Jurnal
Teknologi

Full Paper

UTILIZATION OF SILICA FUME AND CLAMSHELL ASH AS STABILIZATION MATERIALS FOR KAOLIN CLAY

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Article history
Received
22 July 2024
Received in revised form
18 September 2024
Accepted
8 October 2024
Published Online
28 April 2025

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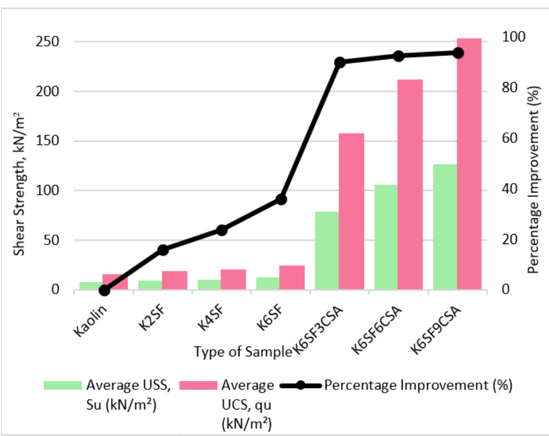
Graphical abstract



Abstract

Soil stabilization, particularly through chemical methods involving the incorporation of binders such as cement, ground granulated blast furnace slag, silica fume, lime, fly ash, and bottom ash is a highly successful and extensively employed method for improving the characteristics of problematic soils. Clay soils are one of the problematic soils that are unsuitable for construction due to their low bearing capacity, significant settlement, compression, and high-water content. The focus of the study was to determine the physical properties of the materials used (kaolin clay, SF and CSA) and the strength of kaolin clay mixed with optimal SF and various percentages of CSA. In this research, kaolin soil was treated with a Silica Fume (SF) and Clamshell Ash (CSA) blend in order of 2, 4, and 6% of SF and 3, 6, and 9% of CSA by dry weight of soil. The molded specimens were cured for 30, 60, 90, and 120 days. The mixing sample was carried out under Unconfined Compression Test to determine the maximum undrained shear strength when mixed with optimal percentage of SF and (3, 6 and 9%) of CSA content. Furthermore, the outcomes of the unconfined compressive strength test demonstrated a substantial enhancement in the soil's strength, increasing by up to 93.71%, from 189.75 kN/m² to 253.43 kN/m², by inclusion of 6% silica fume and 9% clamshell ash after 120 days of curing. Thus, SF and CSA can be utilized for stabilizing soft soils.

Keywords: Soil stabilization, silica fume, clamshell ash, kaolin, unconfined compressive strength

Abstrak

Penstabilan tanah, terutamanya melalui kaedah kimia yang melibatkan penggabungan pengikat seperti simen, sanga relau letupan berbutir tanah, wasap silika, kapur, abu terbang, dan abu dasar adalah kaedah yang sangat berjaya dan digunakan secara meluas untuk menambah baik ciri-ciri tanah yang bermasalah. Tanah liat merupakan salah satu tanah bermasalah yang tidak sesuai untuk pembinaan kerana kapasiti galasnya yang rendah, petempatan yang ketara, mampatan, dan kandungan air yang tinggi. Fokus kajian adalah untuk menentukan sifat fizikal bahan yang digunakan (tanah liat kaolin, SF dan CSA) dan kekuatan tanah liat kaolin bercampur dengan SF optimum dan pelbagai peratusan CSA. Dalam penyelidikan ini, tanah kaolin dirawat dengan campuran Silica Fume (SF) dan Clamshell Ash (CSA) mengikut urutan 2, 4, dan 6% SF dan 3, 6, dan 9%

CSA mengikut berat kering tanah. Spesimen acuan telah diawetkan selama 30, 60, 90, dan 120 hari. Sampel bancuhan telah dijalankan di bawah Ujian Mampatan Tidak Terkurung untuk menentukan kekuatan ricih tidak berdraina maksimum apabila dicampur dengan peratusan optimum SF dan (3, 6 dan 9%) kandungan CSA. tambahan pula, hasil ujian kekuatan mampatan tidak terkurung menunjukkan peningkatan yang ketara dalam kekuatan tanah, meningkat sehingga 93.71%, daripada 189.75 kN/m² kepada 253.43 kN/m², dengan memasukkan 6% wasap silika dan 9% abu kulit kerang selepas 120 hari pengawetan. Oleh itu, SF dan CSA boleh digunakan untuk menstabilkan tanah lembut.

Kata kunci: Penstabilan tanah lembut; asap silika; abu kulit kepah; kaolin; kekuatan mampatan tide terkurung

1.0 INTRODUCTION

These days, poor soil quality is a crucial factor in construction projects. Expansive clay was identified as the problematic soil. The presence of clayey soil poses significant challenges for civil engineers, the construction industry, and property owners [1]. A considerable portion of the extensive clay has active smectite minerals, including montmorillonite, which demonstrate substantial swell-shrink volume variations and desiccation-induced fissuring with the inclusion or removal of water. [2]. Such motions raise significant instability issues for the above structures, necessitating technical measures to mitigate the related socio-economic implications on human life. [3]. Soft soil often consists of fine-grained soils and is categorised as clay because it exhibits a propensity to undergo volume changes when in contact with water. The clay's ability to retain water and present the swell-shrink characteristic in response to fluctuations in moisture is a direct consequence of the microscopic size of its particles, which generates a considerable surface area. [4,5]. The permeability of clay soil is due to the presence of microscopic pore holes in soils with a clay texture, resulting in a slow drainage of water through the soil. Hence, soil treatment is required to ensure that structures constructed on clay do not sustain substantial damage due to the instability and unpredictability of clayey soil.

According to the soil depth, there are numerous stabilising approaches that include The implementation of preloading, removal, and substitution techniques for the unstable layer, stone columns, mixing in the binder's substance, and others. The stabilization approach evolved around five decades ago [6]. Soil stabilization is a geotechnical technique that employs mechanical, chemical, or supplementary treatments to improve engineering properties and strengthen the soil [7, 8].

Besides, the approach of chemical stabilization is the process of adding a binder to the problematic soil to enhance its geotechnical performance, including its mechanical and chemical properties [9]. Chemical additions to soil can improve its strength in many ways, such as by increasing its shearing and compressive strengths, stabilizing its volume, lowering its swelling potential, managing its shrinkage, boosting its plasticity index (PI), permeability, deformation, settlement, and the amount of clay and silt it contains, and making it last longer in harsh weather conditions [10, 11, 12].In earlier times, soil stabilisation mostly depended on the utilisation of calcium-based stabilizers, such as cement and lime. Utilising recyclables as binding materials in soil stabilisation is an economical and environmentally conscious technology that changes the mechanical and chemical properties of soils through pozzolanic interaction. The chemical compounds alter the nature of the soil by acting as compaction aides, binders, and water repellents [13, 14]. It can be assessed through lab testing (Standard proctor test; Atterberg limit test; UCT test, CBR test) to analyse soil stability, density and strength improvement after the addition binder's material. Stabilising additives such as bitumen emulsion, cement, and lime are employed as well.

Furthermore, the materials employed in this research as soil stabilizing agents are silica fume (SF) and clamshell ash (CSA). Studies have found that the chemical composition of different seashells ranges from 92% to 99% calcium carbonate [15, 16, 17]. Besides, 90% of the primary component of lime (CaO), calcium (Ca), is found in seashell powder [20] which makes it a more effective and reasonably priced stabilizing additive. Calcium carbonate ($CaCO_3$) is transformed into carbon and calcium oxide (CaO) by burning the shells at temperatures above 550 °C. The chemical compound CaO in CSA with pozzolanic characteristics can serve as a viable alternative to cement [18]. The variation in calcium oxide content in shells post-calcination primarily hinges on the shell category, cleaning technique, and the calcination technique or temperature applied [19]. Felipe-Sese et al. [20] achieved a calcium oxide content of 87.21% in shells calcined at 1100°C, whereas the same type of seashells (mussel shells) yielded 53.58% calcium oxide at a calcination temperature of 550°C [21], indicating that similar seashells exhibit comparable chemical compositions when subjected to similar calcination temperatures.

Moreover, despite their hazardous nature, silica fumes are utilized in multiple applications of civil engineering involve the alteration of concrete, modifying clay characteristics, and strengthening of pavement subgrades. Expansive soils treated with silica fume exhibited decreased flexibility, free swell index (FSI), and swelling pressure [22, 23]. The incorporation of SF into kaolinite clay led to an enhancement of unconfined compressive strength [24,25,26]. Moreover, CSA primarily consists of calcium oxide (CaO) [27], while silica fume (SF) is made up of over 96.10% SiO_2 [28]. Consequently, they release ionised metals like Al^{3+}, S^{2+}, and Fe^{3+}, known to induce pozzolanic reactions [29], which increase the strength of the soft soil. To evaluate how silica fume and clamshell ash improve the strength of clay soil, lab tests were conducted to examine the mechanical and physical properties of kaolin clay soil, SF, and CSA, as well as kaolin clay stabilized with these materials. The aim is to understand the relationship between the properties of these materials and to find the optimal percentages of SF and CSA that maximize the undrained shear strength of the stabilized kaolin clay soil. Following the tests, the feasibility of utilizing silica fume (SF) and clamshell ash (CSA) as soil stabilization materials can be observed. Their favorable chemical properties, cost-effectiveness, and environmental benefits suggest that SF and CSA could be viable options for soil stabilization, contingent upon the test results. Hence, SF and CSA can be utilized as soil stabilization materials.

2.0 METHODOLOGY

2.1 Materials

As shown in Figure 1, the materials utilized in this experiment are kaolin grade S300, clamshell ash, and silica fume. The soil sample, known as kaolinite clay, was obtained from Kaolin (M) Sdn. Bhd., located in Selangor, Malaysia. The chemical characteristics of kaolin clay, SF, and CSA are shown in Table 1. The SF used during this experiment was scan fume, a compacted sort of SF made especially for concrete, as seen in Figure 1.

Figure 1 Materials: (a) Silica Fume (SF), (b) Clamshell Ash (CSA), (c) Kaolin S300

Seashells gathered from Kelantan's shoreline were cleaned, left to dry for seven days, ground into powder, and then subjected to 800°C heat for sixty minutes in a chamber furnace to create CSA. The apparatus utilized to generate CSA is shown in Figure 2.

Figure 2 Equipment use to produce CSA: (a) Jaw crusher, (b) Chamber furnace

Table 1 Chemical composition of Kaolin, Silica Fume and Clamshell Ash under the test: Kolin (FESEM), Silica Fume (XRD and SEM), CSA (XRD and XRF)

Chemical Composition	Kaolin % [30]	SF % [31]	CSA % [33]
SiO_2	66.11	96.10	1.00
MgO	1.23	0.45	0.30
Fe_2O_3	0.73	0.15	0.40
Al_2O_3	19.25	0.75	0.20
CaO	0.08	0.31	94.10
SO_3	-	-	0.40
SrO	-	-	0.30
Na_2O	-	-	1.00
K_2O	2.85	0.65	-

2.2 Sample Preparation

For this study, laboratory experiments were conducted on kaolin, SF, and CSA, as well as mixes of kaolin with SF and kaolin combined with SF and CSA. All tests performed in the Soil Mechanics Laboratory used the following standard: Mechanical sieve Analysis (BS 1377: Part 2: 1990), Specific Gravity (BS 1377: Part 2: 1990), Atterberg Limit Test (BS 1377: Part 2:1990), Hydrometer Test (ASTM D 422: 1998), Unconfined Compression Test (UCT) (ASTM D2434). The test specimens were comprised of various mixtures of kaolinite clay, silica fume, and clamshell ash. The soft kaolin clay was dehydrated in a universal oven for a duration of 24 hours at a temperature of 105°C. It was then combined with SF in proportions of 2%, 4%, and 6% based on the total dry weight of the soil. This was done to ascertain the optimal SF dosage needed to enhance the engineering characteristics of the kaolin clay. Subsequently, the soft kaolin with the optimum SF level was supplemented with 3%, 6%, and 9% of CSA to assess its ability to stabilize soft kaolin and the optimum CSA content that results in the highest improvement in USS. The specimens were prepared by mixing materials with optimum water content as determined by the Standard Proctor test according to BS 1377: Part 4: 1990 with each 150 g sample for UCT being remoulded to a height and diameter of 78 mm. Table 2 displays the coding scheme used for the research course.

Table 2 Chemical composition for various

Sample Code	Curing Days and Number of Sample				Total Sample
	30	60	90	120	
K	5	-	-	-	5
K2SF	5	5	5	5	20
K4SF	5	5	5	5	20
K6SF	5	5	5	5	20
KXSF3CSA	5	5	5	5	20
KXSF6CSA	5	5	5	5	20
KXSF9CSA	5	5	5	5	20
Total					125

Note:

5	= No of sample for each mixture for for one curing days
X	= 6% of SF (Optimum dosage)
K	= Kaolin
2, 4, 6	= Percentage of Silica Fume
3, 6, 9	= Percentage of Clamshell Ash
SF	= Silica Fume
CSA	= Clamshell Ash
K2SF	= Kaolin + 2% of Silica Fume
K4SF	= Kaolin + 4% of Silica Fume
K6SF	= Kaolin + 6% of Silica Fume
KXSF3CSA	= Kaolin + 6% of Silica Fume + 3% of Clamshell Ash
KXSF6CSA	= Kaolin + 6% of Silica Fume + 6% of Clamshell Ash
KXSF9CSA	= Kaolin + 6% of Silica Fume + 9% of Clamshell Ash

3.0 RESULTS AND DISCUSSION

3.1 Materials Characteristic of Kaolin Clay

The kaolin clay utilized in this investigation was categorized. as A-5 based on its Liquid Limit (LL) and Plastic Index (PI), which are fine silty soils with diameters ranging from 0.002 mm to 0.065 mm based on the AASHTO classification system (AASHTO, 1986) and the Unified Soil Classification System (ASTM, 1992). The sample is classified as fine if the hydrometer test reveals that the kaolin particles are smaller or finer than 0.075 mm depending on the plotted curve, with particle sizes ranging from 0.0008 mm to 0.063 mm as shown in Figure 3. Based on the Atterberg Limit test, the kaolin clay has Liquid Limit (LL)of 40.6%, Plastic Limit (PL) of 33.3%, and Plastic Index (PI) of 7.3%. Table 3 displays the characteristics of kaolin clay.

Table 3 Properties of Kaolin clay

Characteristic	Value
Colour	white
Specific Gravity (G_s)	2.64
ASHTO Classification	A-5
Liquid Limit (LL) (%)	41
Plastic Limit (PL) (%)	33
Plastic Index (PI) (%)	7
Optimum moisture content (OMC) (%)	19
Maximum dry density (MDD) (g/cm³)	1.606
Unconfined Compressive Strength, q_u (kN/m²)	13.17
Unconfined Shear Strength, S_u (kN/m²)	13.17
Axial Strain, ε (%)	1.76

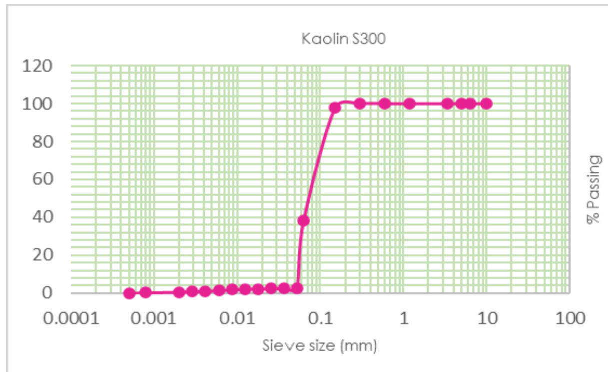


Figure 3 Particle size distribution of Kaolin

3.2 Specific Gravity

The specific gravity (Gs) of the specimen can be identified by carrying out a particle density test. The specific gravity of kaolinite clay varies from 2.62 to [33, 34]. As a result, the Kaolin S300's specific gravity is 2.64, which falls within the range. Meanwhile, the laboratory test results for SF and CSA are 2.33 and 2.56, respectively. With the addition of up to 6% of SF, the specific gravity of the kaolin clay was reduced to 2.5. Moreover, with the inclusion of CSA, up to 9% recorded an increasing trend due to the heavier particle of CSA compared to SF.

3.3 Atterberg Limit

Table 4 illustrates the evolution of the plasticity index, plastic limit, and liquid limit as SF and CSA rises. The LL, PL, and PI for kaolin are 40.6%, 33.3%, and 7.3%, respectively. The data reveals that adding 6% silica fume (SF) to kaolin clay results in a Liquid Limit (LL) of 41%, a Plastic Limit (PL) of 35%, and a Plasticity Index (PI) of 6%. This indicates that SF increases the LL and PL while slightly reducing the PI compared to the control sample, enhancing the clay's water absorption and reducing its plasticity. When combined with clamshell ash (CSA), the effects of SF vary. With 3% CSA added to the 6% SF, the LL decreases to 37%, the PL to 32%, and the PI to 5%. This reduction in LL and PL suggests that CSA enhances soil stabilization by counteracting some of the plasticizing effects of SF. Increasing CSA to 6% results in LL and PL values of 40% and 35%, respectively, with the PI remaining at 5%. The slight increase in LL and PL compared to the 3% CSA mix indicates that higher CSA content continues to stabilize the soil while maintaining similar plasticity levels. At 9% CSA, the LL rises to 42%, the PL to 38%, and the PI decreases to 4%. This shows that further increasing CSA content enhances water absorption and plasticity, reflecting a balance between stabilization and plasticity control. In its stabilized state, the CSA, which is high in calcium oxide (CaO), interacts with water through a cation exchange process; further dissociation may be responsible for the soil's PI reduction with the addition of the ideal percentages of SF mixes [35]. The reduction in plasticity index is triggered by the replacement of the smaller soil particles with CSA content. Hence, a reduction in the Plasticity Index (PI) generally indicates that the soil is becoming more stable, which reflects its ability to deform without cracking or breaking.

Table 4 Summary for Atterberg Limit for all sample

Sample	Liquid limit, LL (%)	Plastics limit, PL (%)	Plastics Index, PI (%)
Kaolin (Control Sample)	41	33	7
SF	91	81	10
CSA	46	45	0
Kaolin + 2% SF	38	30	8
Kaolin + 4% SF	38	32	7
Kaolin + 6% SF	41	35	6
Kaolin + 6% SF + 3% CSA	37	32	5
Kaolin + 6% SF + 6% CSA	40	35	5
Kaolin + 6% SF + 9% CSA	42	38	4

3.4 Compaction Characteristics

The standard proctor compaction test was employed to establish the maximum dry density (MDD) and optimum moisture content (OMC) of untreated kaolin, SF, and CSA, as well as kaolin combined with 2, 4, and 6% of SF, and the ideal percentage of SF with 3, 6, and 9% CSA is shown in Figure 4. The result indicates the MDD and OMC for untreated kaolin clay are 1.63 g/cm³ and 15.8%, respectively. The result of the compaction test of SF and CSA can be performed when mixed with kaolin due to the difficulties in generating consistency in the plastic limit (PL) test. It is seen from Figure 4 that after incorporating various percentages of SF and CSA, the maximum dry unit weight value drops from 1.606 g/cm³. The decrease in the maximum dry density can be ascribed to the compaction resilience resulting from the flocculation of soil particles throughout soil stabilisation [36].

The OMC enhanced with the inclusion of 2, 4, and 6% SF from 19.0% to 20.4%. However, adding up to 6% of CSA with 6% SF, the OMC of the sample decreased to 17.5%. When 9% CSA and 6% SF were added, the OMC rose slightly to 17.8%. This decrease in OMC is due to stabilizing agents displacing water from soil pores, preventing reabsorption. Hence, the percentage water contained in the soil decreased. Conversely, the increase in OMC is because CSA raises the soil temperature, requiring more water for bonding. The consistent proportion of stabilizing agent to original soil weight also reduces the mixture's binding capacity. These findings align with previous research [37].

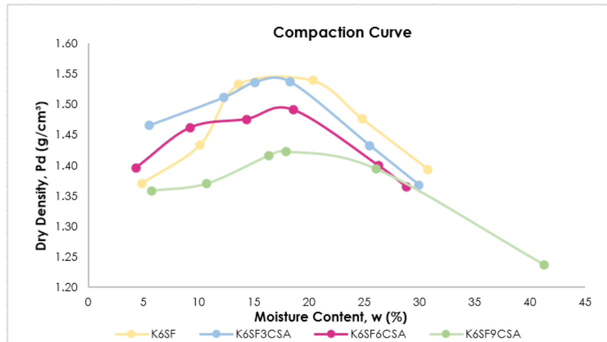


Figure 4 Compaction graph for kaolin treated with different percentages of CSA and 6% SF

3.5 Shear Strength

The addition of 6% SF and 9% CSA to kaolin clay led to a substantial improvement in strength as shown in Figure 6, reaching up to 93.71% after 120 days curing period, compared to the untreated kaolin clay at 6.95 kN/m². Overall, it was evident that the kaolin's UCS improved with an increase in SF, CSA, and curing time, as shown in Figures 5 and 6. After 120 days of curing, the shear strength of the mixture was 18.98, 20.91, and 24.92 kN/m² at 2, 4, and 6% of SF, according to the obtained results. Meanwhile, the addition of 3, 6, and 9% of CSA, as well as the optimum percentage of SF, increased the mixture's shear strength to 157.63, 212.10, and 253.43 kN/m² after 120 days of curing.

The percentage of shear strength improvement for all samples is tabulated in Table 5. Besides, the strength of improvement of the kaolin clay was 16.02%, 23.77%, and 36.02% for kaolin mixed with various samples of SF. The improvement in UCS value may be attributed to the production of chemical compounds such as calcium silicate hydrates and calcium aluminate hydrates, as well as alterations in the microfibres, which correspond to changes in the soil matrix's strength gain [38, 39]. Furthermore, Prior studies have demonstrated that snail and clam shellspossess the components found in ordinary Portland cement (OPCEM) that contribute to its strength, namely calcium oxide (CaO) and silicon oxide (SiO_2) [40]. The presence of CSA and SF in the chemical composition leads to the initiation of pozzolanic processes, thereby enhancing clay strength.

Table 5 Enhancement in shear strength in different samples after a 120-day curing period

Sample	Improvement (%)
K	0.00
K2SF	16.02
K4SF	23.77
K6SF	36.02
K6SF3CSA	89.89
K6SF6CSA	92.48
K6SF9CSA	93.71

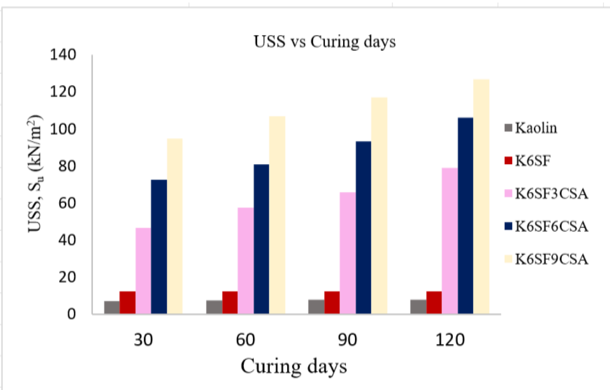


Figure 5 Shear strength graph for kaolin mixed with various percentages of SF

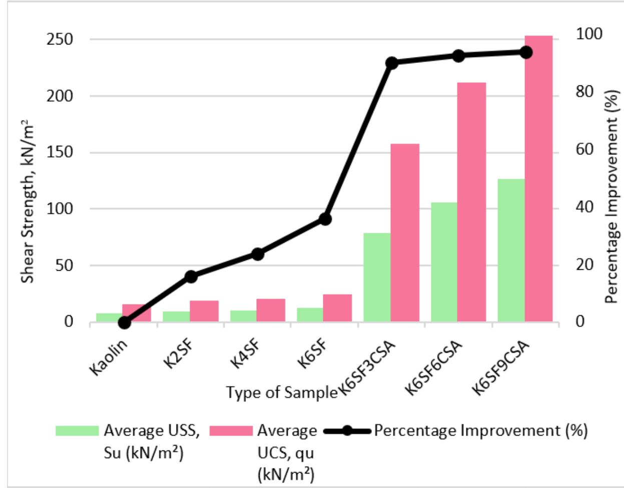


Figure 6 PSD curve of untreated kaolin and treated kaolin after 120 days curing with addition of (2,4,6% of SF) and optimum SF with (3,6,9% CSA)

4.0 CORRELATIONS EQUATION

Table 6 displays the correlation equation for four parameters: specific gravity, Atterberg limits, standard compaction test, and unconfined compression test.

Table 6 Correlations equation of the four variables

Test	Correlations Equations	R^2 Value	Variations (%)
Specific Gravity, Gs	$Gs = -0.0225SF + 2.615$	0.8248	82.48
	$Gs = -0.0053CSA^2 + 0.0378CSA + 2.6635$	0.5450	54.50
Atterberg Limit	$LL = 0.3562SF^2 - 2.0325SF + 40.535$	0.9900	99.00
	$PL = 0.4(SF)^2 - 2.13(SF) + 33.09$	0.9299	92.99
	$PI = -0.0437SF^2 + 0.0975SF + 7.445$	0.6133	61.33
	$LL = 0.1611CSA^2 - 1.1633CSA + 40.21$	0.7992	79.92
	$PL = 0.1222CSA^2 - 0.5CSA + 32.95$	0.8957	89.57
	$PI = 0.0389CSA^2 - 0.6633CSA + 7.26$	0.9935	99.35
Standard Proctor Compaction Test	$pd(max) = -0.0091SF + 1.5889$	0.6269	62.69
	$wopt = 0.22SF + 19.04$	0.9680	96.80
	$Pd(max) = -0.0139CSA + 1.5648$	0.8753	87.53
	$wopt = 0.1028CSA^2 - 1.1683CSA + 20.195$	0.8787	87.87
Unconfined Compression Test (UCT)	$Su = 0.7701SF + 7.5381$	0.9837	98.37
	$Su = -0.5343CSA^2 + 15.044CSA + 13.54$	0.9935	99.35
	$Su = 0.7502SF + 7.7665$	0.9870	98.70
	$Su = -0.8339CSA_2 + 18.875CSA + 13.528$	0.9961	99.61
	$Su = 6.0263SF + 1.9179$	0.9806	98.06
	$Su = -1.2693CSA^2 + 23.757CSA + 14.086$	0.9929	99.29

These parameters are utilised to identify the most suitable model for optimising the use of SF and CSA content stabilisers. According to the regression statistics used in the study, the coefficient of determination (R^2 value) for all parameters tested is greater than 0.5. Therefore, it can be shown that incorporating SF and CSA content accounts for 50% of the variability in the evaluated parameters, making the proven correlation the best model for predicting the optimal stabilizer dosage

5.0 CONCLUSIONS

This research has led to several significant findings, which are outlined as follows: After adding 6% SF and 9% CSA to the soil mixture, the proportion of larger particles was reduced, and smaller particles emerged. It showed that 16% of the particles were smaller than 0.063 mm. This is due to the combination of coarser CSA and finer SF, which changed the matrix of soil particles that filled the gaps between larger particles or bonded them together. Based on the results of the Atterberg limit test, the kaolin-SF-CSA mixture is classed as a silty or clayey sand by AASHTO. The LL and PL of kaolin are approximately 40.6% and 33.3%, respectively. The outcomes of treating kaolin with 6% SF and 9% CSA. LL and PL experience a 1.8% and 4.7% increase, respectively. The PI of kaolin decreased by 1% with a 6% increase in SF content, reducing from 7.3% to 6.6%. Similarly, the PI decreased by 2.2% with a 6% increase in CSA content, declining from 6.6% to 4.4%.

Furthermore, the maximum dry density (MDD) peak values of 1.424 g/cm3 at 9% CSA and 6% SF content, compared to 1.606 g/m3 of kaolin clay, were not ideal for soil improvement. Additionally, the decline in MDD can be ascribed to the restructuring of the soil particle structure, despite the increase in OMC which is necessary to facilitate the formation of CSH compounds and facilitate pozzolanic reaction among stabilizers and kaolin clay. Ultimately, the maximum shear strength recorded was 126.71kPa for soft clay stabilized with 6 % of SF and 9 % of CSA. The shear strength of this stabilised mixture increased by 93.71% compared to untreated kaolin clay. The combination of SF and CSA offers the potential to serve as a substitute material for construction purposes.

Acknowledgement

I would like to express my profound gratitude to all those who have contributed to the success of this research. I wish to extend my sincere thanks to my supervisor, Prof. Ts. Dr. Muzamir Hasan, whose guidance, expertise, and continuous encouragement have been invaluable throughout this research. His insight and constructive criticism have significantly enhanced the quality of this work, and I have learned immensely under his mentor ship. Furthermore, I would like to acknowledge the assistance of Geo-technical Laboratory staff for their exceptional contribution in assisting with laboratory tasks and technical support and also University Malaysia Pahang for providing the necessary resources and research facilities, which have been essential to the successful completion of this research.

Conflicts of interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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