

Four materials are used in this study; soil, lime, silica fume and water. Kaolin clay, which is frequently utilized in the production of ceramics, tooth paste, fodder, paper and dye, was used as untreated soil. As it loses moisture very gradually and is easily managed, kaolin clay has a wide range of uses. It is made up of repeated layers of elemental silica-gibbsite sheets with each layer measuring roughly 7.2 A° in thickness. The layers are bound together by hydrogen bonds and secondary valence forces (Murthy 2002). The kaolin group, which is a hydrous alumina-silicate, has the general chemical make-up formula $Al_2(Si_2O_5)(OH)_4$. Information on the physical properties and chemical composition of kaolin clay utilized for this investigation are available in Tables 1 and 2, respectively.

Silica fume is also termed as micro-silica. Silica fume is utilized as a pozzolanic material in the application of soil stabilization. It is as an industrial waste created from the smelting process of silicon metal and ferrosilicon alloy. It is retrieved as a by-product from making silicon and ferrosilicon alloys during the reduction of high-purity quartz with coal in electric furnaces. Before the mid-1970s, silica fume was allowed to be emitted into the air. After silica fume was considered as non-environmental friendly, collection and landfilling of silica fume were done. It became economically accepted to be used in a variety of applications. In the field of civil engineering works, silica fume has been adopted as a binder material with cement materials or others for the application of the soil stabilization (Obaid and Hadi 2013). Table 3 displays the chemical properties of silica fume utilized for this research.

The lime selected for this research is an industrial hydrated lime. This lime is deemed applicable as a neutralizing agent for water and sewage treatment, as a binder in mortars, as a soil stabilizer, and as a means for maintaining alkaline conditions during the processing of minerals. Hydrated high calcium lime, Ca $(OH)_2$, which is accessible locally, is an established stabilizing agent. In comparison to other types of limes, hydrated lime has proven to be superior in the area of soil stabilization. This is attributed to its trouble-free usage and fine particle size which allows for easy mixing with soil (Amiralian *et al.* 2012). To complete its list of benefits, hydrated lime is also less of a safety hazard. Table 4 displays the chemical properties of lime utilized for this research.

2.1 Laboratory testing

In this study, there were five types of soil samples tested in order to get their physical properties before proceeding to the main test and consolidation test. Thirty physical properties tests for kaolin and the mixtures of kaolin with 6% silica fume with various percentages of lime: Sieve

Fig. 1 Materials of this study

Fig. 2 Mixing of kaolin, lime and silica fume

analysis, hydrometer test, specific gravity test, standard Proctor test, Atterberg limit test and falling head permeability test.

2.2 Preparation of soil mixtures for testing

The materials required in this study were kaolin grade S300, lime and silica fume as shown in Fig. 1. The amount of silica fume and lime required were derived from the dry weight of the kaolin soil itself. In total, there were five specimens required for this study. The kaolin sample acts as the control of the study. The other four soil samples were the mixture Fig. 2. They were dried in the oven at 105^{o}C before mixing. After 24 hours, kaolin soil, lime and silica fume were mixed under dry condition to prepare mixtures by using a soil mixer of kaolin mixed with 6% of silica fume and various percentages of lime (3%, 5%, 7% and 9%).

2.3 Atterberg limits

The purpose of carrying out Atterberg limits tests is to calculate and recognize the plasticity scale in a mathematical context. This is crucial particularly when it concerns clay as its moisture content corresponds with plastic consistency. This test was executed on kaolin clay with a particle dimension lesser than 63 μm. Atterberg limits were further separated into two distinct experiments, namely, liquid limit (w_L) and plastic limit (w_P) tests. The liquid limit test was carried out in compliance with the BS1377 Part 2: 1990: 4.3 with the utilization of the cone penetration technique, while the plastic limit test was executed in accordance with the BS1377 Part2: 1990: 5.3. The mathematical disparity between the liquid and plastic limit is known as the plasticity index (ASTM, 2003). The outcome is classified according to the constrain violation in a descending order of the feasibility solution. The solutions are grouped in accordance with the feasible solution preferred and the infeasible solution. In a situation where two feasible solutions exist, the one with a superior objective function is preferred. And if no feasible solution exists, the one with the lowest constrain violation is preferred.

2.4 Specific gravity

The specific gravity of kaolin was computed through a small pycnometer test. In a small pycnometer, which had been half-filled with distilled water, were placed samples with predetermined masses. The small pycnometer was then positioned within a vacuum chamber which proceeded to remove the air present in the sample which is made up of a mixture comprising the material and distilled water. The sample was left undisturbed for a day, following which distilled water was added into the pycnometer to the brim (ASTM D854-02 2002).

2.5 Compaction test

A standard compaction test was conducted to study the impact of varying combinations of lime on soft clay (kaolin soil) behaviour. Details on the standard compaction test procedure are available in the (ASTM D1557-02). These tests were conducted to establish the highest dry density (MDD) and the best moisture content (OMC) of the soils. The samples were compacted in a 105 mm-diameter mould utilizing the standard Proctor effort. The dry unit weight and moisture content of each sample were determined through the achieved unit weight at the optimum moisture point. This was ascertained by the intersection of slopes derived from the wet-side and dry-side soil of the compaction curve from a minimum of five compaction tests.

2.6 Consolidation test

An automatic consolidation device was used to carry out a series of tests on the saturated and partially saturated samples in accordance with ASTM D2435. Usual practice of consolidation tests followed and the results were analysed based on the “void ratio-effective stress curves” and “settlement-log time curves” (Cuisinier *et al.* 2011, Amirialian *et al.* 2012). Some parts of this data were achieved in previous researches in this area.

2.7 Hydraulic conductivity tests

Swelling in the samples was prevented with compaction mould permeameters, compatible with ASTM standard D5856. The samples were compacted directly inside the compaction mould to avoid limit preferential paths forming along the side of the samples. Two porous stone were inserted, one at the top and the other at the bottom of the sample. In all the experiments, de-aired tap water was used.

To avoid any air being trapped, the flow was applied

Fig. 3 Scanning electron microscope (SEM)

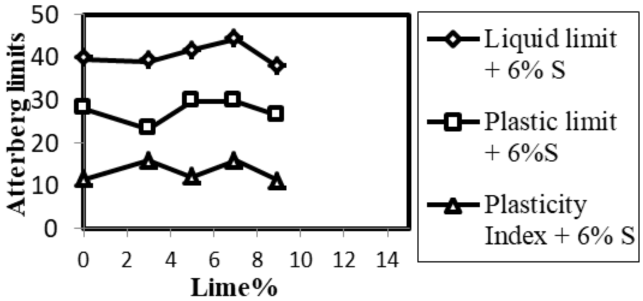

Fig. 4 Effect of lime percentages with 6 % of silica fume on Atterberg limits of soil samples

directed from the lower base to the upper side of the sample. A constant hydraulic head of 2 m, with a hydraulic gradient of 17, was used to ensure proper fluid circulation, the. At the end of the circuit, the fluid volume was checked continuously. On a daily basis, fluid circulation was interrupted to determine the hydraulic conductivity with the falling head procedure. The test was finalized after four consecutive hydraulic conductivity measurements, with a tolerance of ±5% obtained.

2.8 Scanning electron microscope (SEM)

A Zeiss Evo 50XVP scanning electron microscope (SEM) was used to look into the microstructure and morphology of the platinum-coated specimens. This investigation was conducted utilizing different accelerating voltages of 15 kV and 20 kV. Fig. 3 shows the secondary electron detector and a backscattered electron detector used for scanning the samples.

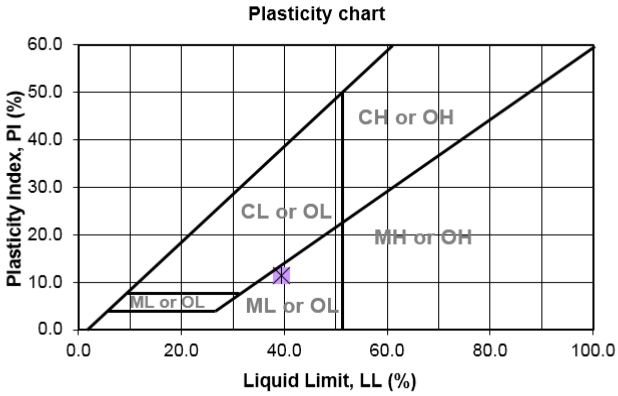

Fig. 5 Plasticity chart for kaolin and kaolin mixed with lime and silica fume (ASTM D2487-2002)

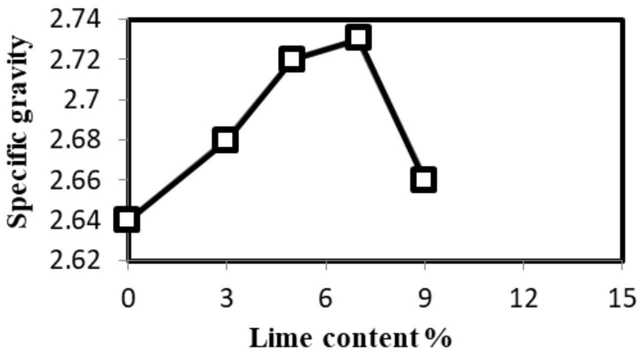

Fig. 6 Relationship between specific gravity with the percentages of lime for the controlled samples and the kaolin mixed with lime and 6% silica fume

3. Results and discussion

3.1 Index properties

The effect of adding lime-SF to the soft soil on Atterberg limits is shown in Fig. 4. As shown in this figure, the liquid limit is increased slightly from 0% to 7% lime content, with 6% silica fume. This is due to the excess lime content (and a decrease in the other reaction material). In 7% lime, there is a decrease in the liquid limit of the Pozzolanic reactions that occur between lime and silica fume; this forms calcium-silicate that cements with soil particles, and in turn causes flocculation/agglomeration of the clay particles, as well as a reduction in the liquid limit.

Besides, the plastic limit is approximately still constant, which indicates that the lime and silica fume content is necessary to achieve the required modification. The reason for this could be explained based on the soil type, the relative amount of silicate clay mineral in the samples, and the associated exchangeable cations, as stated by (Fattah *et al.* 2014).

Based on Fig. 5, and on the Unified Soil Classification System (USCS), it can be observed that the soil classification is still in the ML zone for the soil stabilized with all lime and silica fume contents, mainly due to the small particle sizes and stabilizer amount. A reduction in plasticity occurs in the case the clayey soil is mixed with lime and silica fume, due to converting the soil to the granular mass. In this case, the stronger bonds between the soil particles occur because of the cation exchange that takes place between negative ions on the surface of the clay particles and the calcium ions of the lime.

3.2 Specific gravity

The specific gravity of kaolin and mixtures of K-SF-L was determined by using small pycnometer method. The specific gravity of kaolin was found to be 2.62, which was in the range of particle density of most soil. Generally, the specific gravity of particles of most soil lies between 2.60-2.80 (Head 1986). From previous research works the specific gravity of kaolinite is known to be 2.66 and 2.62, which indicates that kaolinite mineral is part of the composite of kaolin.

Specific gravities (Gs) for the untreated and treated soils were determined, and the results are plotted in Fig. 6. As shown in the figure, the specific gravity of the controlled sample (2.64) was increased with the lime content to 2.72, at 5% lime with 6% silica fume. This increase is due to the molecular rearrangement of the soil matrix, which is caused by the higher density of lime and silica fume, compared to that of the kaolin soft clay. Moreover, the specific gravity remained constant for the samples of stabilized soil containing 5% to 7% lime with 6 % silica fume. Next, the specific gravity of the soil samples decreased from 2.73 to 2.66 for the samples of stabilized soil containing 7% to 9% lime with 6 % silica fume. The decrease in specific gravity of the soil with the increase in lime content was due to the low specific gravity of lime and silica fume.

3.3 Compaction characteristics

Fig. 7 presents the relation between the dry density versus moisture content for kaolin soft clay mixed with 6 % silica fume, and various percentages of lime (3%, 5%, 7% and 9%). Fig. 8 presents the influence of the addition of 6% silica fume and various percentages of lime on the optimum moisture content. The optimum water content increases with the increase in the percentage of lime with 6% silica fume in the kaolin soft clay. The optimum water content of the soil samples rises from 20.0% to 24.7%. The increase in the optimum water content can be caused by the absorption of water by lime and silica fume. This indicates that the mixtures of kaolin-lime-silica fume require a higher amount of water for compaction.

Fig. 9 presents the influence of various percentages of lime content with 6% silica fume on the maximum dry density of soil samples. The addition of the lime and silica fume to the kaolin soft clay causes a decline in the maximum dry density of the soil samples (from 1.504 g/cm^3 to 1.415 g/cm^3 at 9% lime and 6% silica fume). This can be attributed to the replacement of soil by the lime and silica fume in the mixture, which has lower values of dry density (Harichane and Kenai 2012). Another likely reason for this is that the coating of the soil by lime and silica fume results in large particles with larger voids, as stated by Sharma *et al.* (2012). The reduction in dry density could be due to the ion exchange, flocculation and agglomeration effect of soil particles, which reduce compatibility, making soil particles more friable for compaction, hence, the reduced unit weight of the treated soil.

3.4 Permeability test results

Fig. 10 shows the permeability test results of the mixture of kaolin and lime-silica fume. Das (2013) mentioned that the results were stabilized in the range of 1×10^{-13} to 1×10^{-7} m/sec for kaolin and lime-silica fume specimens. Based on the yielded results, the value of the permeability coefficient of kaolin obtained from the falling head permeability test was 4.82×10^{-12} m/s. The coefficients of permeability of the mixture of K+6%SF+3%L, K+6%SF+5%L, K+6%SF+7%L and K+6%SF+9%L were 1.93×10^{-12} m/s, 6.75×10^{-13} m/s, 1.17×10^{-12} m/s and 1.96×10^{-12} m/s, respectively. The coefficient of permeability of the specimens is reduced to 6.75×10-13 m/s at 5% lime content; beyond this point, the coefficient of permeability

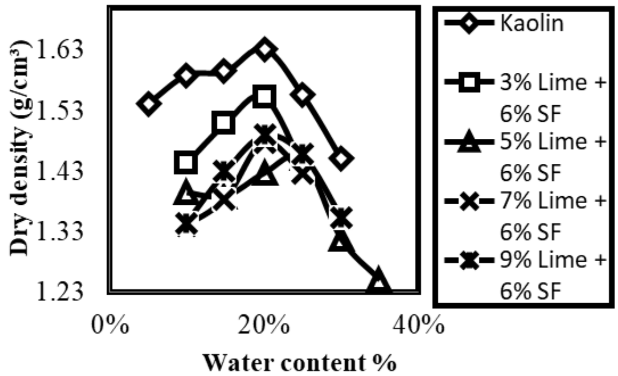

Fig. 7 Changes of the dry density with water content for soil samples stabilized with 6% of silica fume and different percentages of lime content

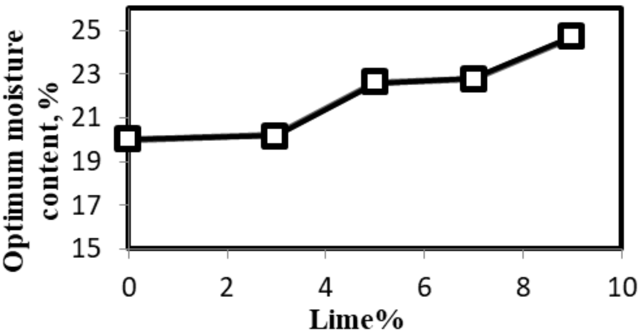

Fig. 8 Influence of 6% silica fume and different percentages of lime on the optimum moisture content of the samples

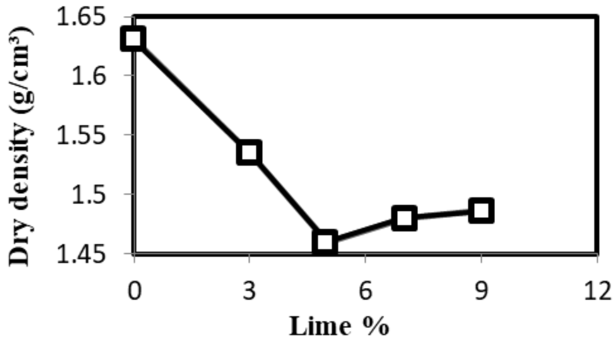

Fig. 9 Influence of 6% silica fume and different percentages of lime on the maximum dry density of kaolin soil

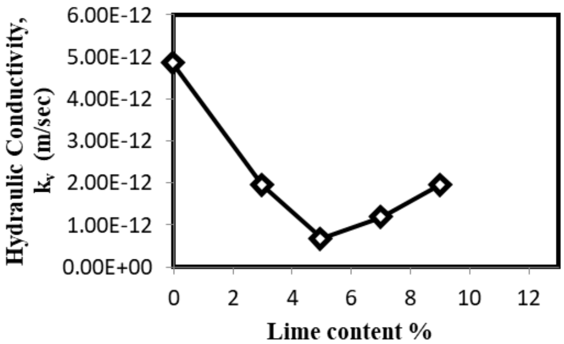

Fig. 10 Graph of coefficient of permeability against the percentages of lime for kaolin and mixture of K-6%SF-L

increases to 1.96×10^{-12} m/s at 9% lime content. As shown in Fig. 10, there is a significant decrease in the permeability of soil samples from 4.82×10^{-12} m/s to 6.75×10^{-13} m/s for the samples of stabilized soil containing 0% to 5% of lime. Exceeding this value, the coefficient of permeability of the soil samples increased from 6.75×10^{-13} m/s to 1.96×10^{-12} m/s for the samples of stabilized soil containing 7% to 9% lime.

Several prior studies only supplied a very limited volume of data regarding the hydraulic conductivity of the mixtures of kaolin stabilized with lime and silica fume. Nalbantoglu and Gucbilmez (2002) mentioned that the coefficient of permeability of the treated stabilized soils increased. Contrarily, Locat *et al.* (1996) pointed out that the hydraulic conductivity of the treated stabilized soils decreased. Other than that, according to Head (1994) the value obtained for kaolin shows the impermeable degree of permeability of kaolin, indirectly indicating its poor drainage characteristic, which generally corresponds to intact clay (practically impermeable). The same is true for the mixtures of kaolin clay mixed with lime and silica fume.

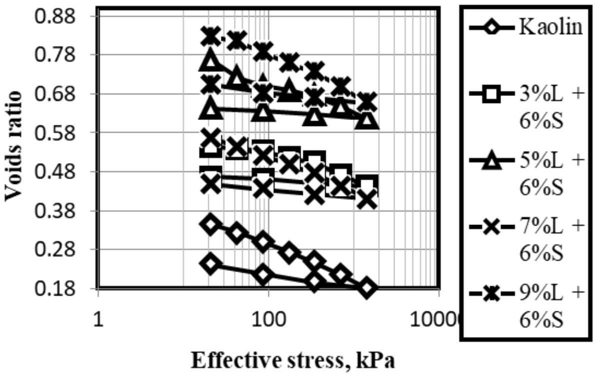

Fig. 11 Void ratio versus effective stress curves from the consolidation test on soil stabilized with different LSF percents

Table 5 Relationship between compression index (c_c) and lime for kaolin mixed with 6% SF

Lime	0	3% + 6%	5% + 6%	7% + 6%	9%+6%
c_c	0.084	0.047	0.042	0.077	0.082

Table 6 Relationships between coefficients of volume compressibility (m_v) (m^2/MN) and Lime content%+6% silica fume mix

Load kPa	Kaolin + lime % + 6%SF				
	0	3%L+6%SF	5%L+6%SF	7%L+6%SF	9%L+6%SF
22.2	10.00	6.61	5.80	5.65	3.58
44.4	0.70	0.13	0.60	0.65	0.34
88.8	0.39	0.12	0.48	0.32	0.36
177.6	0.23	0.11	0.07	0.17	0.17
355.3	0.12	0.05	0.05	0.09	0.07
710.6	0.07	0.05	0.05	0.06	0.06
1421.1	0.04	0.03	0.03	0.03	0.04
Average	1.65	1.014	1.011	0.995	0.6085

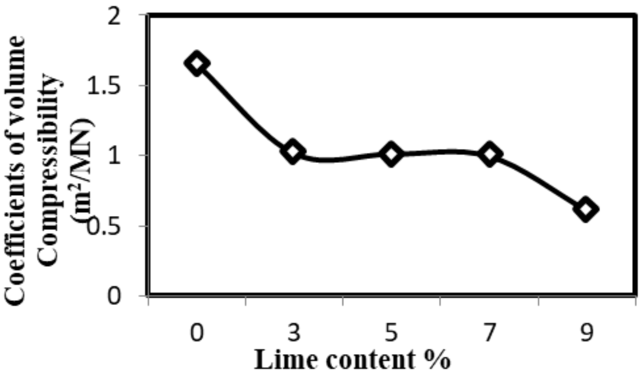

Fig. 12 Effect of Lime content +6%SF on the average coefficient of volume compressibility

3.5 Consolidation test results

Fig. 11 shows the effect of L-SF on the e-log σ_v curve, while Table 5 summarizes the results of the consolidation test under lime-silica fume stabilizer. It can be noticed that lime-silica fume mixes can reduce the compression index c_c at a higher rate than the L-soil mix and SF-soil mix, due to the pozzolanic reaction between lime and silica fume; the optimum percent of Lime-silica fume was found to be 5% L+6% SF mix at the compression index c_c. The increase in the compression index at 7% L+6% SF and 9% L+6% SF is due to a reduction in silicon content in the LSF pozzolanic reaction.

3.6 Coefficient of volume compressibility

The coefficient of volume compressibility, m_v, is defined as the volume change per unit increase in effective stress for a unit volume of soil (Craig 2013). The volume change may be expressed in terms of void ratio or specimen thickness. This parameter is very useful to estimate the primary consolidation settlement. Table 6 and Fig. 12 show the results of the coefficient of volume compressibility of kaolin mixed with lime, silica fume and a combination of them. It can be noticed that the average compressibility coefficient, which decreases with an increase in the stability of the content until 9%+6% L-SF. This could probably be due to the pozzolanic reaction taking place within the soil, which in turn changes the soil matrix. The free calcium of the lime is exchanged with the adsorbed cations of the clay mineral, resulting in a reduction in the size of the diffused water layer surrounding the clay particles. This reduction in the diffused water layer allows the clay particles to come into closer contact with one another, causing flocculation/agglomeration of the clay particles, which transforms the clay into a more silt-like or sand-like material.

3.7 Coefficient of consolidation (cv)

The coefficient of consolidation relates to the time it takes for an amount of consolidation to take place (Bowles 1979). The coefficient of consolidation is governed by two factors; the amount of water squeezed out, and the rate at which that water can flow out. The lower the value of c_v in

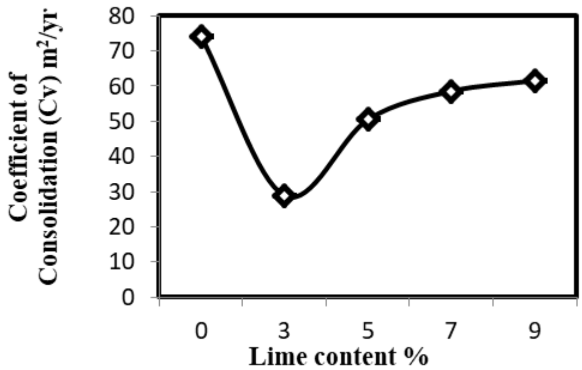

Fig. 13 Coefficient of consolidation of the compacted soil treated with lime-silica fume mix

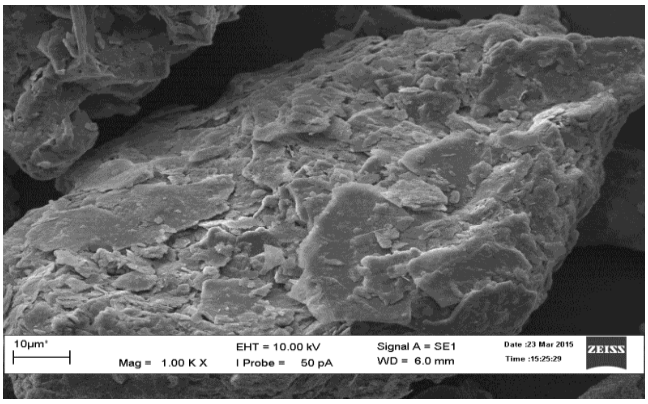

Fig. 14 SEM micrograph of kaolin particles

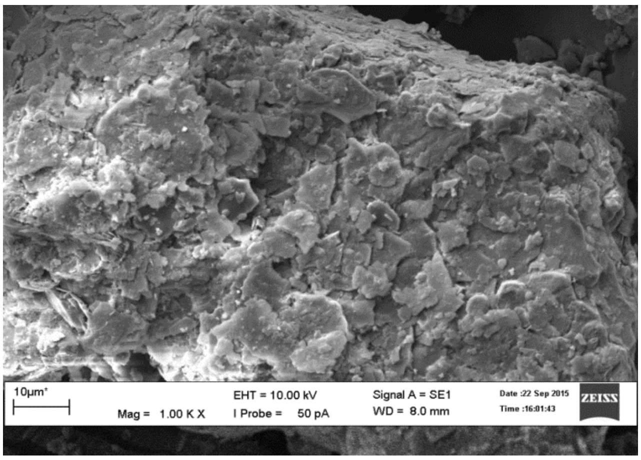

Fig. 15 SEM micrograph of 9% L + 6% SF particles

the soil, the less the grain size, hence, permeability. It is intended to study the effect of stabilizer content on the coefficient of consolidation at a pressure of 355.5 kPa. Fig. 13 shows that the lime content and 6% silica fume mix can reduce the coefficient of consolidation from 74.14 m^2/yr to 28.91 m^2/yr at (3% L+6% SF); after that, there is an increase from 50.50 m^2/yr to 61.55 m^2/yr at (9% L+6% SF).

3.6 Scanning electron microscope (SEM) result

The scanning electron microscope is among the ideal techniques for investing the structure of a material. It provides three-dimensional image with a high resolution. The morphological and elemental characteristics of kaolin, lime, silica fume and L-SF mix were examined with SEM analysis by voltage energies (i.e., 10.0 kV). The secondary electron micrographs, and scanning with a combination of secondary electrons and backscattered electrons, were conducted.

Figs. 14 and 15 show the SEM micrograph of kaolin and kaolin mixed with lime at a focus of 10 μm with 10.0 kV of voltage energy. The secondary electron SEM micrograph of kaolin mix lime- SF particles revealed the polygonal structure of mixtures, as well as its brightness in color.

Fig. 15 shows a micrograph of tertiary clay stabilized with a combination of 9% lime and 6% silica fume. The micrograph illustrates the silt-fine, sand-like structure (open fabric), which is the result of flocculated arrangements. The hydration reaction compounds coated both the relics of clay and silica fume particles. The microstructure is characterized by a relatively high porous system where the pore spaces are relatively large.

4. Conclusions

• A reduction in plasticity (liquid limit and plasticity index) happens when the clayey soil is mixed with lime and silica fume due to converting the soil to the granular mass**.**

• The specific gravity of the kaolin increased from 2.62 as the lime and silica fume are added to 2.72 at 5% lime with 6% silica fume.

• When there is addition of lime and silica fume to kaolin soft clay, there is a decline in the maximum dry unit weight of the soil from 15.04 kN/m^3 to 14.15 kN/m^3 at 9% of lime and 6% silica fume.

• The coefficient of permeability of mixture of K+6%SF+3%L, K+6%SF+5%L, K+6%SF7%L and K+6%SF+9%L were 1.93×10^{-12} m/s, 6.75×10^{-13} m/s, 1.17×10^{-12} m/s and 1.96×10^{-12} m/s, respectively. The coefficient of permeability of the specimens reduced at 5% lime content and beyond this point, the coefficient of permeability increases. There is a noticeable decline in the permeability of soil samples from 4.82×10^{-12} m/s to 6.75×10^{-13} m/s for the samples of soil stabilized with 0% to 5% of lime. Beyond that point, the coefficient of permeability of the soil samples increased from 6.75×10^{-13} m/s to 1.96×10^{-12} m/s for samples of soil stabilized with 7% to 9% lime.

• Lime-silica fume mixes can reduce the compression index (Cc) more than L-soil mix and SF-soil mix due to pozzolanic reaction between lime and silica fume and the optimum percent of lime-silica fume was found to be (5% + 6%) mix. The average coefficient of volume compressibility decreases with increasing the stabilizer content due to the pozzolanic reaction that take place in the soil which in turn changes the soil matrix. Lime content + 6% silica fume mix can reduce the coefficient of consolidation from at 3%L + 6%SF, thereafter there is an increase from at 9%L + 6%SF mix.

• Microstructural development took place in the stabilized soil due to increase for lime content of tertiary clay stabilized with 7% lime and 4% silica fume together. The micrograph shows a new formation of mineral crystal (as a product of pozzolanic reaction) within the pore spaces.

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