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RESEARCH ARTICLE

Stabilization of Expansive Soil using Silica Fume and Lime

M. S. I. Zaini and M. Hasan*

Faculty of Civil Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah, Lebuh Persiaran Tun Khalil Yaakob, 26300 Kuantan, Pahang, Malaysia

ABSTRACT - Structures built on soft clays frequently encounter stability and settlement issues owing to the high compressibility, low shear strength, and poor permeability of such clay types. These characteristics often result in bearing capacity failure and excessive settlement, posing significant challenges to construction projects. Therefore, the study investigates the strength enhancement of expansive clay soil with the inclusion of various percentages and combinations of silica fume (SF) and lime (L). Hence, the mechanical characteristics of various mix ratios of SF and L are examined via the standard Proctor, and unconfined compressive strength (UCS). The samples were treated for 1, 7, 14 and 30 days and examined under the UCS tests. The experimental results show that the strength of the expansive clay significantly rises with the inclusion of SF and L at dissimilar mix ratios and curing days. The mixture of SF and L resulted in a significant strength increment of the kaolinite clay soil up to 80.22%.

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1.0 INTRODUCTION

Kaolinite, referred to as kaolin, emerges as a clay mineral within soil formations, originating from chemical weathering in warm, humid locales such as tropical rainforests [1]. Characterized by its low cation exchange capacity and minimal shrink-swell tendencies, kaolinite exhibits traits of low strength, heightened compressibility, and limited resilience [2-4]. Consequently, conducting thorough analyses becomes imperative to augment the strength, compressibility, and longevity of kaolinite clay soil. Over the year, various of stabilizing agents have been utilized, encompassing conventional options like cement and lime, alongside alternative binders such as cement kiln dust, silica fume, and fly ash, either used independently or in conjunction [5,6]. However, in light of the detrimental environmental impacts associated with cement, there has been a notable transition towards adopting more environmentally friendly alternatives [7-9].

Silica fume (SF) finds application in concrete technology as a pozzolan, thereby proving effective in enhancing soil properties. Incorporating SF into soft clays improves workability and strength while mitigating soil plasticity [10,11]. Similarly, lime is recognized as a viable cementitious material that, when mixed with other soil stabilizers, amplifies pozzolanic reactivity [12-14]. In this study, the focus lies on investigating the impact of varying proportions and combinations of silica fume (SF) (2%, 4%, and 6%) and lime (L) (3%, 6%, and 9%) as soil stabilizers on the strength development of expansive clay soil. The soil samples are cured for 1, 7, 14, and 30 days to assess their effectiveness in soil stabilization. A range of geotechnical properties is analyzed to evaluate the efficiency of SF and L as stabilizing materials for expansive clay soil.

2.0 METHODOLOGY

The experimental program was designed first to characterize the material used which was silica fume and lime and kaolinitic clay soil, followed by the shear strength tests on soft kaolin clay stabilized with silica fume and lime. The summary of laboratory testing program and the standard used are as shown in Table 1. Silica fume, was obtained from Scancem Materials Sdn. Bhd, Malaysia. It is known for its high pozzolanic value owing to its elevated content of silica. Lime utilized in the study was a laboratory grade hydrated lime supplied by CAO Industries, was utilized owing to its compatible chemical compositions which depleted the probability of variations in laboratory results.

Table 1. Laboratory testing program

Material	Test Name	Standard
Kaolin	Atterberg Limit	BS 1377- Part 2: 1990: 4, 5 & 6.5
	Particle Size Distribution	BS 1377- Part 2: 1990: 9.5
	Unconfined Compression Test	ASTM D 2166
	Compaction Test	BS 1377: Part 4: 1990

***CORRESPONDING AUTHOR | M. Hasan** | ✉ muzamir@umpsa.edu.my

Table 1. (cont.)

Material	Test Name	Standard
Silica Fume	Particle Size Distribution	BS 1377- Part 2: 1990: 9.3
Lime	Particle Size Distribution	BS 1377- Part 2: 1990: 9.3
Kaolinitic Clay Stabilized with SF and Lime	Atterberg Limit	BS 1377- Part 2: 1990: 4, 5 & 6.5
	Particle Size Distribution	BS 1377- Part 2: 1990: 9.5
	Unconfined Compression Test	ASTM D 2166
	Compaction Test	BS 1377: Part 4: 1990

2.1 Soil and Soil Stabilizers

Kaolinite clay possesses a mineral structure resistant to water penetration, forming a uniform mixture when in contact with water, owing to its plate-like configuration consolidated by hydrogen bonds and secondary valence forces. The study incorporated various stabilizing agents, including Silica Fume (SF) and Lime (L). SF, obtained from Malaysia, is recognized for its high pozzolanic value due to its elevated silica content. Laboratory-grade hydrated lime (L) was utilized. Table 2 shows the sample coding used in the study. Geotechnical characteristics of kaolinite clay are outlined in Table 3.

Table 2. Sample coding

Sample	Coding	Content (%)		
		Kaolin	SF	L
Kaolin (Control)	C	100	-	-
Kaolin with 2% of Silica Fume	CS2	98	2	-
Kaolin with 4% of Silica Fume	CS4	96	4	-
Kaolin with 6% of Silica Fume	CS6	94	6	-
Kaolin with 6% of Silica Fume and 3% of Lime	CS6L3	91	6	3
Kaolin with 6% of Silica Fume and 6% of Lime	CS6L6	88	6	6
Kaolin with 6% of Silica Fume and 9% of Lime	CS6L9	85	6	9

Table 3. Geotechnical characteristics of kaolinite clay

Characteristics	Unit	Data
Gravel	%	0
Sand	%	40
Clay and Silt	%	60
Liquid Limit	%	41.1
Plastic Limit	%	33.3
Plasticity Index	%	7.8
Maximum Dry Density	g/cm^3	1.55
Optimum Moisture Content	%	21.00
Unconfined Compression Strength	kPa	13.15

2.2 Preparation of Soft Kaolin Clay

The laboratory experiments aimed to stabilize kaolinite clay using various combinations of SF and L to enhance its cementitious properties. Consistency tests were conducted in accordance with BS 1377: Part 2: 1990. Compaction tests, following BS 1377: Part 4: 1990 standards, were performed to determine the maximum dry unit weight (MDD) and optimum water content (OMC) of the soil. Unconfined compression tests (UCT) were carried out on soil specimens cured for different durations (1, 7, 14, and 30 days), following ASTM D2166 protocols. Figure 1(a), Figure 1(b), and Figure 1(c) shows the image of kaolin, SF, and L used in the study.

(a) (b) (c)

Figure 1. Samples of (a) kaolin; (b) SF; and (c) L

3.0 EXPERIMENTAL RESULTS

In the study, a series of laboratory testing was conducted according to the standard as mentioned in Table 1 and the shear strength of the stabilized kaolinitic clay with SF and lime was tested. There are four (4) types of laboratory testing conducted in the study which includes Atterberg limit, particle size distribution, compaction, and unconfined compression test.

3.1 Atterberg Limit

In Figure 2, the Atterberg limits of both unstabilized and stabilized kaolinite clay with various combinations of SF and L are depicted. The introduction of silica resulted in a slight decrease in both plastic limit (PL) and liquid limit (LL) values at concentrations of 2% and 4%, while an increase was observed at 6%. This continuous rise in PL with the addition of SF can be attributed to cation exchange between kaolinite clay minerals and positive cations present in SF. The decrease in plasticity properties of kaolinite clay was a consequence of substituting highly plastic clay particles with less reactive SF particles, leading to flocculation and a subsequent reduction in consistency limits, as discussed by Zaini et al. [15] and Zaini et al. [16]. The PL and LL value of the stabilized kaolinite clay were also reduced when different percentages of lime were utilized with 6% of SF. Given that kaolinite comprises alumino-silicates, the interaction of CaO from lime with the kaolinite clay structure and SF leads to the formation of calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH). These compounds work to balance the ionic bonds within the kaolinite clay minerals' structure, thereby diminishing the cation exchange capacity for water molecules.

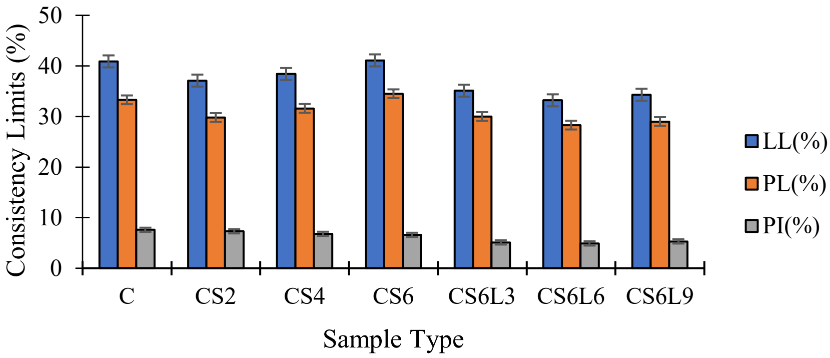

Figure 2. Atterberg limits of unstabilized and stabilized kaolinitic clay

3.2 Particle Size Distribution

Figure 3 presents the particle size distribution (PSD) of kaolinite clay, SF and L. The analysis reveals that 38.4% of the kaolinite clay particles belong to the clay fraction, while 61.6% exhibit finer gradation. The particle size distribution of the SF used in this study falls within the MH (sandy/silty soil) classification, characterized by high plasticity characteristics. Additionally, lime display a coarser particle distribution, with approximately 26% of particles passing through the 75µm sieve and 74% retained above it. Lime are categorized as SC (sandy-clay) particles, consistent with a similar investigation conducted by Hasan et al. [17], [18], [19].

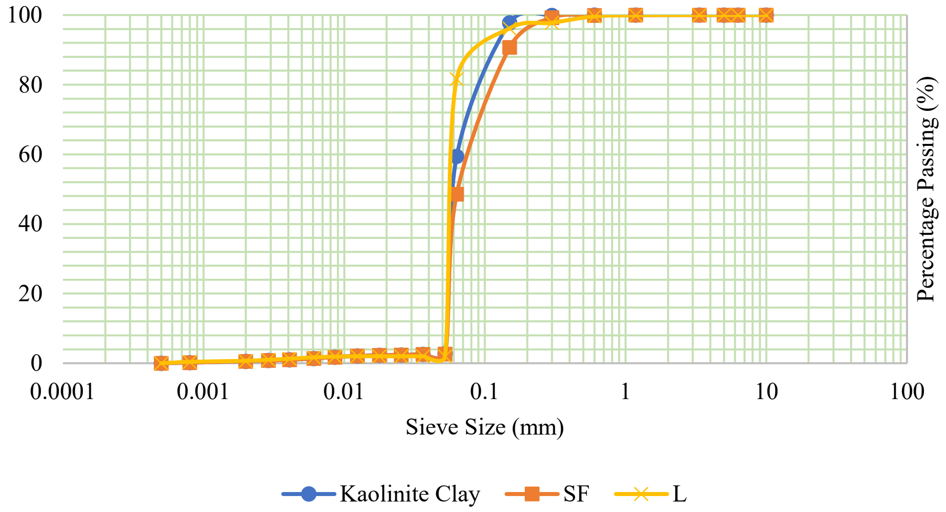

Figure 3. Particle size distribution of soft kaolin clay

3.3 Compaction

Figure 4 illustrates the dry unit weight and moisture content of kaolinite clay stabilized with various combinations of SF, ESA, and L. The maximum dry density (MDD) of the untreated kaolinite clay is measured at 1.56 g/cm³ with an optimum moisture content (OMC) of 22.00%. The reduction in MDD ranges from 1.39 g/cm³ to 1.54 g/cm³, while the OMC values range from 14.00% to 21.00% across different combinations of soil stabilizers. Similar findings were reported by Zaini and Hasan [20]. It is observed that as the dosage of soil stabilizers increases, the MDD decreases, while the OMC values vary. This reduction in thickness of the duplex layer occurs as sodium cations in the diffuse layer of kaolinite clay are replaced by silicon cations [21], [22]. The decrease in maximum dry density (MDD) observed in SF-L combinations, can be attributed to hydration, dissociation, and pozzolanic reactions, which lead to a reduction in the density of the soil matrix.

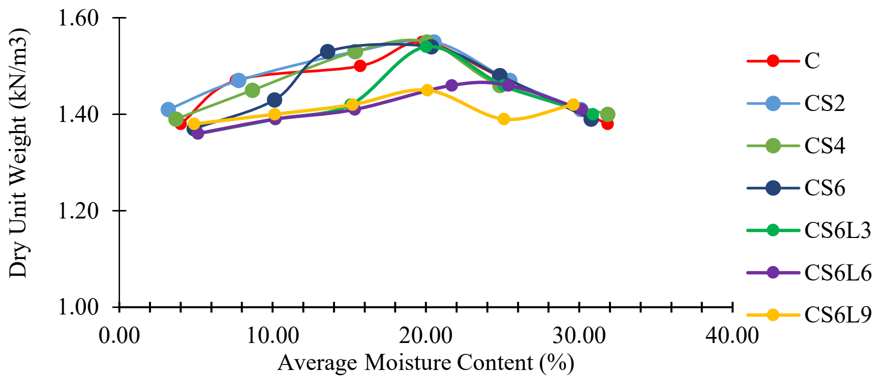

Figure 4. MDD and OMC of kaolinite clay with different combinations SF and L content

3.4 Unconfined Compression Test

Figure 5 highlights the maximum compressive strength across various mixtures of SF, ESA, and L, cured at 1, 7, 14, and 30 days. The data reveals a gradual increase in the compressive strength of kaolinite clay with higher levels of SF content and longer curing periods. The optimal ESA and L content required for sufficient stabilization of kaolinite clay is determined to be 6% and 9%, respectively. Further addition of ESA in kaolinite clay-SF mix leads to a reduction in the UCS, while additional L in kaolinite clay-SF mix results in a significant increment in the UCS. Similar observations were made by Türköz et al. [23], Phanikumar et al. [24], and Yuan et al. [25]. The findings indicate that the application of SF-ESA-L resulted in a substantial increase in UCS, with strength improvement reaching up to 81.03% (69.344 kN/m²). The analysis above reveals that SF does indeed alter the inner structure of the sample, resulting in an increase in shear strength. This alteration stems from the presence of reactive silica in the SF, capable of undergoing chemical reactions with the loess particles in an alkaline environment, thereby producing a binding material [26], [27], [28]. This chemical reaction is directly correlated with the observed improvement in sample strength [29], [30], [31]. Furthermore, to ensure the high production of CSH and CAH obtained from the pozzolanic reaction [32], [33] the optimum usage of SF at 6% is established and mixed with kaolinite clay along with different proportions of ESA, L, and ESA-L stabilizers.

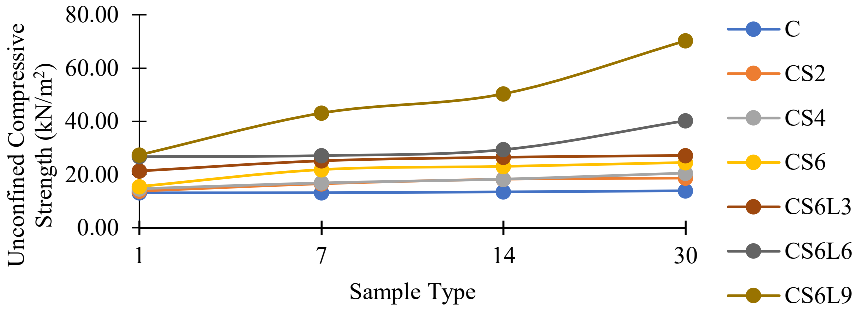

Figure 5. Variation of UCS at various curing periods for kaolinite clay stabilizations

4.0 CONCLUSION

A series of laboratory experiments were conducted to evaluate the impact of various ratios and combinations of SF and L, coupled with different curing durations, on kaolinite clay. The results show a significant reduction in liquid limit (LL) and plastic limit (PL) of the kaolinite clay, following alterations with SF and L at varying percentages and combinations. Furthermore, the utilization of SF and L at different combinations and proportions in kaolinite clay stabilization results in a decrease in maximum dry density (MDD) values and fluctuation in optimum moisture content (OMC) values of the compacted soil. By employing different combinations and proportions of SF and L at varied curing periods, the unconfined compressive strength (UCS) of kaolinite clay is significantly enhanced, with the highest UCS values recorded at 30 days of curing. The study recommends that a mixture of SF, ESA, and L at a ratio of 6:9 is more effective in increasing the strength of kaolinite clay by up to 80.22% compared to other mixtures.

5.0 AUTHOR CONTRIBUTIONS

Muhammad Syamsul Imran Zaini: Original draft preparation, Conceptualization, Methodology, Software

Muzamir Hasan: Supervision

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7.0 DATA AVAILABILITY STATEMENT

The data used to support the findings of this study are included within the article.

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9.0 CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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