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UNDRAINED SHEAR STRENGTH OF SOFT CLAY MIXED WITH DIFFERENT PERCENTAGES OF LIME AND SILICA FUME

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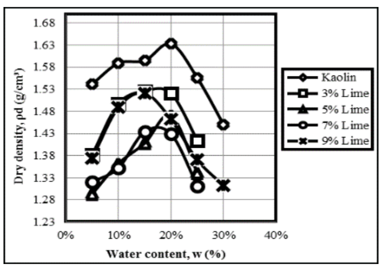
Graphical abstract



Abstract

Soil stabilisation, as a cost-effective and environmentally friendly method, is used in the building of systems like roads, dams, canals and river levels. Chemical stabilisation of soil is carried out by adding binder or by-products like lime and silica fume to the soil thereby modifying the geotechnical performance of the soil. Various researchers have carried out research on the properties of soil, such as its compaction, compressibility, hydraulic conductivity, and strength characteristics. The focus of the study was the determination of the physical properties of the soft clay used and the strength of soft clay (kaolin) mixed with 6 % of silica fume and various percentages (3 %, 5 %, 7 % and 9 %) of lime. Unconfined compression test was carried out on the soft clay and the mixtures of soft clay-lime-silica fume to investigate the effect of lime stabilisation with silica fume additives on the unconfined compressive strength of the mixtures. Based on the results obtained, all soil samples were indicated as soils with medium plasticity. From 0 % to 9 % of lime with 6 % of silica fume, the decreased in the maximum dry density was by 5.92 % and the increased in the optimum moisture content was by 23.5 %. Decreased in the coefficient of permeability of the mixtures occurred when compared to the coefficient of permeability of the soft clay itself. The improvement in shear strength of soft clay mixed with 6 % silica fume and 5 % lime was 29.83 % compared to the shear strength of the soft clay sample. The optimal percentage of lime-silica fume combination was attained at 5.0 % of lime and 6.0 % of silica fume in order to improve the shear strength of soft clay. It can be concluded that lime-silica fume additives improved the unconfined compressive strength of the soft clay.

Keywords: Undrained shear strength; soil stabilisation; soft clay; silica fume; lime

Abstrak

Penstabilan tanah, sebagai kaedah kos efektif dan mesra alam sekitar, digunakan dalam pembinaan sistem seperti jalan, empangan, terusan dan aras sungai. Penstabilan kimia pada tanah dijalankan dengan menambahkan bahan pengikat atau bahan buangan seperti kapur dan wasap silika kepada tanah dan dengan itu mengubahsuai prestasi geoteknik tanah. Ramai penyelidik telah menjalankan kajian tentang sifat tanah, seperti pemadatan, mampatan, keberaliran hidraulik dan kekuatan. Fokus kajian ini adalah untuk menentukan sifat fizikal tanah liat lembut yang dikaji dan kekuatan tanah liat lembut (kaolin) yang dicampurkan dengan 6 % wasap silika dan pelbagai peratus kapur (3 %, 5 %, 7 % and 9 %). Ujikaji mampatan tak terkurung dijalankan pada tanah liat lembut dan campuran tanah liat lembut-kapur-wasap silika untuk menyiasat kesan penstabilan kapur dengan campuran wasap silika pada kekuatan mampatan tak terkurung terhadap campuran tersebut. Berdasarkan keputusan yang diperolehi, kesemua sampel didapati merupakan tanah dengan berkeplastikan sederhana. Dari 0

% hingga 9 % kapur dengan 6 % wasap silika, penurunan dalam kepadatan kering maksimum adalah pada 5.92 % dan kenaikan dalam kandungan lembapan optimum adalah pada 23.5 %. Penurunan dalam kebolehtelapan pada campuran berlaku berbanding kebolehtelapan tanah liat lembut itu sendiri. Penambahbaikan dalam kekuatan ricih pada campuran yg distabilkan adalah 29.83 % berbanding kepada kekuatan ricih sampel tanah liat lembut. Peratusan optima bagi kombinasi kapur-wasap silika yang diperolehi adalah pada 5 % kapur dan 6 % wasap silika bagi menambahnaik kekuatan ricih untuk tanah liat lembut. Ia boleh disimpulkan bahawa bahan tambah kapur-wasap silika dapat menambahbaik kekuatan mampatan tak terkurung bagi tanah liat lembut.

Kata kunci: Kekuatan ricih tak tersalir; penstabilan tanah; tanah liat lembut; wasap silika, kapur

1.0 INTRODUCTION

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 stabilisation are the approaches practiced for enhancing the properties of weak soils. In Malaysia, the typical practice ground treatment methods are surface reinforcement, sand or stone column, preloading, prefabricated vertical drains, use of piles and chemical stabilisation.

Soil stabilisation is a process where soil material becomes more stable. Application of chemical method to stabilise organic clay is sufficiently reliable to modify the soil properties by means of some solid or liquid additive and in many cases it is the only possible measure for strengthening weak soil [1]. Various soil stabilisation techniques are suitable for stabilisation involving expansive clayey soil. These kinds of methods consist the application of chemicals, soil replacing, rewetting, moisture control, compaction control, surcharge loading and thermal methods [2,3]. Instead of using chemical product, recycled or reused materials usually are might offer more economical options for a variety application of soil stabilisation.

Chemical stabilisation methods are adopted in order to provide the soil strength improvement, total and differential settlements and permeability reduction. Soil stabilisation is an economical and environmental method implemented to accustom the soils' mechanical and chemical characteristics by the pozzolanic reaction [4,5]. Lime and silica fume are very good stabilizing agent to improve soils characteristics and also the performance of the soils itself. By using silica fume as one of the materials, it can help us getting rid of pollution. This is because silica fume is one of the industrial wastes nowadays. In addition, silica fume also have the ability to reduce the effects regarding freezing and also thawing cycles on the strength as well as permeability within the landfill liner and cover systems [6]. Lime provides an economical as well as powerful way of chemical improvement. Most of the countries around the world usually use lime as a stabilizing agent to improve the soils characteristics. Lime stabilisation is actually popular regarding improving traffic ability, loading capacity of foundations of road and embankment and also for erosion control. Lime creates long lasting improvements in soils characteristics offering structural benefits. There are diversified types of usable admixtures. The chemical reaction between soils and admixtures boosts the physical and engineering properties. Replacement of soft soil with suitable soil is still extensively utilised when construction has occurred on soft soil deposit. This approach leads to a costly design as large amount of suitable soil are required to be transported. When there is an addition of admixtures to the soil in the appropriate quantities, the properties of the soil can be improved. The types of admixtures applied for soil stabilisation are dependable on the types of soils, the required properties, the environmental condition and the cost-effectiveness consideration.

2.0 SAMPLE PREPARATION

2.1 Kaolin-Lime-Silica Fume Mixture Preparations

The materials required in this study were kaolin grade S300, lime and silica fume as shown in Figure 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 Figure 2. They were dried in the oven at 105°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 %).

2.2 Specimen Preparation for Unconfined Compression Test

The soil sample was oven-dried to obtain its initial dry weights. Then, the sample was mixed with the required amount of water at optimum water content. After mixing, the sample was compacted to predetermined density in a cylindrical steel mould of dimensions 100 mm high x 50 mm diameter. The specimen was prepared by using the customized steel mould of 180 mm height and 50 mm internal diameter. By using a steel hammer, the specimen is compacted in three layers with five free fall blows for each layer.

3.0 RESULTS AND DISCUSSION

This part presents the results and analysis from the laboratory tests conducted on kaolin S300, kaolin S300 mixed with 6% of silica fume and 3%, 5%, 7% and 9% of lime respectively. The summary of the properties of the kaolin and the mixtures of kaolin-lime-silica fume is tabulated in Table 1. The tests conducted were sieve analysis, fine analysis, specific gravity test, falling head permeability test, standard proctor test and Atterberg limits test. The tests were done in order to prove kaolin clay and the mixtures have the similarity characteristics of soft clay. The main objective of this study was to determine the undrained shear strength of kaolin clay and kaolin clay mixed with various percentages of lime and 6 % of silica fume. To do so, unconfined compression test (UCT) was used to find out the required information for the study.

Table 1 Summary of soil samples properties

Properties	Kaolin	3%L + 6%SF	5%L + 6%SF	7%L + 6%SF	9%L + 6%SF
Liquid Limit, w_L (%)	39.50	39.10	41.70	44.20	37.40
Plastic Limit, w_P (%)	28.00	27.39	29.67	28.26	26.33
Plasticity Index, I_P	11.50	11.71	12.03	15.94	11.07
Specific Gravity, G_S	2.62	2.68	2.72	2.73	2.66
Standard Compaction Characteristics:					
• Maximum Dry Unit Weight, $\gamma_{d\ (max)}$ (kN/m^3)	15.04	15.00	14.47	14.18	14.15
• Optimum Moisture Content, w_{opt} (%)	20.00	20.00	22.60	22.80	24.70
USCS (Plasticity Chart)	ML	ML	ML	ML	ML
Permeability Coefficient, K_f (m/s)	4.82×10^{-12}	1.93×10^{-12}	6.75×10^{-13}	1.17×10^{-12}	1.96×10^{-12}

3.1 Particle Size Distribution

The grain size distribution curves for the soil-lime-silica fume mix, as obtained from sieve and hydrometer analyses, are presented in Figure 1. The curves are significantly shifted to the coarser side, and as the percentages of lime and silica fume increase; the soil becomes more granular. This may be caused by the immediate pozzolanic reaction that causes the flocculation of clay particles. These results are compatible with the findings of [7], who mentioned that the reduction in clay content occurred as the lime content increased. This was due to a corresponding increase in the percentage of coarse particles. As shown in the Figure 1, the grain sizes range from clay to fine silt. Majority of the size of kaolin clay and the mixtures were found to be in the range of 0.3 mm and 0.0006 mm. Thus, this soil was suitable to be stabilised with lime and silica fume, as it was categorized as a fine-grained soil. Based on Figure 1, the percentage of clay is over 10 %; hence, the soil meets the requirements for lime-silica fume stabilisation.

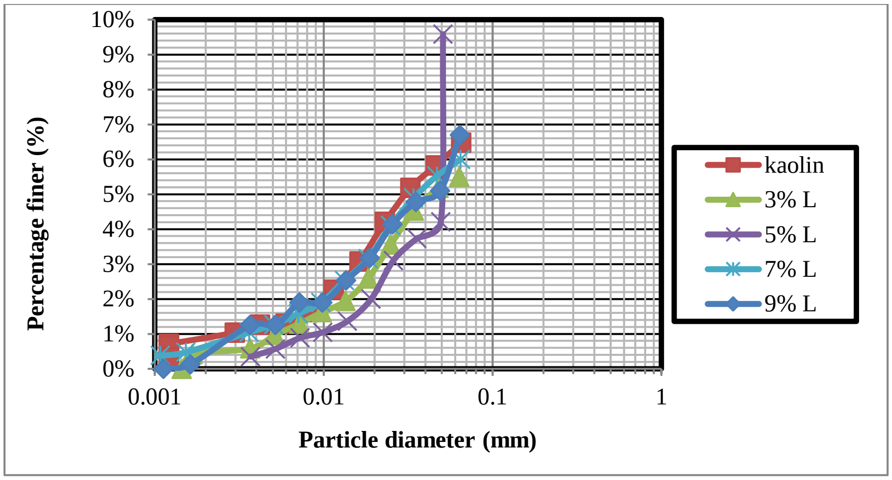


Figure 1 Particle size distribution of soil samples

3.2 Atterberg Limits

The effect of adding lime-SF to the soft soil on Atterberg limits is shown in Figure 2. As shown in this figure, the liquid limit had increased slightly from 0% to 7% lime content, with 6% silica fume. This was due to the excess lime content (and a decreased in the other reaction material). In 7% lime, there was a decreased in the liquid limit because of the pozzolanic reactions that occurred between lime and silica fume; this formed calcium-silicate that cemented with soil particles, and in turn caused flocculation/agglomeration of the clay particles, as well as a reduction in the liquid limit. Besides, the plastic limit was approximately still constant, which indicated that the lime and silica fume content are 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 [8].

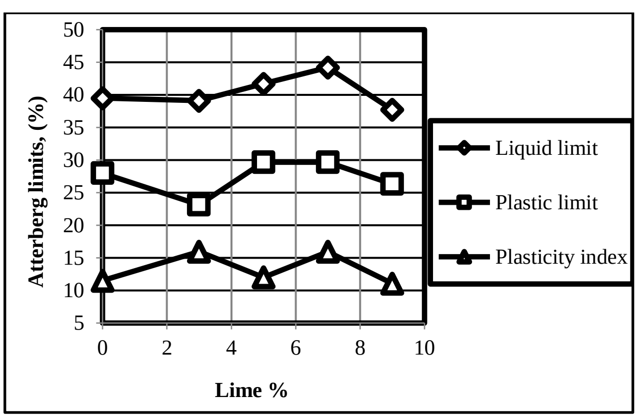


Figure 2 Effect of lime percentages with 6 % of silica fume

Based on the Unified Soil Classification System (USCS), it can be observed that the soil classification is still in the ML zone for the soil stabilised with all lime and silica fume contents, mainly due to the small particle sizes and stabiliser amount. A reduction in plasticity occurred in the case the clayey soil was 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 occurred because of the cation exchange which took place between negative ions on the surface of the clay particles and the calcium ions of the lime.

3.3 Specific Gravity

Figure 3 shows the results of specific gravity (G_s) for the untreated and treated soils. As shown in the figure, the specific gravity 2.64 of the controlled (untreated) sample increased with increasing lime content to 2.72, at 5% lime with 6% silica fume. This increment was due to the molecular rearrangement of the soil matrix, which was caused by the higher density of lime and silica fume, compared to that of the soft kaolin clay. Moreover, the specific gravity increased for the samples of stabilised 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 stabilised soil containing 7% to 9% lime with 6 % silica fume. The decreased in specific gravity of the soil with the increased in lime content was due to the low specific gravity of lime and silica fume on Atterberg limits of soil samples.

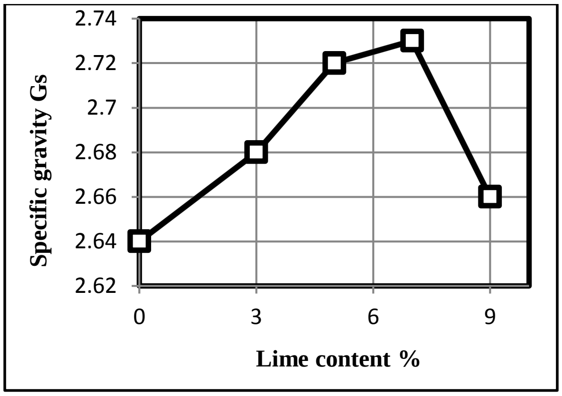


Figure 3 Effect of lime stabiliser content on specific gravity of kaolin mixed with 6% SF

3.4 Compaction

Figure 4 presents the relation between the dry unit weight versus moisture content for soft kaolin clay mixed with 6 % silica fume, and various percentages of lime (3%, 5%, 7% and 9%).

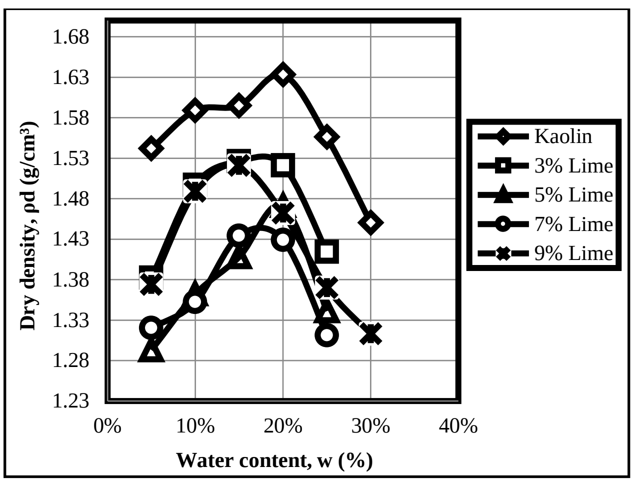


Figure 4 Changes of the dry density with water content for soil samples stabilised with 6 % of silica fume and different percentages of lime content

Figure 5 presents the influence of the addition of 6 % silica fume and various percentages of lime on the optimum moisture content. The optimum water content increased with the increased in the percentage of lime with 6 % silica fume in the soft kaolin clay. The optimum water content of the soil samples rised from 20.0 % to 24.7 %. The increased in the optimum water content can be caused by the absorption of water by lime and silica fume. This indicated that the mixtures of kaolin-lime-silica fume required a higher amount of water for compaction.

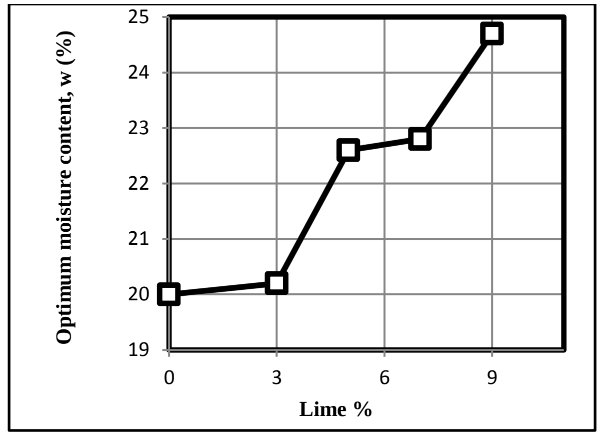


Figure 5 Influence of 6 % silica fume and percentages of lime on the optimum moisture content of the samples

Figure 6 presents the influence of different percentages of lime contents with 6% of silica fume on the maximum dry unit weight of soil samples. With the addition of the lime and silica fume in the soft kaolin clay, there was a decline in the maximum dry unit weight of the soil samples which were from 15.04 kN/m^3 to 14.15 kN/m^3 at 9 % of lime and 6 % of silica fume. This can be attributed to the replacement of soil by the lime and silica fume in the mixture [9]. It may also be attributed to the coating of the soil by the lime and silica fume which resulted in large particles with larger voids. The reduction in dry unit weight could be due to the ion exchange, flocculation and agglomeration effect of soil particles which reduce compaction, make soil particle more friable for compaction and hence the unit weight of the treated soil reduced.

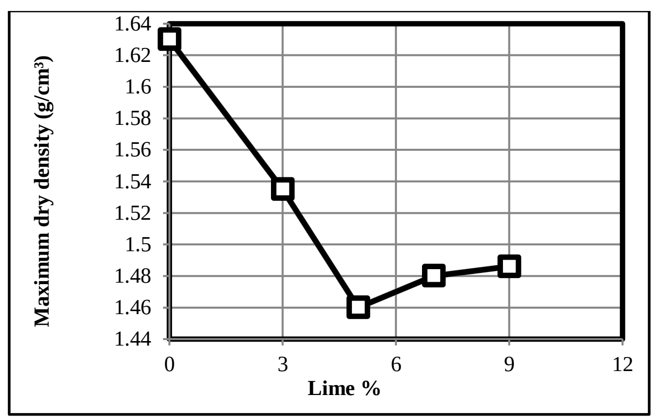


Figure 6 Influence of 6 % silica fume and various percentages of lime on the maximum dry unit weight

3.5 Permeability

Figure 7 shows the permeability test results of the mixture of kaolin and lime-silica fume. Das and Sobhan [10] mentioned that the permeability results is 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 for the mixture with K+6%SF+3%L, K+6%SF+5%L, K+6%SF+7%L and K+6%SF+9%L were 1.93x10^{-12} m/s, 6.75x10^{-13} m/s, 1.17x10^{-12} m/s and 1.96x10^{-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 increases to 1.96×10^{-12} m/s at 9 % lime content. As shown in Figure 4.27, 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 stabilised 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 stabilised soil containing 7% to 9% lime.

The increased in permeability with an increased in lime content is due to the pozzolanic reactions. The formation of lime particles aggregates results in the soil becoming more granular in nature, and results in a higher resistance to compression at similar stress levels. This produces soil with a more open fabric, and results in an increase in permeability. The hydrated lime and clay undergo pozzolanic reactions in the stabilisation phase, and produce calcium silicate gel, which is tough water-insoluble. The clay lumps are immediately coated and bound by silicate gel, and then filled up the void space and block the soil pores [11]. The increase in permeability is attributed to the changes in the soil sample structure due to particle rearrangements. Conversely, a decreased in the permeability was due to the addition of fine content.

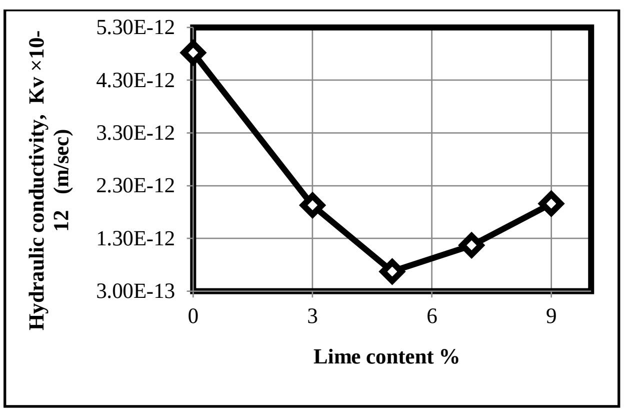


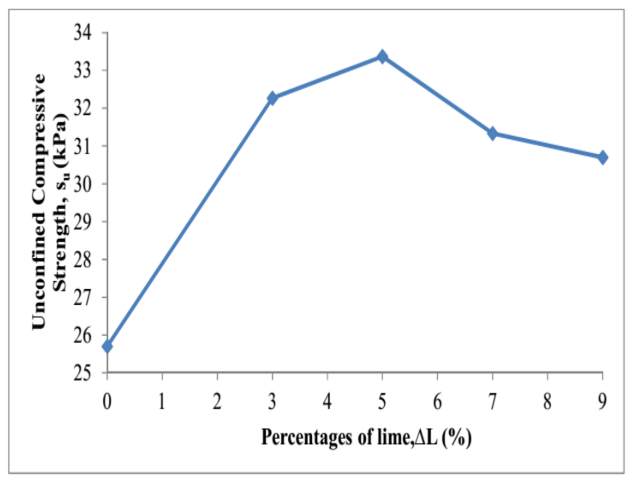
Figure 7 Hydraulic conductivity against the percentages of lime for kaolin mixture with 6% SF

3.6 Shear Strength

The average shear strength of the controlled sample was 25.70 kPa. Besides, the incremental addition of percentages of lime increases the overall shear strength of the samples compared to controlled samples. From the results obtained, the shear strengths of the mixtures were 32.27 kPa, 33.37 kPa, 31.33 kPa and 30.70 kPa at 3 %, 5 %, 7 % and 9 % of lime with the addition of 6 % of silica fume. The effects of percentages of lime with 6% of silica fume on the shear strengths for soil samples are shown in Figure 8.

The percentages of shear strength improvement of all the samples were tabulated in Table 2. The improvement in shear strengths of the mixtures were 25.55 %, 29.83 %, 21.92 % and 19.46 % compared to the shear strength of the controlled samples. From Table 2, it is noticed that undrained shear strength increases with lime content from 0 % to 5 % of lime. So, the optimum percent was 5 % of lime with 6 % of silica fume, which exhibits an improvement of 29.83 %. This increase was due to pozzolanic reactions (the released silica and alumina react with the calcium from the lime to form cement), within the lime-soil mixture and resulting in strength gain over time, while from 5 % to 7 % of lime, there was a decrease in undrained shear strength due to reduction in one compound of the pozzolanic reaction (silicon in soil).

Figure 8 Effect of lime with 6 % of silica fume on shear strength



of soil samples

Table 2 Result of improvement in shear strength obtained from unconfined compression test

L-SF (%)	3-6 %	5-6 %	7-6 %	9-6 %
Improvement in Shear Strength (%)	25.55	29.83	21.92	19.46

Notation: L-SF is the mixture of lime and silica fume

4.0 CORRELATIONS

The relationships between parameters were obtained by establishing the regression lines. Table 3 show the samples that had been stabilised with lime and silica fume which the correlation line for improvement in the properties of soft kaolin clay with versus percentages of lime and 6% of silica fume. From the table shows the Equations of correlation together with the coefficient of determinations, R^2.

Table 3 Correlation equations with respective coefficients of determination values

Tests	List of Correlation Equation	Value of R^2
Specific Gravity	$G_S = -0.0036\Delta L^2 + 0.0392\Delta L + 2.6133$	0.8848
Atterberg Limit	$w_L = -0.1044\Delta L^3 + 1.2633\Delta L^2 - 3.135\Delta L + 39.56$	0.9659
	$w_P = -0.0337\Delta L^3 + 0.377\Delta L^2 - 0.8573\Delta L + 27.931$	0.7944
	$I_P = -0.0707\Delta L^3 + 0.8862\Delta L^2 - 2.2777\Delta L + 11.629$	0.7245
Permeability Test	$K_t = 1x10^{-13}\Delta L^2 - 1x10^{-12}\Delta L + 5x10^{-12}$	0.9889
Compaction Test	$w_{opt} = 0.0399\Delta L^2 + 0.1839\Delta L + 19.827$	0.9153
	$\gamma_{d\,(max)} = -0.117\,\Delta L + 15.133$	0.8763
Unconfined Compression Test	$s_U = -0.2391\Delta L^2 + 2.6139\Delta L + 25.97$	0.9329
	$\Delta s_U = -0.9305\Delta L^2 + 10.171\Delta L + 1.0507$	0.9329

5.0 CONCLUSION

The major focus of this research work was to determine the shear strength of soft kaolin clay after being mixed with lime and silica fume under unconfined compression test. Based on the laboratory test results obtained, the following conclusions are drawn:

(a) The sizes of kaolin clay and the stabilised mixtures were found to be in the range between 0.0006 mm to 0.3 mm. This indicated that the grain sizes of kaolin clay and the stabilised mixtures were ranged from fine clay to fine silt.

(b) Specific gravity of soft kaolin clay was determined to be 2.64, due to the fact that kaolin contained substantial amount of kaolinite mineral in its compositions. Specific gravities of the mixtures were found to be 2.68, 2.72, 2.73 and 2.66, respectively. The kaolin, kaolin mixed with 6 % of silica fume and various percentages of lime (3 %, 5 %, 7 % and 9 %) were indicated as soils with medium plasticity based on their Atterberg limits. According to the Unified Soil Classification System, it is proven that kaolin, kaolin mixed with 6 % of silica fume and various percentages of lime (3 %, 5 %, 7 % and 9 %) were categorized in ML zone.

(c) Lime-silica fume mixture decreased the maximum dry density and increased the optimum moisture content. From 0 % to 9 % of lime with 6 % of silica fume, the decreased in the maximum dry density was by 5.92 % and the increased in the optimum moisture content was by 23.5 %.

(d) The addition of lime and silica fume to soft kaolin clay led to a decreased in the coefficient of permeability compared to the coefficient of permeability of soft kaolin clay itself. The soft kaolin clay and the stabilised mixtures showed impervious degree of permeability and generally corresponding to clay soil, indicating a poor drainage characteristic. The results presented that the optimal percentage of lime-silica fume combination was attained at 5 % of lime and 6 % of silica fume.

(e) The highest shear strength achieved was 33.37 kPa for soft clay stabilised with 5 % of lime and 6 % of silica fume. The improvement in shear strength of this stabilised mixture was 29.83 % compared to the shear strength of the kaolin sample.

(f) Based on the results, it can be concluded that lime-silica fume mixture was an effective stabiliser for improving the geotechnical properties of clayey soil samples to be suitable for engineering projects.

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