Effectiveness of Silica Fume Eggshell Ash and Lime Use on the Properties of Kaolinitic Clay

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Abstract

The study aims to investigate the properties of kaolinitic clay using silica fume, eggshell ash, and lime. The experiment employs varying amounts of silica fume (2%, 4%, and 6%), eggshell ash, lime (3%, 6%, and 9%), and combinations of silica fume, eggshell ash, and lime, which are cured for 1, 7, 14, and 30 days. The investigated properties of the soils include the improvement of Atterberg limits, maximum dry density (MDD), optimum moisture content (OMC), specific gravity, compressive strength, morphology characteristics, and chemical compositions. The results reveal that the optimal application of these materials can be achieved at 6% silica fume, 6% eggshell ash, and 9% lime mixture into the soils and increase the shear strength by as much as 88.74% at 30 days of curing.

Keywords: kaolinitic clay, silica fume, eggshell ash, lime, soil stabilization

1. Introduction

Kaolinite is a mineral classified within the kaolin group of clay minerals, characterized by the chemical formula $Al_2Si_2O_5(OH)_4$. Kaolinite is the primary mineral component of kaolinitic clay [1]. Meanwhile, Kaolinitic clay contains a significant proportion of kaolinite minerals [2]. Kaolinitic soil is a challenging soil type commonly encountered in construction projects, known for its problematic properties related to changes in moisture levels [1-3]. These soils are characterized by a range of engineering characteristics and weaknesses, which include significant sediment retention, low shearing strength, insufficient plasticity, excessive compressibility, dispersion, enlargement, erosion, or vulnerability to environmental factors [4-5]. A significant concern for the entire country is that these problematic soils may lead to disasters and the related costs of repairing and rebuilding structures. Kaolin is an important type of clay mineral, highly resistant to other types of clay minerals [6-7]. Therefore, techniques such as soil stabilization and soil improvement have been proposed by previous researchers to modify the technical properties and boost the shear strength of unstable soils, including kaolinitic clay [8].

Soil improvement aims to enhance the existing soil properties to meet the requirements of construction projects [9-10]. Mixing problematic soil with waste from industry, agriculture, and other sources is one of the latest approaches to improving soils [11]. Among the latest approach to soil improvement is to substitute disconcerted soil with materials such as concrete, geotextiles, and geocross sections [4]. Current studies explored the application of waste as an ideal option for construction materials in various development projects. The utilization of industrial waste, such as fiber waste, sludge, fly dust, rubber chips, etc., as a substitute for soil improvement [5, 8]. Furthermore, previous researchers have also focused on the utilization of pozzolan in the manufacture of composite cement. Examples of pozzolans include igneous ash [6] and leaf ash [2], which are

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noteworthy as supplementary cementitious materials due to their high silica content, ready availability, and evident pozzolanic properties. Nevertheless, the plentiful supply of waste in the agro-degradable sector has caught the interest of scientists as a possible means to improve soil quality [12].

Agroresidue material, such as eggshell waste, can be used because eggshells, which are mostly composed of calcium carbonate ($CaCO_3$), can minimize the amount of cement necessary to create concrete [13]. With more than nine million tonnes of eggshell waste produced each year around the world, it's clear that there is a rise in egg production as Canada and France produce over 2 billion and 1 billion eggs per year [8, 14]. As a result, approximately 160,000 tons of eggshell waste are produced and disposed of in landfills each year [14]. Furthermore, the use of eggshell waste could reduce the amount of waste sent to landfills, contributing to sustainability efforts [15]. Nevertheless, it is necessary to stress that the applicability of this approach depends on the specific characteristics of the soil, the level of eggshell waste, silica fume (SF), and lime (L) used in combination with methods for mixing these materials [14]. Furthermore, eggshell waste has the potential to introduce contaminants or pathogens that could adversely affect soil quality and human health [12].

Previous studies have investigated the application of SF, eggshell ash (ESA), and L as soil stabilizing agents, but none have reported on the combinations of these materials. A study conducted by Hasan et al. [14] investigating the effect of SF and ESA on the engineering properties of the kaolinitic soil proved that the utilization of SF and ESA did alter the engineering properties of the soil and increase the strength of the kaolinitic soil up to 68.8%. On the other hand, Zaini and Hasan [8] investigated to determine the effect of the SF and L on the stabilization of problematic soil which proved that the materials do contribute to the improvement in various engineering properties and strengths.

This study investigates the use of SF, ESA, and L for soil stabilization. The kaolinitic clay was stabilized by using various percentages of SF with weight percentages of 2%, 4%, and 6%. The weight percentages of ESA and L used are 3%, 6%, and 9%. The stabilizing potential of these materials is compared based on the improvement of kaolinitic clay properties such as Atterberg limits, maximum dry density (MDD), optimum moisture content (OMC), specific gravity, compression strength, morphology characteristics, and chemical compositions. In the past, there had been research showing the comparison between the stabilizing potential of SF, ESA, and L on kaolinitic clay. Therefore, the utilization of SF and ESA with L via soil mixing technique can provide an ideal and sustainable solution in cement replacement material as it can alter the geotechnical properties and significantly enhance the strength of the kaolinitic clay soil. Finally, the utilization of ESA from eggshell waste can reduce pollution by reducing the production of waste in landfills and reducing carbon dioxide emissions to the environment.

This study instigates the utilization of ESA as a new soil stabilization method and technique for kaolinitic clay soil. As compared to the conventional methods, the illustrated method is practical to enhance the shear strength of the kaolinitic clay soils. Besides, the study also appraises the effect of ESA and L fuse with SF on the shear strength parameters of the kaolinitic clay soil. Thus, the sequel of the research contributes to better knowledge and understanding of the behavior of the ESA related to soil stabilization in kaolinitic clay soil.

2. Methodology

In this section, the methodology proposed was further discussed to achieve the objectives of the research including laboratory testing and procedure, calibration work, and the analysis of the data that were performed. The research was started by selecting the soil stabilization technique followed by the choosing and collecting of the research materials. The materials in the research such as kaolinitic clay soil, SF, ESA, and L were tested to determine their respective characteristics by laboratory testing following the American Society of Testing Material (ASTM) and British Standard (BS).

2.1. Materials selection

The site of the materials used in the study, including kaolin, SF, ESA, and L, is depicted in Fig. 1. The kaolinitic clay used was acquired from Kaolin (Malaysia) Sdn. Bhd, located in Selangor, Malaysia. The soil was utilized to generate consistent kaolinitic clay samples. The primary characteristics of the soil used in the experiment are presented in Table 1. SF is an extremely pozzolanic material that contains a significant quantity of amorphous silica. Fig. 1 shows the location of the supplier for the compacted gray SF, Scancem Materials Sdn. Bhd, Malaysia. This fine material has a 56% finer sieve of 0.075 mm and is mainly made up of spherical amorphous silicon dioxide (SiO_2). The scanfume concrete-densified SF used in this can trigger pozzolanic activity, making it highly reactive. The eggshell was collected from local restaurants in Pahang, Malaysia.

Table 1 Fundamental properties of kaolinitic clay, silica fume, eggshell ash, and lime

Parameters	Unit	Kaolinitic clay	Silica fume	Eggshell ash	Lime
Gravel	%	0	0	0	0
Sand	%	40.55	51.40	73.21	18.33
Clay and silt	%	59.45	48.60	26.79	81.67
AASHTO	-	A-5	-	-	-
Specific gravity	-	2.62	2.33	2.38	2.35
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 compressive strength	kN/m^2	13.15	-	-	-
Undrained shear strength	kN/m^2	6.58	-	-	-
pH	-	4.5	6.89	6.32	9.21

Note: AASHTO, American Association of State Highway and Transportation Officials

The resulting ESA is coarser in texture, with only 24% passing through a 0.075 mm sieve. ESA was chosen as a stabilizer in this study due to the abundant availability of eggshell waste and its sustainability compared to other stabilizers such as cement. ESA can also be obtained from Egg Tech Manufacturing Sdn. Bhd., located in Selangor, Malaysia. The L was obtained from CAO Industries Sdn. Bhd., located in Selangor, Malaysia, was considered reasonably priced and affordable. In this study, SF and L were utilized due to their high pozzolanic reactivity characteristics which can react with calcium hydroxide [$Ca(OH)_2$] to form additional cementitious compounds. Moreover, ESA contains massive calcium ions that can react with clay minerals and other components of the kaolinitic clay soil. The combinations of SF, ESA, and L as kaolinitic clay stabilizing agents can repair soil structure, enhance strength, promote flocculation, and increase the durability of kaolinitic clay soil.

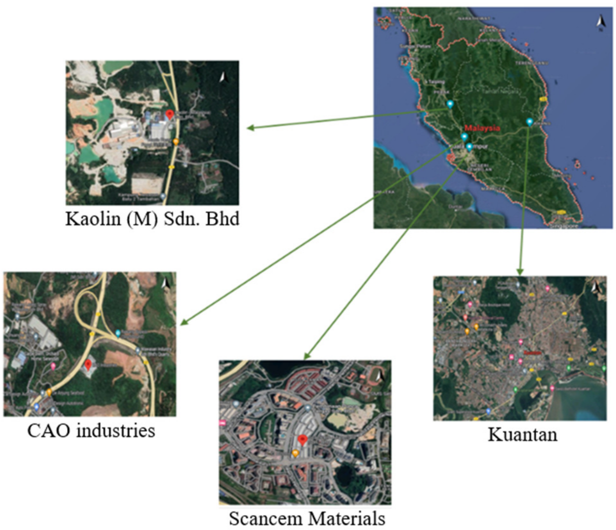


Fig. 1 Spatial distribution of the investigated materials

2.2. Preparation of sample

Multiple laboratory tests were performed on different mixtures, including kaolin, SF, ESA, and L, as well as kaolinitic soil admixtures with SF, ESA, and L as depicted in Fig. 2. The different proportions of stabilizers used in the study were decided to refer to previous research conducted by Zaini and Hasan [8] and Hasan et al. [14] and using a trial-and-error method. The sequences involved altering kaolin with SF, then with SF-ESA, followed by SF-L, and finally kaolin altered with SF-ESA-L.

At first, the kaolinitic soil was mixed with three different proportions of SF and was tested under an unconfined compression test (UCT). The mixture that led to the optimum value of strength was fixed and was continuously tested following the sequence mentioned before. Kaolinitic soil was desiccated in an oven at 110 °C for 24 hours and mixed with SF in different proportions (2%, 4%, and 6%) based on the total dry soil weight.

The kaolinitic-SF admixture was further admixed with various amounts of ESA and L, i.e., 3, 6, and 9 % based on the total dry soil weight. The ESA used in this study was made by cleaning chicken eggshells with tap water, drying them for seven days, crushing them with a crushing machine, and then calcinating them at 700 °C for 90 minutes in an industrial furnace. The proportions of SF-ESA and SF-L admixtures used were chosen based on the findings of Hasan et al. [14]. Soil samples were collected to be used in the compression test by combining the soil with its optimum water content. The specimens have been placed and compacted in a steel mold with a dimension of 76 mm in height and 38 mm in diameter. For each sample tested, five samples were prepared and subjected to different curing periods of 1, 7, 14, and 30 days.

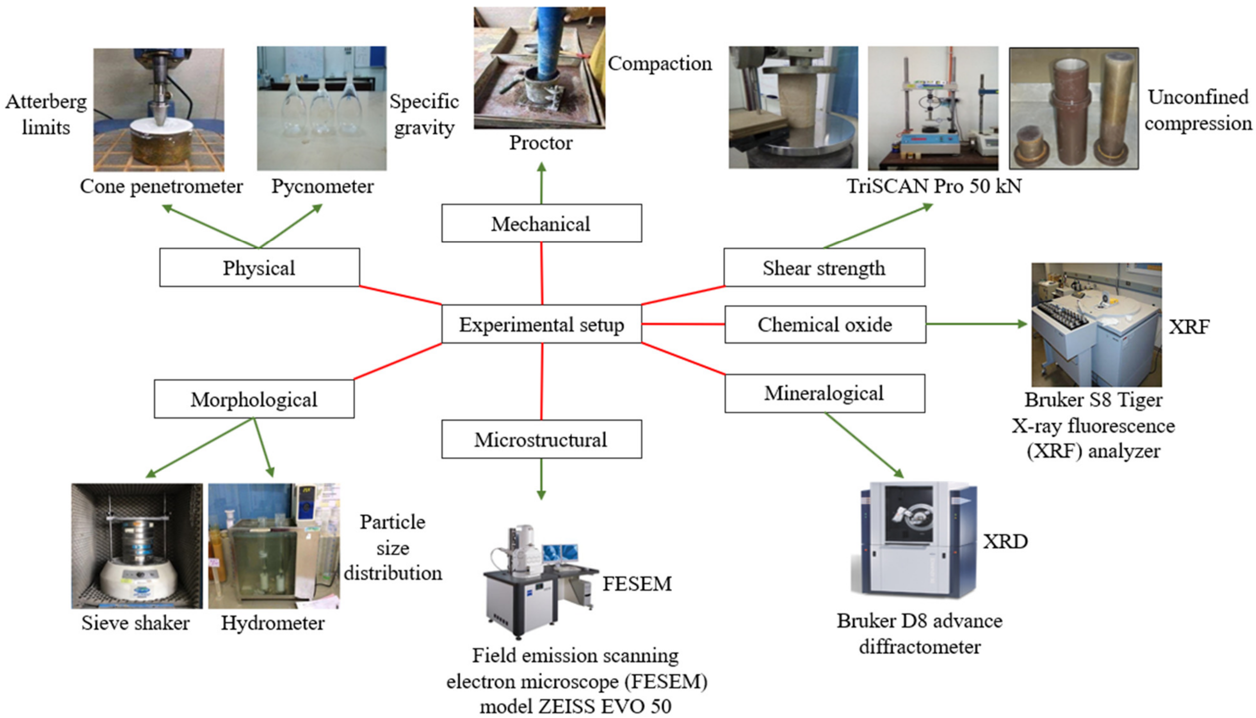


Fig. 2 Experimental setup for kaolinitic clay analysis

2.3. Characteristics of materials

The physical properties of the treated and untreated kaolinitic clay were evaluated using the Atterberg limit and specific gravity test. Atterberg limits can be used to quantitatively measure the plasticity range of clay soil. The soil can be found in four phases, namely solid, semi-solid, plastic, and kaolin liquid, depending on the moisture content. To determine the liquid and plastic limits (PL), cone penetration methods were used, and these tests were carried out following the guidelines of BS 1377-2:2022 [16]. The plasticity index (PI) is the numerical difference between the liquid limit (LL) and the PL, indicating the range of water content in which the soil exhibits plastic properties [16].

A small-scale pycnometer test was performed following BS 1377-2:2022 [16] to calculate the specific gravity of kaolinitic clay and altered kaolinitic clay. Distilled water was first poured into a small pycnometer bottle, filled halfway, and then the kaolinitic clay was added to the bottle. The specific gravity of the kaolinitic clay was determined by weighing the pycnometer and calculated after removing air from the sample, which was then left in a vacuum chamber for a day.

2.4. Physical behavior of materials

The mechanical properties of treated and untreated kaolinitic clay were evaluated using a standard compaction test based on the BS 1377-2:2022 [16] standard. By using the free fall method, three layers were formed and compacted one by one with 25 blows for each layer and the distance from the tip of the hammer to the soil of approximately 30 cm. This test involved determining the OMC and MDD of the materials.

2.5. Shear resistance of materials under undrained conditions

The strength characteristics of the untreated and treated kaolinitic clay were evaluated by performing UCT tests. Both treated and untreated kaolinitic clay had a density of 1.74 kg/cm^3, which was consistently maintained in the UCT tests to ensure the consistency of the data. The mass of the sample was manipulated so that all of the samples tested for UCT would have the same density. ASTM D1266-16 [17] was followed to perform the UCT test. This study investigated the effects of various mixtures of SF, ESA, and L on the mechanical characteristics of samples treated with different setting times (1 day, 7 days, 14 days, and 30 days.)

2.6. Chemical constituents and mineralogical characterization of materials

The chemical oxide compositions of the kaolinitic soil, SF, ESA, L, and kaolinitic clay admixtures with varying proportions of SF, ESA, and L were analyzed using a Bruker S8 Tiger X-ray fluorescence (XRF) analyzer according to ASTM standards E1621-13 [18]. For this test, 10 g of each of the samples was gathered and stored in an airtight plastic bag before being dispatched to the laboratory for testing. The results of this analysis were essential in assessing the suitability of SF, ESA, and L as stabilizing agents for the kaolinitic clay based on their respective chemical oxide compositions.

The mineral and crystallography of kaolin, SF, ESA, L, and kaolin mixed with various percentages of SF, ESA, and L were analyzed using the Bruker D8 advance diffractometer at the 2-theta (2θ) position with ASTM standards D3906-19 [19]. 10 g of each sample was gathered and retained in an airtight ductile bag before being sent to the laboratory. XRD analysis is crucial to complement the XRF analysis conducted.

XRD allows examination of the phases in crystalline substances, which further examines the composition of the substances and gives information on the calcium oxide (CaO), $CaCO_3$, $Ca(OH)_2$ constituents, and other calcium (Ca) phases or iron (Fe) phases, such as iron oxide (FeO), iron trioxide (Fe_2O_3), iron oxide black (Fe_3O_4), iron carbide (Fe_3C), and other Fe phases. Consequently, compounding the results of both the mineralogical and chemical oxide composition approaches permits a finer and more absolute delineation of any given crystalline specimen.

2.7. Physical structure of materials

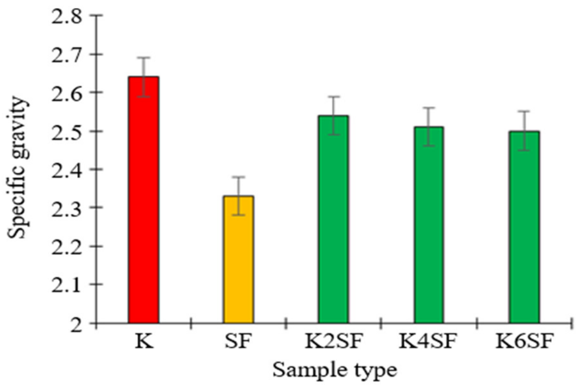
BS 1377-2:2022 [16] was referred to perform the sieve analysis. The grain size distribution of the fine soil was determined through the hydrometer test [20]. A set of sieves with various opening sizes, ranging from 20 mm to 0.063 mm, was used to analyze the particle sizes of both untreated and treated kaolinitic clay. A distribution curve was plotted based on the fraction of particles sustained in each sieve. A semilogarithmic graph was used to plot the percentage passing versus the particle size outcomes. The similarity of the classification group of the soil material was established by comparing the results of the altered and unaltered kaolinitic clay.

3. Findings and Interpretation

In this section, a detailed discussion was made regarding the results obtained from various laboratory test conducted to meet the objective of the study. The physical properties, mechanical properties, strength properties, chemical oxide compositions, mineralogical properties, and structural morphology were discussed in detail.

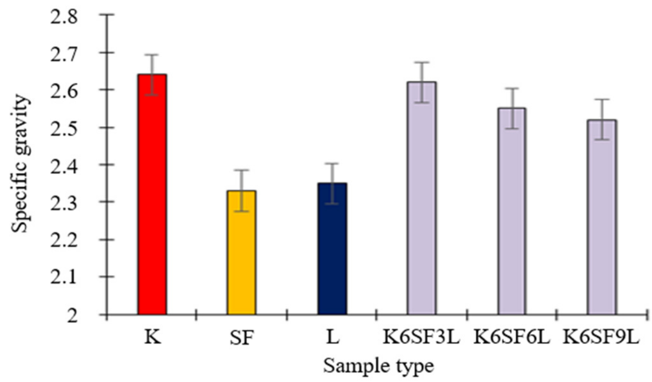
3.1. Physical properties of kaolinitic clay and altered kaolinitic clay

Fig. 3 shows the specific gravity values of the altered and unaltered kaolinitic clay samples, including those altered with SF, ESA, and L, and various combinations of these stabilizers. As shown in Fig. 3, the specific gravity of the kaolinitic clay altered with 2%, 4%, and 6% SF is substantially higher than that of the raw SF. However, the specific gravity of the altered kaolinitic clay is less than that of the unaltered kaolinitic clay. A higher specific gravity indicates that the soil particles are in denser and more closely packed conditions [21]. The arrangement of particles in the altered kaolinitic clay is denser compared to the raw SF, however, due to the various percentage replacement of SF in the soil, the particle arrangement of the altered kaolinitic clay became less dense than the untreated kaolinitic clay. Thus, leading to the specific gravity reduction.



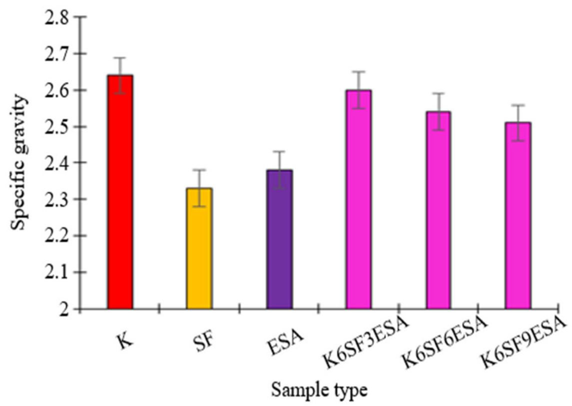
(a) SF

Note:
K2SF, kaolin with 2% of SF;
K4SF, kaolin with 4% of SF;
K6SF, kaolin with 6% of SF



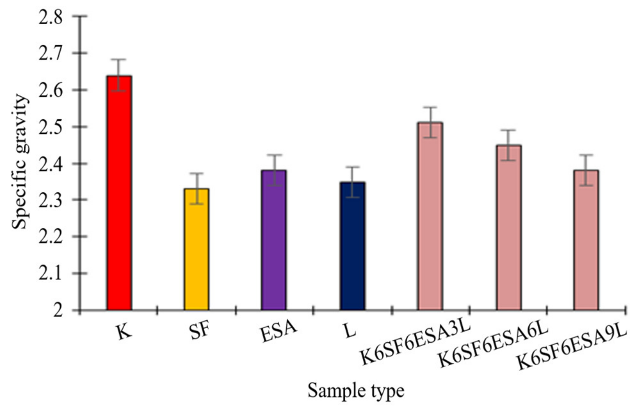
(b) SF-L

Note:
K6SF3L, kaolin with 6% of SF & 3% of L;
K6SF6L, kaolin with 6% of SF & 6% of L;
K6SF9L, kaolin with 6% of SF & 9% of L



(c) SF-ESA

Note:
K6SF3ESA, kaolin with 6% of SF & 3% of ESA;
K6SF6ESA, kaolin with 6% of SF & 6% of ESA;
K6SF9ESA, kaolin with 6% of SF & 9% of ESA



(d) SF-ESA-L

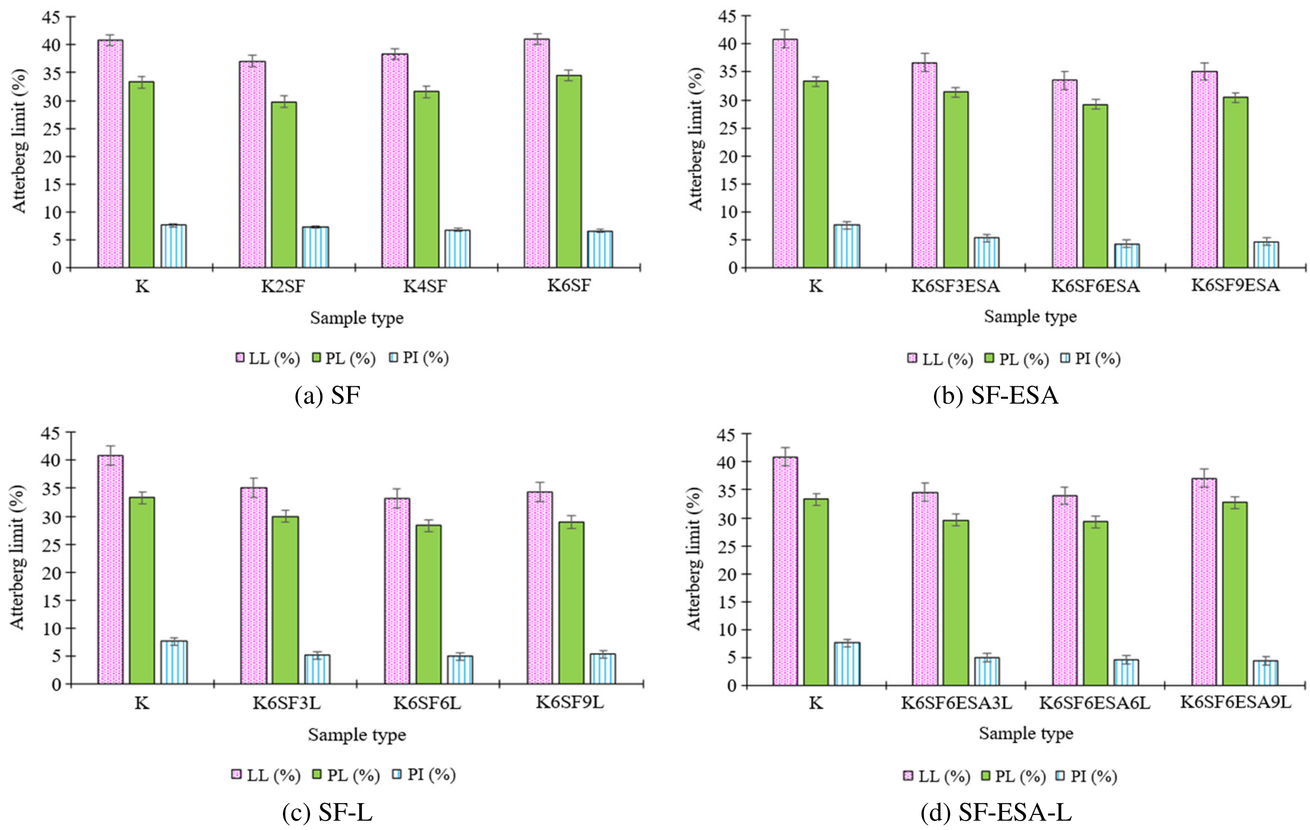
Note:
K6SF6ESA3L, kaolin with 6% of SF, 6% of ESA & 3% of L;
K6SF6ESA6L, kaolin with 6% of SF, 6% of ESA & 6% of L;
K6SF6ESA9L, kaolin with 6% of SF, 6% of ESA & 9% of L

Fig. 3 Stabilizer ratios' impact on altered kaolin specific gravity vs. unaltered kaolinitic soil (K)

Similar findings were reported by Hasan et al. [14] regarding the use of SF in the stabilization of kaolinitic clay. The trend is also examined by altering the kaolinitic clay with various amounts of ESA, L, and ESA-L combinations. Using higher ratios of stabilizer in the treatment leads to greater reductions in specific gravity. The largest reduction in specific gravity was observed when the kaolinitic clay was altered with various proportions of ESA and different ratios of L, resulting in a specific gravity of 2.51 (a reduction of 4.92%), 2.45 (a reduction of 7.20%), and 2.38 (a reduction of 9.85%), respectively. The diminution in specific gravity was similar for various proportions of ESA and L, with a reduction of 1.52%, 3.79%, and 4.92% for ESA and 0.76%, 3.41%, and 4.55% for L.

The increase in SF, ESA, and L caused substantial changes in the consistency limits. The results of these tests, including PL, LL, and PI for both unaltered and altered kaolinitic clay samples with varying proportions of SF, SF-ESA, SF-L, and SF-ESA-L, were shown in Fig. 4(a) to Fig. 4(d). As per Fig. 4(a), the utilization of SF reduced the PL and LL of kaolinitic clay to 2% and 4%, from 33.3% to 29.8% and 31.6%, and from 41.1% to 37.1% and 38.4%, respectively. Nonetheless, the addition of 6% SF increased PL and LL to 34.5% and 41.1%. The PI of the SF-altered kaolinitic clay sample persistently decreased at 2%, 4%, and 6% from 7.6% to 7.3%, 6.8%, and 6.6%.

An increase in SF content reduced the PI of kaolinitic clay, leading to improved soil workability. The rise in PL at 6% of SF could be due to the exchange of cations between the kaolinitic states and the cationic ion present in SF. Similarly, the expansion of the dispersed dual layer, initiated by alterations in a particular volume, resulted in an increase in LL at 6% of SF. The substitution of nonplastic SF molecules for highly plastic clay molecules resulted in the depletion of the clay's plasticity properties. Furthermore, including SF in the kaolinitic clay causes flocculation, leading to a decrease in the PI. Similar investigations were conducted in the examination by Hasan et al. [14] and Türköz et al. [22].



(a) SF (b) SF-ESA

(c) SF-L (d) SF-ESA-L

Fig. 4 Stabilizer ratios' effect on altered kaolin consistency limits vs. unaltered kaolinitic soil (K)

ESA and L have nearly identical chemical compositions, with L having slightly higher levels of SiO_2 and CaO than ESA. Fig. 4(b) and Fig. 4(c) show a reduction in PL and LL of the altered kaolinitic clay with increasing ratios of ESA and L with values decreasing from 33.3% to 31.4%, 29.2%, 30.4%, and 30.0%, 28.3%, 29.0%, respectively. Increasing the L-ESA ratio also results in lower PI values. The SF-ESA-L compound (see Fig. 4(d)) has a massive content of SiO_2 and CaO content, resulting in increased volume and intensified molecular adhesion in the altered kaolinitic clay, resulting in significant reductions in PL, LL, and PI. Türköz et al. [22] also found that increasing the L content in a fixed proportion of SF and ESA at 6% usage reduces PL due to the migration of cation between calcium aluminate hydrate (CAH) and Ca^{2+} in ESA and L.

3.2. Mechanical properties of kaolinitic clay and altered kaolinitic clay

The association between MDD and OMC of altered kaolinitic clay with multiple degrees of SF, ESA, and L is shown in Fig. 5. The unaltered kaolinitic clay had an MDD of 1.55 g/cm^3 and an OMC of 21%, which is identical to the findings reported by previous investigations [23-24]. The kaolinitic clay samples showed a reduction in MDD and OMC value when the soil was altered with 2% SF, with an MDD and OMC of 0.04 g/cm^3 and 3.0%. MDD steadily increased to 1.51 g/cm^3 and 1.52 g/cm^3 when SF levels of 4% and 6% were used, while OMC continuously decreased to 17.5% and 17.9%, respectively. The increase in OMC was symmetrically limited, due to the lower specific gravity and heterogeneous particle size of the SF, resulting in the formation of enlarged cavities

However, the findings were contradictory to the research by Türköz et al. [22], which showed that the use of 2%, 4%, and 6% of SF reduced the specific gravity of kaolinitic clay but did not substantially affect its grain size, resulting in a slight reduction in OMC for the different utilization ratios of SF. This may be due to the inconsequential replacement of SF, which displaces kaolinitic clay particles during treatment.

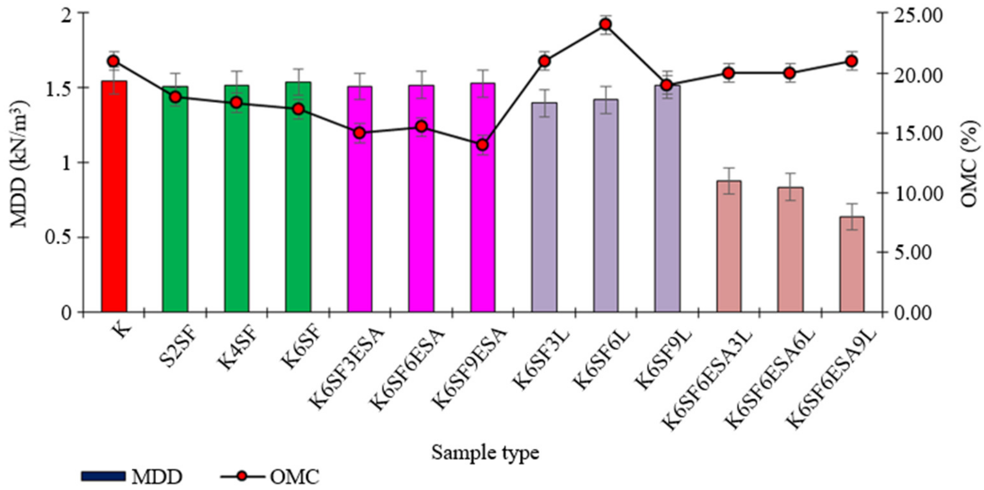


Fig. 5 OMC and MDD relationship in altered and unaltered kaolinitic clay

At the optimal 6% SF level, the kaolinitic clay was further altered with multiple proportions of ESA and L singularly and in ESA-L composites. The results revealed a substantial reduction in MDD with values ranging from 1.51 to 0.64 g/cm^3 compared to 1.55 g/cm^3 for unaltered kaolinitic clay. The reduction in MDD and OMC was attributed to the saturation, segregation, and pozzolanic transformation that occurred during the SF-ESA and SF-L assortments. Hence, the addition of ESA and L caused the kaolinitic clay elements to pack closely, altering the specific area of the sediment sample. As a result, water absorption was necessary to initiate the chemical reaction between the fine molecules, which ultimately improved the kaolinitic clay. In the presence of water, ESA and L act as flocculation agents in kaolinitic clay soil which reduces the electrostatic repulsion during the interaction of the stabilizers and the kaolinitic clay particles [15].

Through this process, the kaolinitic clay elements become closely packed which increases the particles-to-particle contact and reduces sediment void spaces in the sample. Besides, the alterations of the kaolinitic clay elements into closely packed particles lead to the reduction of the available surface area per unit volume caused by the reduction of the sediment void spaces of the sample [14].

3.3. Unconfined compressive strength of kaolinitic clay and altered kaolinitic clay at various curing times

Fig. 6 and Table 2 show the unconfined compressive strength (UCS) of unaltered kaolinitic clay and altered kaolinitic clay with multiple degrees of SF, ESA, and L at different setting times. Primarily, the kaolinitic soil was altered with 2%, 4%, and 6% SF at setting times of 1 day, 7 days, 14 days, and 30 days. The compressive strength of kaolinitic clay increases gradually from 13.154 kN/m^2 to 13.794 kN/m^2 (1 day of curing), 16.534 kN/m^2 (7 days of curing), 18.238 kN/m^2 (14 days of curing), and 18.664 kN/m^2 (30 days of curing), when 2% of SF is admixed with kaolinitic clay. The maximum of 15.512 kN/m^2, 21.844 kN/m^2, 23.058 kN/m^2, and 24.530 kN/m^2 was reached at different curing times of 1 day, 7 days, 14 days, and 30 days when 6% of SF was utilized.

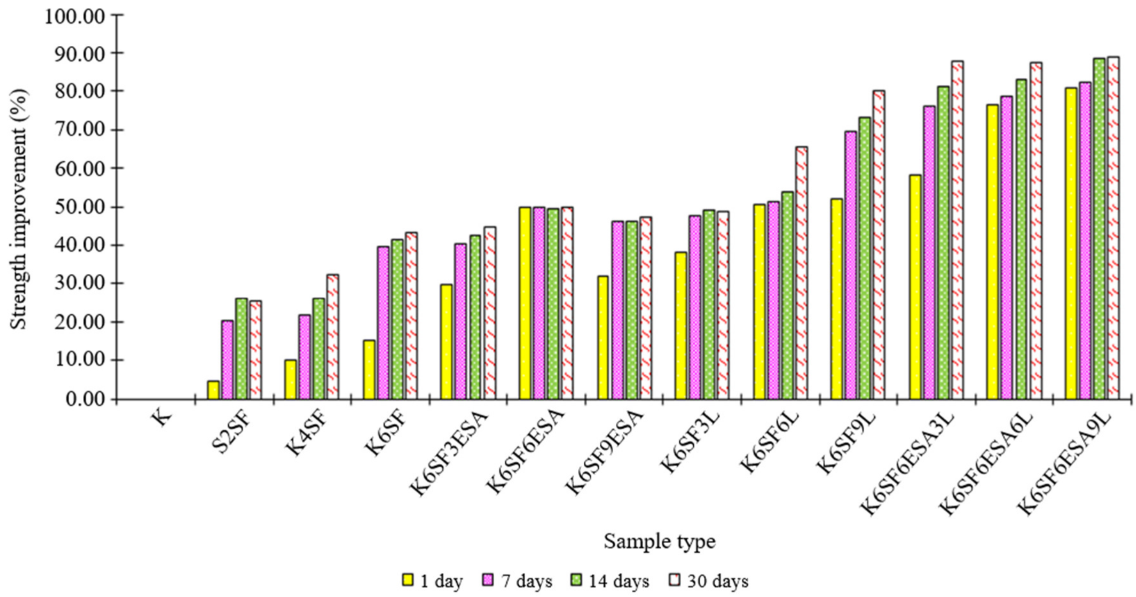


Fig. 6 Impact of stabilizer proportions on compressive strength in altered and unaltered kaolinitic clay

Table 2 Unconfined compressive strength variation with SF, ESA, and L inclusions at four different curing days

Sample	Unconfined compressive shear strength (kN/m^2) at various curing days			
	1 day of curing	7 days of curing	14 days of curing	30 days of curing
K	13.154	13.178	13.482	13.896
K2SF	13.794	16.534	18.238	18.664
K4SF	14.662	16.844	18.272	20.554
K6SF	15.512	21.844	23.058	24.530
K6SF3ESA	18.728	22.068	23.498	25.192
K6SF6ESA	26.240	26.306	26.734	27.670
K6SF9ESA	19.378	24.514	25.152	26.460
K6SF3L	21.328	25.144	26.486	27.168
K6SF6L	26.702	27.104	29.346	40.222
K6SF9L	27.376	43.078	50.324	70.242
K6SF6ESA3L	31.582	55.528	71.592	112.452
K6SF6ESA6L	56.034	61.944	79.496	110.462
K6SF6ESA9L	69.344	75.150	117.144	123.436

The reinforcement of soil structure is due to the presence of adequate amounts of amorphous silica and alumina in SF that can trigger the pozzolanic reaction in the soil, which is consistent with previous investigations of Zaini and Hasan [8] and Mahmutluoğlu and Bağrıaçık [25]. Consequently, 6% SF was used for the subsequent reinforcement in the strength of kaolinitic clay, irrespective of the setting time. In the presence of moisture and calcium hydroxide, SF undergoes a pozzolanic reaction which can lead to the formation of the calcium silicate hydrates (CSH) gel. The formation of the CSH gel contributes to the development of denser interlocked particles within the soil matrix thus effectively altering the mechanical characteristics of the kaolinitic soil [8].

The findings indicated that constant use of the SF-ESA-L admixture at various setting times resulted in a maximum UCS performance of up to 81.03%, 82.46%, 88.49%, and 88.74% strength enhancement. The use of L with SF and ESA exceeded the UCS value of unaltered and altered kaolinitic soil with SF, SF-ESA, and SF-L. However, the physical-chemical interactions that govern the material properties of altered admixtures kaolinitic are mechanisms that contribute to an improvement in soil strength. Moreover, the setting time is a crucial parameter that determines the level of sediment progression [25], leading to maximum enhancement in resistance to deformation through reactions such as dissociation and cation interchange, which enhance the link between soil molecules.

3.4. Effect of soil stabilizer on the shear strength parameters

The unconsolidated undrained (UU) test was performed to determine the shear strength of kaolinitic clay altered with different ratios of stabilizers by examining three samples of different penetration with various confining pressures (70kPa, 140 kPa, and 280 kPa). The improvement in the cohesion (c) and internal friction angle (Φ) for kaolinitic clay combined with various percentages of SF, ESA, and L significantly increases with increasing stabilizer content and curing times compared to the unaltered kaolinitic clay. According to Table 3, the improvement in the cohesion value after the kaolinitic clay was stabilized with SF, ESA, and L is significant, indicating a higher linking force between soil particles. Cohesion is defined as the force that holds particles together within the soil and a higher cohesion value results in a stronger linking force between soil particles. Zaini and Hasan [7] demonstrated a substantial increase in cohesion value through the use of soil stabilization. Therefore, this study provides evidence that the use of combinations of SF, ESA, and L in various percentages can increase the cohesion value of the samples by up to 18.1 kPa, which improves the linking force between soil particles.

Table 3 Variation with SF, ESA, and L inclusions at four different curing days

Sample	Stabilizer content (%)			1 day of curing		7 days of curing		14 days of curing		30 days of curing	
	SF	ESA	L	c (kPa)	Φ (°)	c (kPa)	Φ (°)	c (kPa)	Φ (°)	c (kPa)	Φ (°)
K	0	0	0	13.9	24.0	13.9	24.0	13.9	24.0	13.9	24.0
K2SF	2	0	0	10.0	24.8	10.5	25.2	11.0	25.7	11.6	26.3
K4SF	4	0	0	10.3	25.3	10.9	25.6	11.3	26.0	12.2	26.8
K6SF	6	0	0	10.7	26.1	11.2	26.3	11.9	26.5	13.0	28.0
K6SF3ESA	6	3	0	11.0	26.9	11.8	27.2	12.7	27.5	13.4	28.5
K6SF6ESA	6	6	0	11.6	27.0	12.6	27.8	13.1	28.1	14.6	28.9
K6SF9ESA	6	9	0	12.4	27.3	14.1	28.3	14.3	28.7	15.4	29.4
K6SF3L	6	0	3	13.9	27.5	14.6	28.6	15.1	29.1	15.8	30.3
K6SF6L	6	0	6	14.4	28.1	14.9	28.9	15.5	30.5	16.3	30.9
K6SF9L	6	0	9	15.1	28.9	15.3	30.2	15.9	31.1	16.7	31.5
K6SF6ESA3L	6	6	3	15.5	30.1	15.8	30.7	16.4	31.8	17.1	32.1
K6SF6ESA6L	6	6	6	15.9	30.5	16.1	31.1	16.8	32.3	17.5	32.7
K6SF6ESA9L	6	6	9	16.3	31.2	16.6	31.9	17.2	32.6	18.1	33.4

In addition, the highest improvement in shear strength was observed at an optimal friction angle of 33.4°. A higher friction angle is obtained when there is an increase in the shear stress and normal effective stress. The internal angle of friction is a crucial parameter in characterizing the shear behavior of soil. Strength, stability, and deformation properties can be determined using an internal angle of friction. Zaini et al. [15] demonstrated that the size of the particle of the material substantially influences the behavior of the altered kaolinitic clay, including the rigidity, the angle of friction, and the shear strength characteristics. Therefore, in this study, the kaolinitic clay altered with various percentages of stabilizers leading to higher shear stress and effective normal stress, which affected the friction angle.

3.5. Chemical oxide compositions of kaolinitic clay and altered kaolinitic clay

Table 4 shows the oxide compositions of kaolinitic clay both before and after treatment with SF, ESA, and L. To modify the properties of kaolinitic clay, it is essential to consider both the pozzolanic reactivity and the cementitious characteristics. Similar to cement, ESA and L undergo the hydration process, and previous research has examined the saturation products of ESA [14-15]. SiO_2 and CaO are crucial components of cementitious substances, and their ability to react with water is limited by the availability of water. Pozzolanic reactivity is a static interaction that can modify the engineering properties of kaolinitic clay depending on two factors: the amount of $Ca(OH)_2$ and the surface area of pozzolan. As the quantity of water increases during the hydration process, CaO will react with water to form calcium hydroxide. However, the dissociation reactions can result in rapid changes in the plasticity and workability of kaolinitic clay. Examples of physicochemical responses that influence the characterization of kaolin-SF-ESA-L mixtures include cation exchange, emulsification of kaolinitic clay molecules, accumulation, and pozzolanic processes.

Table 4 Chemical composition comparison of unaltered and altered kaolinitic soil

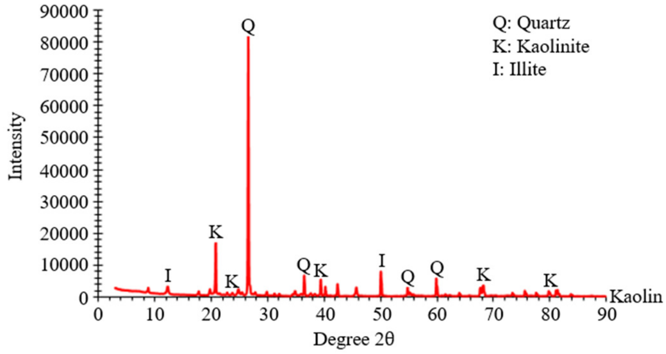
Sample type	Compositions (%)					
	SiO_2	CaO	Al_2O_3	Potassium oxide (K_2O)	Magnesium oxide (MgO)	Fe_2O_3
K	65.22	0.09	19.24	2.84	1.22	0.72
SF	73.21	0	0.45	4.27	3.73	0.71
ESA	0.02	62.5	0.01	0.05	0.71	0.02
L	1.4	72.6	0.38	0	1.03	0.34
K2SF	66.60	0.04	18.87	2.87	1.27	0.72
K4SF	70.02	0.04	18.48	2.90	1.32	0.72
K6SF	70.23	0.07	18.11	2.93	1.37	0.72
K6SF3ESA	60.64	1.96	17.53	2.84	1.35	0.72
K6SF6ESA	61.58	3.83	16.96	2.76	1.34	0.68
K6SF9ESA	64.60	5.68	16.38	2.67	1.33	0.65
K6SF3L	62.02	7.54	17.55	2.87	1.38	0.69
K6SF6L	63	9.41	16.98	2.79	1.36	0.64
K6SF9L	64.21	11.28	16.41	2.73	1.33	0.61
K6SF6ESA3L	64.51	13.15	14.39	2.72	1.32	0.58
K6SF6ESA6L	67.32	15.02	10.59	2.69	1.3	0.54
K6SF6ESA9L	69.31	16.89	9.23	2.64	1.27	0.49

According to Table 4, the majority of ESA (62.5%) and L (72.6%) are made up of CaO, while SF consists primarily of SiO_2 (73.21%). In this study, CSH and CAH can be formed with $Ca(OH)_2$ from ESA and L, and SiO_2 and Al_2O_3 from SF and kaolinitic clay, in the presence of moisture. The high content of SiO_2 in SF leads to a higher pozzolanic reactivity which can interact with kaolinitic clay particles via electrostatic attraction and adsorption of the surface. The alteration of kaolinitic clay using SF can lead to changes in surface charge properties and enhance the formation of larger flocculation and aggregation. The elemental analysis of SF, ESA, and L, concerning the SiO_2 and CaO contents, is similar to the investigations as examined by Hamada et al. [11].

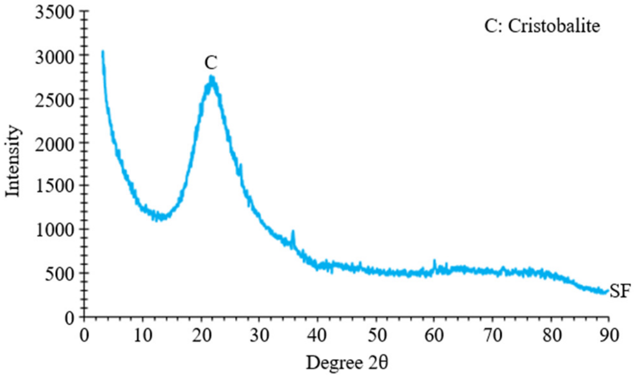
Consequently, SF contains a substantial amount of silica and is an excellent pozzolan that can be used as a soil-reinforcing agent. In addition, ESA and L react with pozzolanic elements to form a calcium silicate (Ca_2SiO_4) paste. CSH immediately fills and adheres to the kaolinitic clay fragments in the soil, sealing the soil pores. In addition, ESA and L slowly transform from the gel state to a clear state, resulting in interlocking between molecules in the problematic soil. However, this gel crystallizes into CSH, such as tobermorite and hillebrandite, which can increase the strength and decrease the expansion of the kaolinitic clay.

XRD analysis assisted in the conception of the mineral alterations, which occurred in soft kaolin clay on the inclusion of SF, ESA, and L in terms of crystalline stages, physical characterization of single elements, and the ideal combination [15]. The dominant minerals for kaolinitic clay comprised of quartz, kaolinite, and illite, cristobalite for the SF, calcite, and portlandite for the ESA and L, and kaolinite, quartz, calcite, cristobalite, and muscovite for the optimum amalgamation. SiO_2 was inherited dominantly from SF. The XRD patterns of kaolinitic clay, SF, ESA, and L are illustrated in Figs. 7(a) to 7(d), indicated the formation of new peaks based on the mineralogical compositions of the utilized materials. Identical investigations have been examined by Hasan et al., [14] on the behavior of SF and ESA stabilizers in kaolinitic clay.

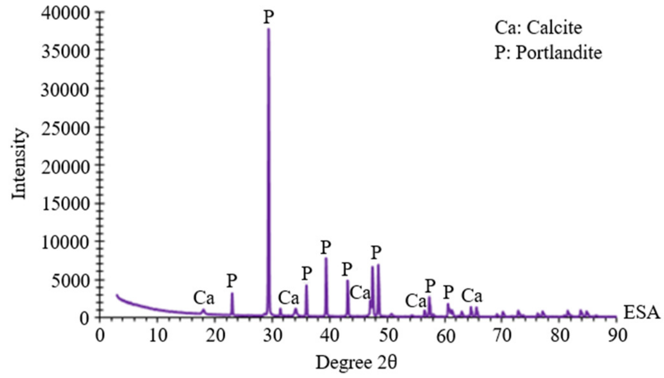
Fig. 7(e) demonstrates the XRD analysis of altered kaolinitic clay with different ratios of SF, SF-ESA, SF-L, and combinations of SF-ESA-L. The primary mineralogical components of kaolinitic clay are kaolinite and quartz, while illite is the minor phases. Zaini and Hasan [8] stated that most recurrent crystalline clay minerals comprise kaolinite, illite, smectite, and montmorillonite. Differentiation between the maximum points of soft kaolin clay as the primary material and the combination of kaolinitic clay with SF, SF-ESA, SF-L, and SF-ESA-L shows that the peak intensities of the quartz and kaolinite (see Fig. 7(e)) are slightly reduced than the unaltered kaolinitic clay due to the establishment of the cementation amalgamation.



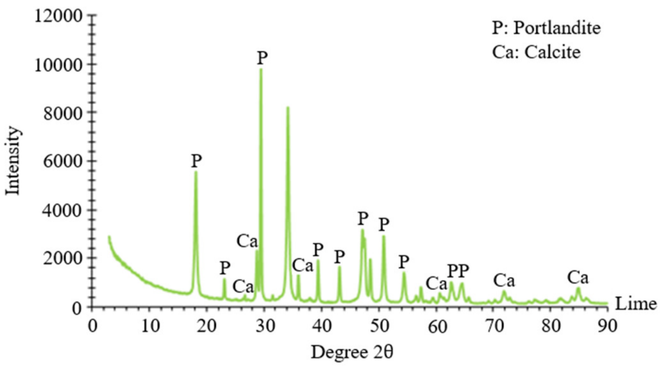
(a) Unaltered kaolinitic clay



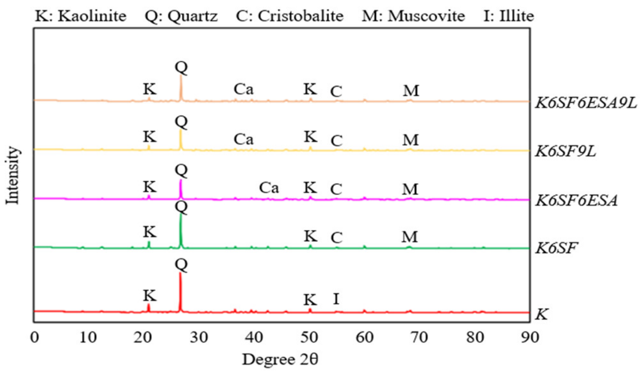
(b) Silica fume



(c) Eggshell ash



(d) Lime

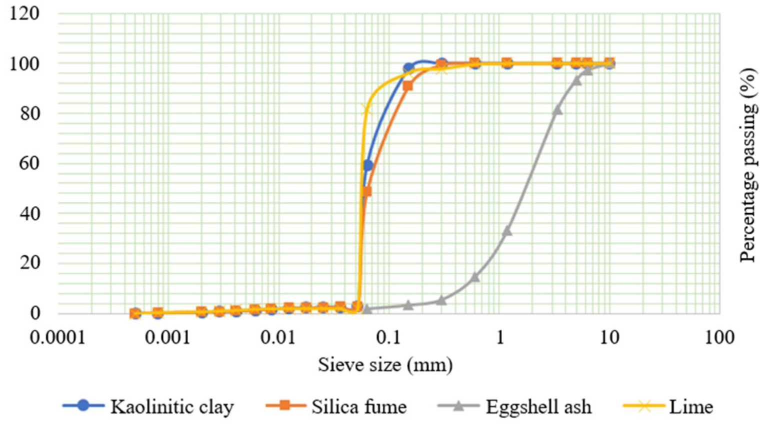


(e) Altered kaolin with optimum utilisation of SF, ESA, and L

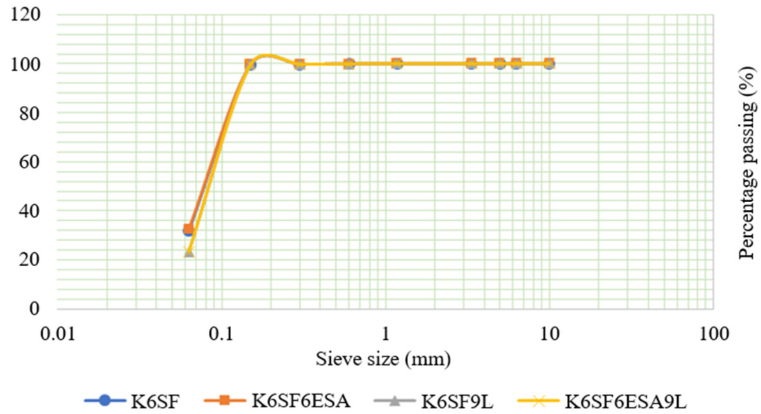
Fig. 7 XRD pattern

3.6. Structural morphology of the kaolinitic clay and altered kaolinitic clay

Fig. 8 shows that the addition of SF, ESA, and L to stabilize the kaolinitic clay led to the formation of a coarser sediment structure, which shifted the sieve curve of the altered kaolinitic clay toward the irregular side. The altered kaolinitic clay soil is classified as silty soil (A-5) according to AASHTO. The percentages of gravel, fine sand, clay, and silt in the altered kaolinitic clay were 0%, 40.55%, and 59.45%, respectively, when treated with 6% SF, 0%, 67.4%, and 32.8%, respectively, when treated with 6% SF and ESA, and 0%, 76.6%, and 23.4%, respectively, when altered with 6% SF, 9% L, and an association of ESA-L. When incorporating 6% SF, 6% ESA, and 9% L, the highest levels of pozzolan and CaO content were achieved, leading to the maximum undrained shear strength (USS), according to the UCT result. The morphology analysis of SF and ESA has been examined by Ofuyantan et al. [13] and Türköz et al. [22].



(a) PSD of unaltered kaolinitic clay, SF, ESA, and L

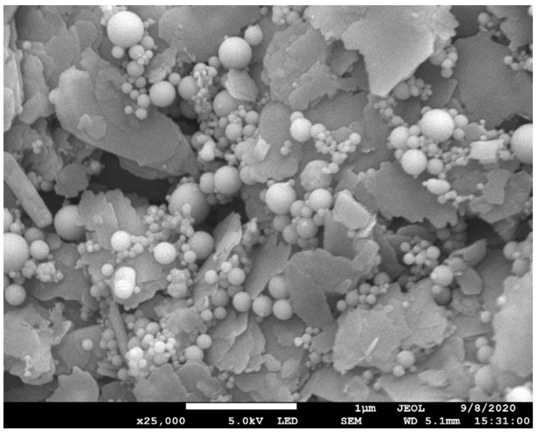


(b) PSD of altered kaolinitic clay

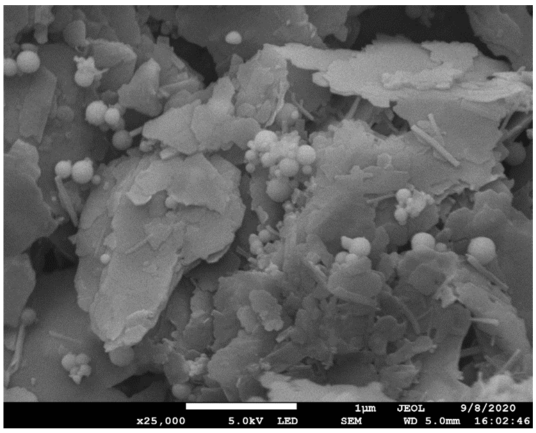
Fig. 8 Particle size distribution of kaolinitic clay, raw materials, and stabilized kaolinitic clay

3.7. Microstructural analysis of the kaolinitic clay and altered kaolinitic clay

Kaolinitic clay has a scabrous-shaped microstructure, while the SF molecule has a tiny globular shape with a molecule size of a thousand micrometers. The ESA and L molecules appeared to be the same because they had a rocky, scattered morphology and a fluctuating molecule size apportionment. Similar microscopic analysis has been examined by [14]. The inclusion of ESA and L is an identical sequel to morphological alterations. Based on Figs. 9(a) to 9(d), it can be examined that the scabrous and even molecules of kaolinitic clay shatter into uneven lumps upon the inclusion of SF, ESA, and L. This strengthens the linkage between the molecules, enhances the strength, and diminishes the plasticity indices. Identical investigations have been studied by Zaini and Hasan [8] on the effect of L on clays and Hasan et al. [14] on the effect of ESA on the kaolinitic clays.

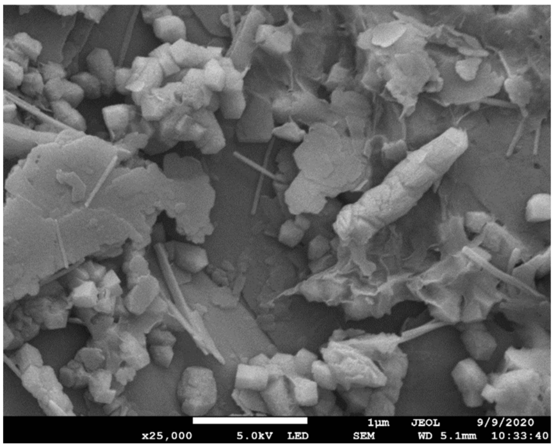


(a) Treated with 6% of SF

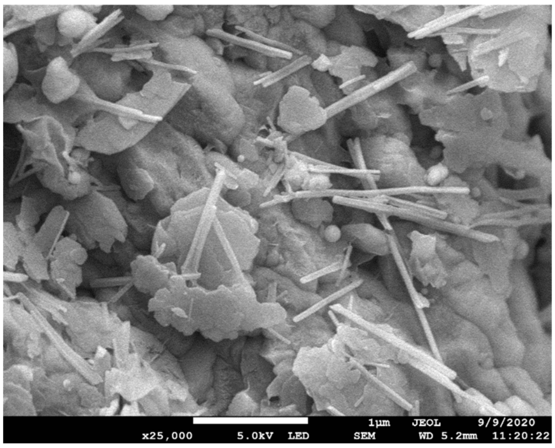


(b) Treated with 6% SF and 6% of ESA

Fig. 9 Morphological microstructure of altered kaolinitic clay



(c) Treated with 6% of SF and 9% L



(d) Treated with 6% of SF, 6% of ESA, and 9% of L

Fig. 9 Morphological microstructure of altered kaolinitic clay (continued)

The establishment of unpigmented cementitious amalgamation (CAH and CSH) on the surfaces of clay molecules acts as a criterion for pozzolanic reactivity (see Figs. 9(a) to 9(d)). Similar establishments have been reported for numerous types of soil [26-28]. Ca^{2+}, proffer by ESA and L, retaliates with the alumina and silica that exist in SF and kaolin throughout the pozzolanic reaction [15, 29]. Additionally, the flocculation and aggregation mechanism has taken place in the kaolinitic clay molecules when ESA and L are used as the microstructure of the kaolinitic clay is altered (see Fig. 9(d)).

4. Conclusions

The study explored the effectiveness of SF, ESA, and L to improve the geotechnical properties of kaolinitic soil such as compaction, Atterberg limits, shear strength parameters, particle size analysis, chemical oxide compositions, mineralogical, morphological and microstructure. The SF, ESA, and L mixtures are utilized with different percentages and combinations, and no previous research has been conducted. Therefore, the conclusions can be drawn as follows.

(1) The kaolinitic clay used in the study belongs to the A-5 group, classified as silty soil, with a LL of 41.1%, PL of 33.3%, and PI of 7.8%. Its specific gravity is 2.62, and the MDD is 1.55 kg/m^3 with an OMC of 21.00%. After the addition of SF-ESA-L, the kaolinitic clay falls into the A-4 group, classified as sandy soil (SM), with a specific gravity of 2.38 and a sand equivalent (SE) value of 26.31%. The altered kaolinitic clay with SF-ESA-L has a lower LL value of 36.6%, PL of 32.7%, and PI of 3.9%. The MDD decreases to 0.64 kg/m3, while the OMC remains at 21.00%.

(2) The optimal use of SF-ESA-L significantly improved the shear strength of the kaolinitic clay, increasing it from 13.154 kN/m^2 to 69.344 kN/m^2, resulting in an 81.03% strength improvement. The addition of SF, ESA, and L also altered the cohesion (c) and internal friction angle (Φ) of the kaolinitic soil, increasing them from 13.9 kPa and 24° to 18.1 kPa and 33.4°, respectively.

The study recommends using 6% SF, 6% ESA, and 9% L to enhance the strength of problematic soil and modify the characteristics of kaolinitic clay, resulting in improvements of up to 88.74% after 30 days of curing. For future applications, it is suggested to apply this soil stabilizing technique to real case studies for practical insights and validation. Additionally, assessing the performance of altered soils under different environmental factors will ensure the reliability of laboratory testing data in real construction projects.

Conflicts of Interest

The authors declare no conflict of interest.

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