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Original Article

Effect of optimum utilization of silica fume and eggshell ash to the engineering properties of expansive soil

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ABSTRACT

The utilization of substance stabilizer in soil improvement can diminish the obstructive ecological effect in the development business, and respond as the soil stabilizers to the kaolin clay soils. In any case, the improvement of kaolin clay stays a test because of the significant expense and non-eco-accommodating materials like concrete and lime. This examination exhibits the capacity of SF in the mix with ESA in stabilizing the delicate kaolin clay soils, by means of particle size distribution (PSD), specific gravity, Atterberg limits, compaction parameters and undrained shear strength (USS) parameters. Its impact on the undrained shear strength upgrade was concentrated through the concrete substitution material in kaolin clay soil at the replacement degree of 2%, 4% and 6% (by dry weight of kaolin clay soil) of SF and ESA replacements of 3%, 6% and 9% (by dry weight of kaolin clay and SF content). The consideration of SF with ESA shows a lower specific gravity (4.9% decrease), lower plasticity index (PI) (48.4% decrease), diminished maximum dry density (MDD) (5.5% decrease), expanded in optimum moisture content (OMC) (8.7% increase), and higher USS (68.8%) when contrasted with the untreated kaolin clay soils and those treated with SF. The blends of SF and ESA as soil adjustment specialists effectively upgrade the undrained shear strength of the kaolin clay soils up to 68.8% strength improvement with the best percentage of 6% SF and 6% ESA for optimum enhancement of the expansive soil, which minimizing the expenses and as an eco-accommodating materials in soil improvement.

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1. Introduction

Among these kinds of soil, clay soil is known for its dangerous properties by their natural ability to go through volumetric changes relating to changes in the dampness system [1–6]. Also, the subsequent catastrophes and the extended expense of healing and fixes of designs that are established on far-reaching soils is a worldwide concern [1,3,4]. Monetary misfortunes, legitimate cases, cost of protection for infrastructural and primary disappointments on the sweeping soils have been accounted for in the writing [5,7]. What has become even more unsettling is that, elated turns of events and reformist lodging on these clay appear to be unavoidable particularly with the uncommon ascent on the planet current populace [5,7,8].

Clay soil is flaky fit with molecule estimates under 2 μm (5 μm in some characterization framework) [9,10] and for the most part, has an enormous surface region with a predominant of oxide content of SiO_2, Al_2O_3 and Fe_2O_3 [11]. The clay body was a mixture in equal proportion of two natural kaolinitic clays, with higher (strong) and lower (weak) clay mineral contents with Loss on Ignition (LOI) of above 8.00% [9]. The little size of the molecule related to an exceptionally huge surface region causes the clay to display high capacity in holding water, subsequently making the swell-recoil trademark when subject dampness varieties [3,4,12,13]. Besides, the previous researcher had stated the liquid limit, plastic limit and plasticity index of the expansive soil which lies above 49.00%, between the range of 25.00%–30.10% and between 19.80%–30.40% respectively [10,11]. Such extensive properties have made the clay soil become a problematic soil that needs uncommon treatment for the development action [12,14]. The utilization of clay soils to fabricate the squares can be an effective option according to a useful perspective, chiefly by diminishing the expenses of mortar inclusion and effortlessness to construct the brickwork [11]. Along these lines, it is significant to upgrade and improve the clay properties utilizing adjustment procedures that can react to the exceptional interest circumstances.

Soil improvement is one of the standard strategies completed to overhaul the idea of black-top layers and road subgrade. This technique engages improving the current material properties at the errand site and meets the advancement subtleties [5,15,16]. The communication of soil improvement is for the most part used to improve the geotechnical and genuine properties of the clay. The latest procedure for soil improvement is to replace the confounded soil with more grounded materials like concrete, truly soil, geotextiles and geo-cross sections [16] settling subject matter experts. A segment of these stabilizer added substances includes various kinds of bitumen, pozzolanic added substances, lime and cement. Soil improvement or soil treatment with added substances is a very much educated and incredibly adroit strategy that has been used to improve the toughness and mechanical properties of the expansive soils [5].

The customary stabilizers, as hydrated lime, basic Portland concrete, oil sulfonate and dark top are habitually used to improve the physical–mechanical properties of such clay [12,17]. Generally, concrete has been utilized hugely for the clay stabilizer contrasted with different materials [18,19]. In any case, the generous creation on a very basic level influences the regular quality. The creation of cement in the substantial business is a critical wellspring of CO_2 surge and cause the arrival of dangerous ozone hurting substances [19]. The substantial amassing collaboration can convey from as low as 600 kg to 1200 kg of CO_2 radiation to the air for every metric ton of water-driven cement made [2,13,18–22]. Thus, a decline of substantial creation on the characteristic impact has been begun by replacing it with another viable material, for instance, pozzolan (i.e. eggshell ash, silica fume, fly ash, hazard quiet debris, etc.) [23]. To restrict the change costs, substantial superseding with waste materials, similar to fly flotsam and jetsam, rice husk trash and biomass garbage has been for the most part applied for all intents and purposes. The effect factors, for instance, substantial substance, water content, easing condition, and replacement extent and compaction energy on the microstructure and planning characteristics of cement settled soils have been broadly investigated [24]. Previous researchers have been highlighting utilizing pozzolan in the production of blended cement. Pozzolan such as volcanic ash [25] and fly ash [26,27] are notable supplementary cement replacement materials due to the high rich in siliceous material, substantial availability and exhibit pozzolanic reactivity. Nevertheless, agro waste products have newly attracted the focus due to the massive availability of solid waste from this field [28].

As recently referenced materials are considered as should be expected and preceded soil stabilizers, as of now, most experts are taking more significant interests in the utilization of waste materials. Despite the land occupation, the waste distribution centre made from various gathering ventures causes various common issues as well [5,15,16]. Subsequently, productive use of assets is perhaps the main issues that ought to be featured today [29]. Immense assessments have been made on the execution of present day results or reused materials as substantial replacement materials in the soil change procedure [30]. Additionally, the joining of waste materials as alternatives in the geotechnical field is seen as one of the critical ways to deal with advance a sound environment [24,31]. As of now, it has become apparent that waste materials are used for various planning and geotechnical properties and decrease their environmental impact on the environment. Moreover, using waste materials have exceptional properties for some planning and geotechnical applications. The properties of waste materials like sturdiness, strength and high deterrent are needed for the arrangement of the foundation of a design and turnpike improvement [4].

In present-day countries, basically half of the general population lives in earth houses of which at any rate 30% of the general population is in common areas and 70% are in the metropolitan districts [32,33]. Cultivating or current solid waste organization issues have been highlighted overall which lead to characteristic concerns. Yearly, the present surveyed overall waste age volume is about 1.3 billion tons with a typical expansion of 2.2 billion tons by 2025 consistently [33]. In most horticultural countries, colossal measures of agro and non-agro wastes are not reasonably and adequately utilized and managed which creates a risk to the environment [33–36]. Agrarian wastes are as stores through the turn of events and arrangement of unrefined provincial things like natural items, dairy things, yields, poultry, etc. In contrastingly, the materials during a creation cycle that are made silly like wastes from the plant, preparing and mining practices make the mechanical wastes or non-agro wastes [33]. From the past assessment, it is exhibited that these agro-wastes have a high potential to be used in building improvement materials subject to their extraordinary physicomechanical properties [33,37–39] and these materials are the most economical, environmentally sustainable and energy-efficient materials [33]. In addition, from the past research articles similarly, the researchers have displayed the variety of mechanical wastes use for different advancement applications [33,40–42].

In this investigation, the agro-squander material that is utilized as clay balancing out specialist is eggshell ash (ESA) and silica fume (SF). A few investigations have executed calcium particles utilization from sources, for example, limestone and eggshells as minimal expense options in contrast to unadulterated calcium salts [43,44]. The waste chicken eggshells contain a limestone or calcium carbonate usually called calcite ($CaCO_3$) [45–47]. Eggshell Ash (ESA) is another bio-squander material that can be used to lessen the concrete in substantial creation [48]. Eggshells, the result of eggs utilized, can develop a disturbance in our current circumstance through unpredictable clearing [49]. Also, the eggshells which is the hard outside layer of an egg make up around 10% of the egg weight with a typical heap of 60 g [45–47].

There is a slight expansion of moving in egg creation worldwide and it is needed to deliver in excess of 8 million tons of eggshell waste every year [47]. Eggs usage in families and bistros are insignificantly diverged from the utilization of eggs in egg breaking plants for huge scope assembling of liquid eggs for food and non-food related things use [45]. The total amount of eggs dispatched off breaking plants in Canada and France is by and large 2.3 billion and 1 billion, independently. Wisely, 6600 tons of limestone powder is conveyed from 1 billion eggs [45–47]. In 2011, 8979.8 million eggs were consumed and this number had been extended to 12,235.3 million eggs in 2017 and it is needed to dynamically increase in the looming years [50]. Around 150,000 tons of eggshell (ES) waste is masterminded in landfills. Thusly, it might be exhibited that as the general population continues to create, the eggshell wastes increases basically [47,50]. Additionally, the evacuation of ES is one of the huge issues as it can convey an annoying smell and hypersensitivities. Thusly, this will achieve understanding ecological issues that may demand a genuine treatment [50]. At times, present day associations pay however much 100,000 dollars to dispose of the eggshell waste in landfills and achieved the over-farthest reaches of landfill limit [50].

The eggshells have a couple of utilizations, for instance, in arranging calcium phosphate ceramic creation material or as the unrefined material for biodiesel and as an adsorbent in the departure of ionic pollutions and compost [46] a huge of eggshells are going unused and unloaded on the land [47]. Hence, ESA has been used by other researchers due to the high content of CaO which can enhance the low calcium in high-volume FA (HVFA) concrete and cement mortar [44,48]. By utilizing eggshell powder in the assembling of the materials can diminish ecological issues, for example, the removal of eggshell squander and the high utilization of concrete [47]. In addition, re-use eggshells would propel the reusing of farm waste and thwart its redirection to landfills [45]. Property hatching offices and egg breaking plants are available all over the place, achieving transportation issues for getting the rough result. In any case, if a couple of regions are centred around where useful entireties can be made, the advancement is available to make minimal close by on the spot recuperation workplaces. Also, there is only a foreordained number of studies have been done on the re-usage of eggshell waste as an elective material [45].

In the production of biodiesel, the eggshell waste is used as a solid [50,51] and a stabilizer for the expansive clay soil [50,52]. Besides, the ESA is moreover used as a gas pedal for substantial bound materials to play out its effect on the strength properties of cement offset lateritic soil. The eggshell contains creating layers of $CaCO_3$ that construction 95% of the shell [50]. With the penetrable erratic particle size of 2–900 mm that affluent in calcite ($CaCO_3$) present in the ESA, it is also can be used for divider tile creation [50,53]. ESA is a useful stabilizing material for clay soil [54]. Besides, ESA also is a suitable material to replace part of lime in soil stabilization [48] and can replace cement in improving the soil properties [47]. However, it is very hard to find a manufacturer that can produce the ESA due to the new material application used in the construction industry [46,54].

The high strength of cement can be delivered utilizing silica-rage (SF) as a substitution for concrete or by utilizing an added substance [55,56]. SF or also known as micro silica, are non-crystalline polymorphs and amorphous of silicon dioxide (SiO_2) present in a round shape particle [57,58]. SF is a result of silicon which having an enormous surface region ($30\ m^2/g > SF > 10\ m^2/g$) and microparticles sizes of around 200–1100 nm [59]. The SiO_2 present in the SF is about 90% and 96% [58,60,61] and present in the form of quartz with the total alkalis present was limited to 0.17% [62].

The specific gravity and the LOI of the SF is around 2.22 [62] and above 2% [61] respectively. In construction, the SF was used as an additive or cement replacement material to produce high strength concrete [55]. In the past investigations, SF was acclimatized to the earth soil with the mix of different materials like lime, concrete, sawdust, bamboo slag, and so on and the outcomes expressed that the expansion of SF can change the properties of the clay and improve the strength boundaries of clay soil [56–58]. The SF is often applied in the fabricating of unfired building brick [59], structural concrete [62] and etc.

As of now, due to the pozzolanic conduct and filler normal for the SF, the SF was utilized to reinforce the substantial in a brief time frame due [57]. The acquaintance of SF contributed with higher compressive strength/warm conductivity values proportions and more prominent compressive strength contrasted with the fly ash, because of the pore-filling and pozzolanic impact of silica fume itself [57,58]. These materials have numerous unfriendly consequences for the climate likewise, and use of these materials as a fractional concrete substitute could prompt cleaner creation [62].

Consequently, in this current investigation, the hole is loading up with the capability of utilizing the mix of SF and

ESA in delicate earth soil as a clay adjustment specialist and another elective strategy to upgrade the shear strength of the clay soils. In light of the past investigation, there are a ton of explores directed identified with the use of ESA in concrete substitution material however a couple of them examined the use of the ESA as clay improvement. The ideal combination among SF and ESA with the clay soils not exclusively can upgrade the shear strength of the delicate clay soils but also lower the specific gravity, reduced the plasticity index (PI), decreased the maximum dry density (MDD), and increased the optimum moisture content (OMC). Thus making the silica fume-egg shell ash mixture a sustainable material for weak soil stabilizing agent which is environmentally friendly and cost-effective.

2. Experimental investigation

The type of material such as kaolin clay, silica fume and eggshell ash is discussed in details in this section. Coherently, the experimental methods used to achieve the objective of the study was also explained.

2.1. Materials

Kaolin S300 bought from Kaolin (M) Sdn. Bhd. was utilized as the clay example in this current examination. It is white shading dirt fabricated in the lab and is fine in size. Kaolin, which is otherwise called kaolinite clay is a kind of soil that either can be found in nature or made in the research centre [12]. Kaolin is fine in size and is a white tone in the characteristic state as demonstrated in Fig. 1. The basic engineering properties of Kaolin S300 are shown in Table 1. The chemical composition of this soft kaolin is tabulated in Table 2.

A dark tone densified SF as demonstrated in Fig. 2. It is a fine material with a 56% better at 0.075 mm sifter, created from the creation of essential silicon at 2000 °C. The kind of SF utilized in this investigation was Scanfume, a densified SF for concrete, which has a huge surface space of at least 15,000 m^2/kg The chemical composition of SF is as shown in Table 2.

The crude chicken eggshells were gathered from the eateries in Kuantan, Pahang. The crude chicken eggshells were then washed, air-dried for seven (7) days, squashed and warmed at 800 °C for 1 h by utilizing the chamber heater to produce the ESA. The ESA shaped from calcination was dim in shading as was put away in a desiccator for 24 h to chill off the debris and forestall the hydration interaction among ESA and dampness from the air. From that point onward, the ESA was put away in a water/airproof holder. The example arrangement of the ESA appears in Fig. 3.

Fig. 1 – White Kaolin.

Table 1 – Basic engineering properties of Kaolin S300.

Properties	Unit	Result
Gravel	%	0
Sand	%	48
Clay and Silt	%	52
USCS classification		ML
AASHTO classification		A-5
Group index		11
Initial moisture content	%	0.97
Specific gravity, G_s		2.64
Liquid limit, LL	%	40.7
Plastic limit, PL	%	31.4
Plasticity index, PI	%	9.3
MDD, $\rho_{d(max)}$	g/cm^3	1.606
OMC, W_{opt}	%	19
UCS,[a] q_u	kN/m^2	42.11
USS, S_u	kN/m^2	21.06

[a] UCS refers to unconfined compression strength.

2.2. Experimental methods

The fundamental designing properties of the entirety of the materials were resolved through the expressed research centre tests. The underlying dampness content for kaolin, SF, and ESA is 0.97%, 1.21% and 0.40%, individually. The underlying substance of the relative multitude of materials utilized is not high, as the Kaolin S300 is the consumed kaolin, rather than the common soil, along these lines the dampness content is limited through the consuming activity previously. Kaolin S300 was picked rather than the common soil is to control the normalization of the investigation. A similar idea goes to SF and ESA, the underlying dampness substance of the two materials are low as SF was delivered at 2000 °C while the ESA at 800 °C. The underlying dampness substance of the materials was likewise exposed to the capacity strategy and the climate of capacity. Those materials that have been put in a hermetically sealed holder would have a lower dampness content when contrasted with others.

Then, the delicate kaolin was treated with 2%, 4% and 6% of SF by the dry weight of the soil and the modifications in the physical, strength and compaction properties of soil were

Table 2 – Chemical composition of Kaolin, SF and ESA.

Composition	Unit	Kaolin	SF	ESA
SiO_2	%	66.11	74.02	0.02
CaO	%	0.08	0.00	62.50
Al_2O_3	%	19.25	0.45	0.01
K_2O	%	2.85	4.27	0.05
MgO	%	1.23	3.73	0.71
Fe_2O_3	%	0.73	0.71	0.02
Loss on ignition (LOI)	%	8.16	2.55	6.00

Fig. 2 – Grey colour-densified Silica Fume.

Table 3 – Samples coding.

Sample	Coding	Content (%)		
		Kaolin	SF	ESA
Kaolin (Control)	K	100	–	–
Kaolin with 2% of Silica Fume	K2SF	98	2	–
Kaolin with 4% of Silica Fume	K4SF	96	4	–
Kaolin with 6% of Silica Fume	K6SF	94	6	–
Kaolin with 6% of Silica Fume and 3% of Eggshell Ash	K6SF3ESA	91	6	3
Kaolin with 6% of Silica Fume and 6% of Eggshell Ash	K6SF6ESA	88	6	6
Kaolin with 6% of Silica Fume and 9% of Eggshell Ash	K6SF9ESA	85	6	9

Table 4 – Standards of laboratory testing.

Test	Standard
Mechanical Sieve Analysis	BS 1377: Part 2: 1990
Hydrometer Test	BS 1377: Part 2: 1990
Specific Gravity Test	BS 1377: Part 2: 1990
Atterberg Limit	BS 1377: Part 2: 1990
Standard Proctor Test	BS 1377: Part 4: 1990
Unconfined Compression Test (UCT)	ASTM D2166

analyzed. Table 3 shows the example coding that was utilized all through this examination. The level of SF that ascribed to the most extreme undrained shear strength (USS) was set apart as the ideal SF content. This ideal SF content was then admixed with delicate kaolin and 3%, 6%, and 9% of ESA by the dry weight of the soil example. The geotechnical attributes of the soil blend and the ideal ESA content comparing to the most extreme strength were then characterized. The level of SF and ESA received in this current examination were picked dependent on the past investigates [12,54]. The lab tests and guidelines that applied to consider the designing properties of kaolin, SF, ESA and the kaolin–SF–ESA blend were introduced in Table 4.

The mechanical sieve analysis is conducted in accordance to the BS 1377: Part 2: 1990 as shown in Fig. 4(a). The test was carried out to determine the particle size distribution of the raw kaolin clay soil sample and kaolin clay soil sample stabilized SF and ESA. Hydrometer test or fine analysis was carried out in accordance with BS 1377: Part 2: 1990. This laboratory test is conducted to determine the grain-size distribution of the sample that passes through the 63 μm sieve. 50 g from the remaining sample in the pan after sieve analysis was used in this laboratory test.

The specific gravity of the soil samples was determined with the small pyknometer method in accordance to BS 1377: Part 2: 1990 as shown in Fig. 4(b). 10 g of the oven-dried sample

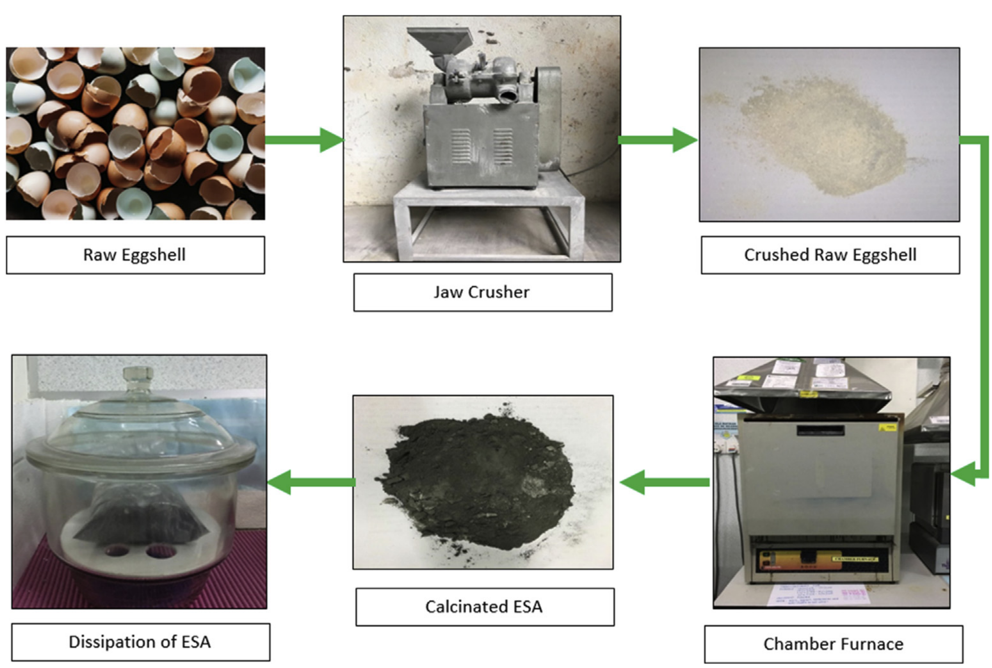


Fig. 3 – Sample preparation of the ESA.

that passed through 2 mm BS sieve was used for the test and was repeated twice until the results vary not more than 0.03 Mg/m^3.

The Atterberg limit of the soil sample was determined in accordance to BS 1377: Part 2: 1990. A liquid limit (LL) is determined via cone penetration method with the test specimen of at least 300 g which passed through the 425 μm and the plastic limit (PL) was determined by rubbing about 20 g of the prepared sample taken from LL sample as shown in Fig. 4(c). The test was carried out to distinguish between silt and clay.

The Standard Proctor Compaction Test in accordance to BS 1377: Part 2: 1990 was adopted in this research as illustrated in Fig. 4(d). 3 kg of an oven-dried soil sample that passing the sieve size of 4.75 mm has been used in the standard compaction test to determine the optimum moisture content (OMC) and the maximum dry density (MDD) of the soil sample used in the study.

In this assessment, the unconfined compression tests (UCT) were performed to investigate the mechanical properties of kaolin, SF and ESA as shown in Fig. 4(e). Field Scanning electron microscopy (FESEM) tests were furthermore prompted to notice the microstructure of the models when mixing the kaolin in with the SF and ESA. Furthermore, the strength limits of the internal granulating point and connection according to the Mohr-Coulomb rule were in a like manner chosen. The examples utilized for this test were set up by compacting soil tests with an ideal water substance of the soil. The models were prepared and compacted in a barrel-moulded steel structure with the components of 100 mm in high × 50 mm in distance across. The height to width extent of the models will be someplace in the scope of 2.0 and 2.5 as indicated by ASTM D2166. The models were compacted by using the catapulting unclogger. The compacted models should be managed watchfully to diminish the chance of extra upsetting effect, switches up there, or loss of water content. The cylinder moulded model should be in the uniform indirect cross-fragment with the completions inverse to its longitudinal centre point.

Besides, to ensure the consistency of the model and the result precision during the UCT test, the thickness of the model is controlled utilizing steady volume and control of the mass of the model. The UCT were driven on models at a speed of 0.5%–2% every moment until shear disappointment. There were five (5) examples tried for every one of the example blends to decide the shear strength of the example. The connections of the designing properties of delicate kaolin with the differing SF and ESA content was likewise settled.

3. Results and discussion

The determination of optimum utilization of silica fume and eggshell ash is discussed in this section. The results obtained

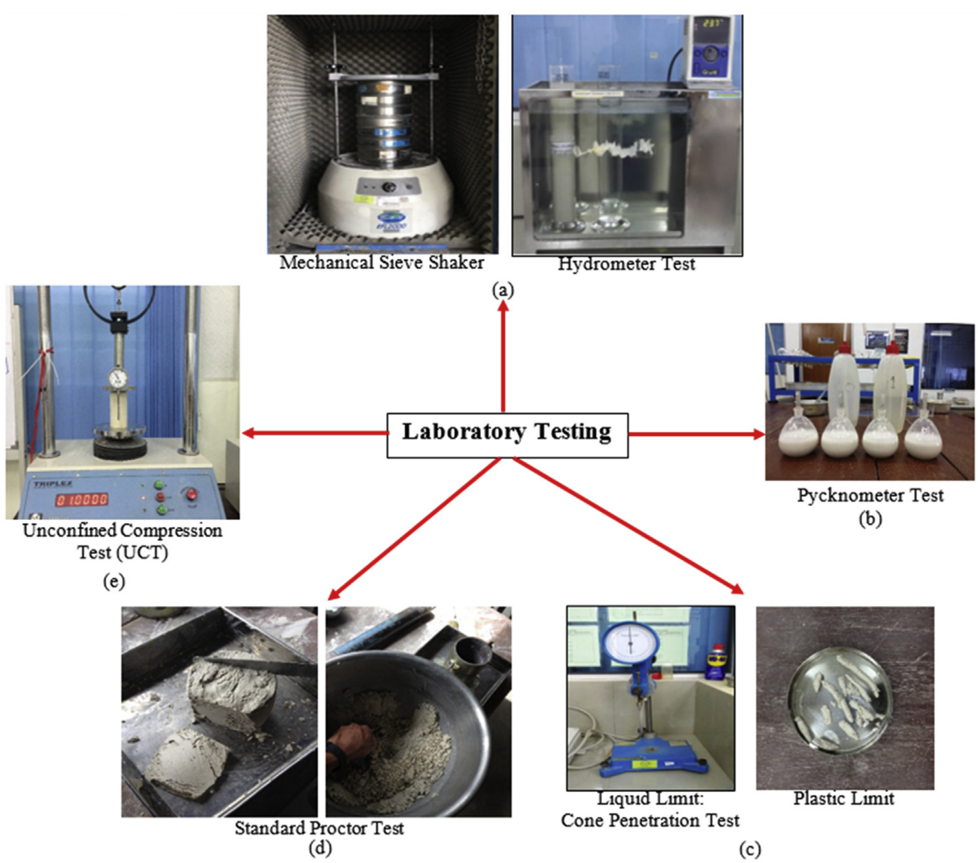


Fig. 4 – Laboratory test conducted (a) Particle Sieve Analysis (b) Specific Gravity Test (c) Atterberg Limit Test (d) Standard Compaction Test (e) UCT.

Table 5 – Determination parameter of the optimum Kaolin-SF dosage.

Sample	Average UCS, q_u (kN/m^2)	Average USS, S_u (kN/m^2)	Average axial strain, ε (%)	Strength improvement (%)
Kaolin (Control)	42.11	21.06	1.26	–
K2SF	45.11	22.56	1.67	7.10
K4SF	51.26	25.63	1.66	21.00
K6SF	58.80	29.40	1.90	39.60

from each of the laboratory testing are also discussed in details in this section.

3.1. *Determination of optimum utilization of silica fume and eggshell ash*

The fundamental properties of the Kaolin S300, SF, ESA and the kaolin–SF–ESA combination of the ideal rate is introduced. The conduct of the soil combination is researched and dissected through the compaction test and UCT. The standard compaction test was led on kaolin; kaolin admixed with 2%, 4%, and 6% of SF; and kaolin admixed with an ideal level of SF that adds to the greatest USS and 3%, 6%, and 9% of ESA. The USS properties were analyzed through the UCT test, where kaolin; kaolin with 2%, 4%, and 6% SF; and kaolin admixed with an ideal level of SF relate to the greatest USS and 3%, 6%, and 9% of ESA. The ideal level of SF was achieved first and afterwards continue with the compaction test to get the OMC and the MDD of the kaolin-SF blend with 3%, 6%, and 9% of ESA. The results of the compaction test were then applied in the UCT test to get the greatest level of ESA required concerning a definitive USS strength. The level of SF and ESA applied were picked dependent on the past explores [12,54]. The untreated Kaolin S300 tests were going about as the control tests in this investigation. Its solidarity properties were then contrasted and tests treated with various SF and ESA content, with the reason to examine the capacity of improvement in the delicate kaolin that the stabilizers can offer. Tables 5 and 6 shows the assurance boundary of the ideal stabilizer measurement for SF and ESA individually.

Because of the result ordered in Table 5, there is just an insignificant improvement for kaolin with 2% SF by a dry weight of kaolin consolidated, which is just 7.1% ($q_u = 45.11$ kN/m^2, $S_u = 22.56$ kN/m^2, $\varepsilon = 1.67\%$). The immaterial worth recorded is a result of the low SF content present in the treated model which came to fruition to the unable improvement sway. There is a slight addition in q_u (51.26 kN/m^2) and S_u (25.63 kN/m^2) esteem when the kaolin was admixed with 4% at the normal pivotal strain of 1.67%. The strength improved at 21.00% with a distinction of 9.15 kN/m^2 in q_u value and 4.57 kN/m^2 in S_u value when contrasted with the controlled example. The outcome demonstrates that the consideration of 4% of SF began to produce results in upgrading the shear strength of the dirt, by advancing the beginning phase of the pozzolanic response. The strength continues to improve at 39.60% when the kaolin was admixed with 6% of SF content. There is an enormous edge of progress in q_u value (from 42.11 kN/m^2 to 58.80 kN/m^2), S_u value (from 21.06 kN/m^2 to 29.40 kN/m^2) and ε value (from 1.26% to 1.90%) when contrasted with different examples. The best improvement is acquired by the consideration of 6% SF in kaolin applied in this examination. From the outcomes acquired from UCT, it tends to be found that the strength properties of the kaolin improved with the expanded level of SF by a dry weight of the soil, with the SF content that is going from 0% to 6%. The best USS of the treated example is accomplished when the kaolin is blended in with 6% of SF by weight of dry soil test. At 6% of SF admixed with the kaolin, the best improvement is recorded, which is at 39.60%. Accordingly, the ideal level of SF is 6% by weight of the dry soil. A comparative outcome was acquired by the past analyst [12], where the shear strength of the treated kaolin expanded with the SF content up to 6%, and the shear strength was then decreased when the substance of SF surpassed 6%. The further incorporation of SF causing the decrease in shear strength because of the shortfall of aluminium compound for the pozzolanic response [12,56].

The kaolin test that contains 6% of SF were additionally tried by blending it in with three (3) diverse level of ESA (3%, 6% and 9%) for additional strength improvement. In light of the information recorded in Table 6, at a normal axial strain of 2.11%, the normal q_u value and S_u value an incentive for kaolin admixed with 6% SF and 3% ESA is 62.82 kN/m^2 and 31.41 kN/m^2 separately. An improvement of 49.10% was determined in term of USS, where the worth expanded from 21.06 kN/m^2 to 31.41 kN/m^2. The 3% of ESA content did not give a huge impact on the strength of the kaolin test as the strength just increment 4.02 kN/m^2 for q_u and 2.01 kN/m^2 for S_u when contrasted with the ideal combination of kaolin admixed with 6% of SF. For the kaolin test that was blended in with 6% of SF and 6% of ESA, The q_u and S_u value recorded were 70.50 kN/m^2 and 35.55 kN/m^2 with an axial strength of 2.47%. At this degree of

Table 6 – Determination parameter of the optimum Kaolin–SF–ESA dosage.

Sample	Average UCS, q_u (kN/m^2)	Average USS, S_u (kN/m^2)	Average axial strain, ε (%)	Strength improvement (%)
Kaolin (Control)	42.11	21.06	1.26	–
K6SF3ESA	62.82	31.41	2.11	49.10
K6SF6ESA	70.50	35.55	2.47	68.80
K6SF9ESA	63.30	31.65	2.06	50.30

combination, the strength improvement recorded an upgrade of 68.8%, where the addition was recorded from a worth of 21.06 kN/m^2 to 35.55 kN/m^2.

Then, the kaolin admixed with 6% of SF was blended in with a 9% of ESA content by the dry weight of the example, with the reason to inspect the strength properties of this stabilizers mix. The q_u and S_u values recorded is somewhat lower than the strength got for kaolin admixed with 6% SF and 6% ESA which is at 63.30 kN/m^2 and 31.65 kN/m^2 separately at an axial strain of 2.06%. Despite the fact that the q_u and S_u value recorded for this example is lower than the kaolin test admixed with 6% of SF and 6% of ESA. Be that as it may, the strength improvement recorded for this example is higher contrasted with the kaolin test admixed with 6% of SF and 3% of ESA at a worth of 50.30%. In light of the information recorded (Tables 5 and 6), it tends to be demonstrated that a reduction in USS was recorded when 9% of ESA was blended in with the control test. The underlying expansion in USS is because of the slow development of CSH, the cementitious compound. The high CaO content from the ESA structures the cementitious bond among the dirt particles, with the incorporation of water, in this way improved the strength of the kaolin test. The strength of the example began to lessen when abundance ESA was added to the kaolin test. Further expansion of ESA dislodges the soil and structures a feeble connection between the soil and CSH [12,54,56]. Along these lines, in light of the UCT direction, the ideal stabilizer measurements for this investigation was recorded at 6% of SF and 6% of ESA because of the most extreme improvement recorded which is at 68.8% as delineated in Fig. 5. Therefore, it is suggested that the shear strength of the kaolin clay was greatly influence by the optimum content of SF and ESA of about 6% respectively. The shear strength of the material is an important determinant of the function of the material which can be used as an indicator for optimum content of soil stabilizing agent.

In Fig. 5, the error of the data was observed for the shear strength values of the soil samples. The variability of the data is observed for the data of soil sample of raw kaolin clay with the kaolin clay treated with optimum SF content (K6SF) and the kaolin clay treated with optimum SF content and ESA content (K6SF6ESA). The error bar in the figure indicates that there is a significant difference in the shear strength value of the raw kaolin compared to the K6SF and K6SF6ESA sample as the error bars are not overlapped and the size of the error bars are small. Besides, none of the data points is the same between K6SF and K6SF6ESA as both of the error bars for the soil sample were also not overlapped and small in size.

Table 7 – Specific gravity, G_s of the raw materials and treated kaolin samples.

Sample	Specific gravity, G_s
Kaolin (Control sample)	2.64
SF	2.33
ESA	2.38
Kaolin + 2% SF	2.54
Kaolin + 4% SF	2.51
Kaolin + 6% SF	2.50
Kaolin + 6% SF + 3% ESA	2.60
Kaolin + 6% SF + 6% ESA	2.54
Kaolin + 6% SF + 9% ESA	2.51

3.2. *Physical properties of soil samples*

3.2.1. *Specific gravity*

The specific gravity for Kaolin S300 is 2.64, which decided the kaolin as the kaolinite mud as referenced by past scientists which expressed that the specific gravity for kaolinite dirt lies between the scope of 2.62 and 2.66 [12,56,63]. The lower the specific gravity, the lighter the particles. The incorporation of SF diminished the specific gravity of the delicate kaolin. A 5.3% decrease in specific gravity was resolved with the expansion of SF up to 6% by a dry weight of soil, where it dropped to 2.50 from 2.64. The expansion of the 3%, 6% and 9% of ESA to the kaolin-6SF (K + 6SF) combination showed an underlying addition of specific gravity at 3% ESA content as ESA is coarse, and it was then diminished to 2.51. This is inferable from the adjustment

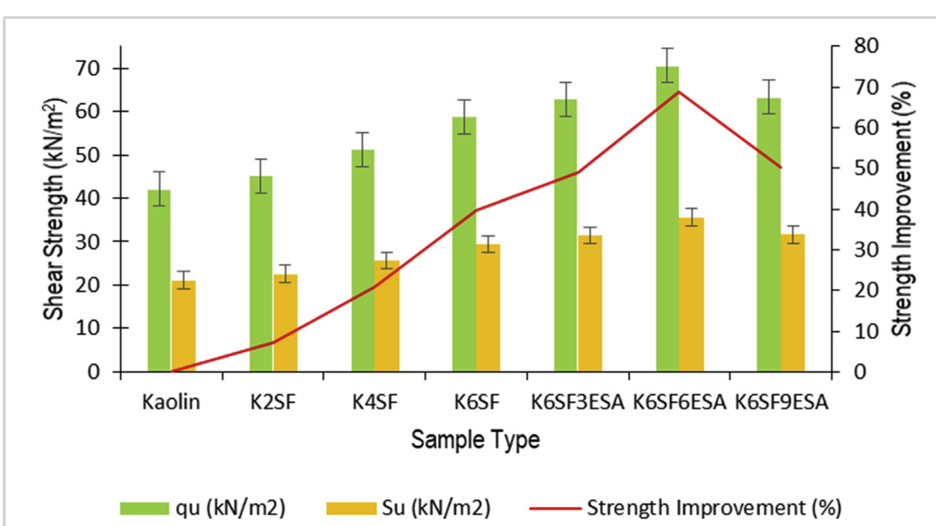


Fig. 5 – Relationship between type of samples with sample strength (kN/m^2) and strength improvement (%).

Table 8 – Summary of Atterberg Limit of treated and untreated samples used in the study.

Sample	LL (%)	PL (%)	PI (%)
Kaolin (Control sample)	40.7	31.4	9.3
SF	90.5	80.5	10.0
ESA	27.4	21.6	5.8
Kaolin + 2% SF	37.7	29.8	7.9
Kaolin + 4% SF	38.3	31.6	6.7
Kaolin + 6% SF	41.1	34.5	6.6
Kaolin + 6% SF + 3% ESA	37.0	31.4	5.6
Kaolin + 6% SF + 6% ESA	34.1	29.2	4.9
Kaolin + 6% SF + 9% ESA	35.2	30.4	4.8

of soil particles as lighter SF and ESA were added. The impact of the incorporation of SF and ESA to the delicate kaolin is as demonstrated in Table 7. Henceforth, it tends to be reasoned that the crude SF is the lightest contrasted with different materials examined. The blends of the kaolin with SF and ESA brought about the augmentation in the specific gravity value.

The specific gravity of the kaolin-SF blend dropped to 2.5 from 2.64, with an addition worth of SF up to 6%. This event is ascribed to the reshuffling of the soil grid as lighter SF is added to kaolin, accordingly framing a lighter soil combination. Different rates of ESA were remembered for the kaolin, with 6% SF. The underlying expansion in specific gravity is because of the expansion of heavier ESA when contrasted with SF. The further decrease in specific gravity with ESA content up to 9% is because of the revamp of soil particles and framing a lighter design contrasting with kaolin. Therefore, the trend of the specific gravity suggested that the incorporation of the pozzolanic materials such as SF and ESA can reduce the specific gravity of the kaolin clay and is a good combination to be used as a stabilizing agent of the expansive soil.

3.2.2. *Atterberg Limit*

The dampness content for the infiltration at 15 mm, 20 mm, and 25 mm was resolved through Liquid Limit (LL) test. The consistency of the example was resolved by means of the Atterberg Limit test. Table 8 sums up the Atterberg limit furthest reaches of each example tried. The LL and Plastic Limit (PL) for kaolin is 40.7% and 31.4% individually, while the PI is 9.3%. The LL and PL of SF are high, which is 90.5% and 80.5%, separately because of the great water adsorption normal for the SF and makes the SF be truly friable. For ESA, the LL and PL recorded are 27.4% and 21.6% individually with the PI worth 5.8%.

The LL and PL were at first decreased by 7.4% and 5.1%, from 40.7% to 37.7% and from 31.4% to 29.8%, individually, with 2% of SF included. At that point, both LL and PL esteem expanded with the addition of SF content up to 6%. The PI of the examples diminished with the expansion of SF from 0% to 6% which demonstrated that the dirt substance of the examples tried diminished with the expansion of SF. For ESA, both LL and PL esteem diminished by 17.0% and 15.4% separately with ESA content up to 6%. Further consideration of ESA expanded the LL and PL of the example. The PI recorded a diminishing pattern alongside the expanded ESA content which is owing to the capacity of ESA to coarsening the dirt examples. The PI of the kaolin was diminished by 29.0% with the expanded substance of SF (from 9.3% to 6.6%) while addition in ESA content, brought about a 27.3% decrease of PI (from 6.6% to 4.8%).

In light of the outcomes acquired (Table 8 and Fig. 6), both of the stabilizers can tie and flocculate the kaolin to become coarser particles, with a decrease of fine earth content through the cation trade action and pozzolanic responses. These results are like the past examinations directed by different analysts, aforementioned in the past area and section [64–66]. The lessening in PI upon the expansion of SF and ESA shows that the extensive qualities of kaolin clay are diminished.

In Fig. 6, the error of the data was observed for the Atterberg limits (LL, PL and PI) of the soil samples. The variability of the data is observed for the data of soil sample of raw kaolin

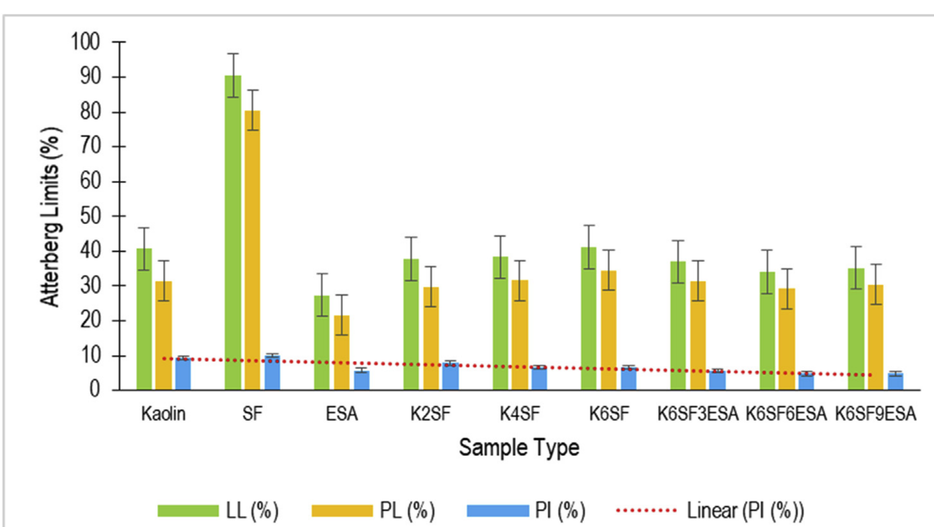


Fig. 6 – Relationship between types of a sample with sample Atterberg limits (%).

clay with the kaolin clay treated with optimum SF content (K6SF) and the kaolin clay treated with optimum SF content and ESA content (K6SF6ESA). The error bar in the figure indicates that there is no significant difference in the LL, PL and PI values of the raw kaolin compared to the K6SF and K6SF6ESA sample as the error bars are extensively overlapped and the size of the error bars are large. Besides, it can be observed that there is also no significant difference between K6SF and K6SF6ESA sample as the error bars for both of the sample in view of the Atterberg limits is overlapped and the size of the error bars for both of the sample is also large.

3.2.3. *Standard Compaction Test*

The Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) of untreated kaolin, SF, ESA, kaolin admixed with 2%, 4% and 6% of SFA and optimum kaolin-SF admixed with 3%, 6% and 9% of ESA content are determined via a series of Standard Proctor Compaction Test. The dry density initially showed a rising trend with the addition of water up to 19% and then dwindling. The MDD for untreated kaolin was 1.606 g/cm^3, with an OMC of 19%. According to previous findings, MDD of clay soil is within the range of 1.4 g/cm^3 to 2.0 g/cm^3 while the OMC is ranging from 14% to 30% [12,54,56,67–70]. Thusly, the compaction aftereffects of the untreated kaolin acquired in this examination are in the scope of qualities expressed by the past scientists. The trouble to shape soil consistency in the PL test brought about the inadmissible compaction test to be completed for the SF and ESA. Furthermore, the mass thickness of the compacted SF and ESA was continued expanding with the expansion of water. Hence, in light of the information acquired, SF and ESA are not appropriate for compaction test except if and the results are not characterized except if both of the materials are admixed with the soil example like kaolin.

The outcome obtained from UCT recorded that the ideal SF content comparing to a definitive strength is at 6%, hence, different rates of ESA were then added to the kaolin admixed with 6% SF for additional strength improvement of untreated kaolin. Fig. 7 shows the compaction bend of the kaolin-SF test admixed with 0%, 3%, 6%, and 9% of ESA. The compaction bend plotted to show that the molecule game plan of the example changed with the expansion of ESA with high CaO content, hence the particular space of the example is modified and more water is needed for the substance response among the fine particles, to set off the adjustment interaction.

Table 9 – Summary of compaction properties of kaolin admixed with various percentage of stabilizers.

Sample	MDD (g/cm^3)	OMC (%)
Kaolin	1.606	19.0
Kaolin + 2% SF	1.550	19.5
Kaolin + 4% SF	1.548	19.8
Kaolin + 6% SF	1.522	20.4
Kaolin + 6% SF + 3% ESA	1.555	19.7
Kaolin + 6% SF + 6% ESA	1.525	20.5
Kaolin + 6% SF + 9% ESA	1.517	20.8

The lab results of the standard compaction test are summed up in Table 9. Subsequently, the higher MDD of the clay shows a superior presentation in development work, yet it additionally implies that the expanding pressure is high for the expansive soil [52].

Fig. 8 represent the connection between MDD and OMC of the kaolin test admixed with 6% of SF and different level of ESA. The MDD of the treated example was at first expanded to 1.555 g/cm^3 from 1.522 g/cm^3 at 3% of ESA substance and diminished to 1.525 g/cm^3 and 1.517 g/cm^3 at 6% and 9% of ESA content. The OMC of the treated example diminished to 19.7% from 20.4% because of the adsorption limit of ESA, owing to the ESA porosity properties, and the addition in OMC with the incorporation of ESA up to 9% is expected to the expanded CaO content in the balanced out the example and subsequently, more water is requested [23] for the development of CSH particles and pozzolanic response with the presence of SF. The pattern of the diagram acquired in this examination is rational with the investigation directed by the past specialists [54,71]. Based on the data discussed, it can be concluded that the addition of both SF and ESA can reduce the swelling tendency of the soft kaolin.

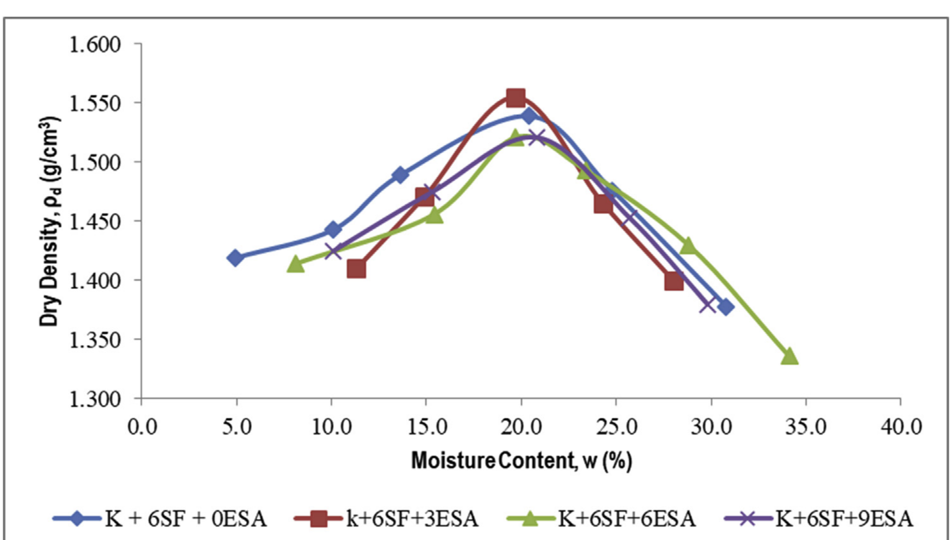


Fig. 7 – Compaction curve of kaolin admixed with 6% SF and various percentage of ESA content (%).

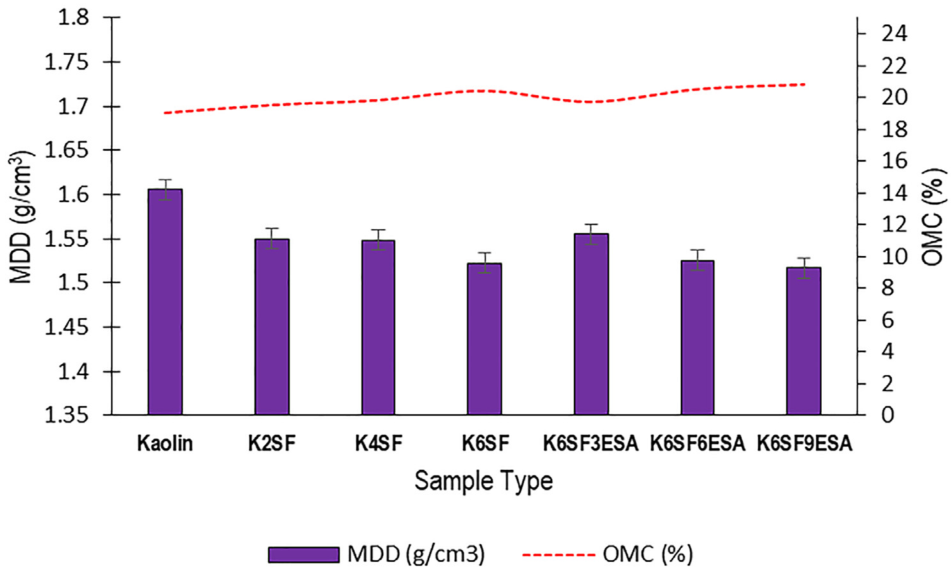


Fig. 8 – The correlation between MDD (g/cm^3) and OMC (%) of the kaolin sample admixed with 6% of SF and various percentage of ESA content (%).

In Fig. 8, the error of the data was observed for the maximum dry density (MDD) value of the soil samples. The variability of the data is observed for the data of soil sample of raw kaolin clay with the kaolin clay treated with optimum SF content (K6SF) and the kaolin clay treated with optimum SF content and ESA content (K6SF6ESA). The error bar in the figure indicates that there is a significant difference in the MDD value of the raw kaolin compared to the K6SF and K6SF6ESA sample as the error bars are not overlapped and the size of the error bars are small. Besides, the data points between K6SF and K6SF6ESA is almost the same as both of the error bars for the soil sample were extensively overlapped but with small variations of data due to the smaller size of the error bars.

3.3. *Chemical oxide compositions*

Cementitious properties and pozzolanic response are the two vital elements in settling the delicate mud soil. The pozzolanic response is a sluggish interaction and is basically liable for the improvement of solidarity. For the most part, CaO and SiO_2 are considered as the fundamental constituents of cementitious material while both of the materials show go about as a limiting specialist when water is added. At the point when hydration happens, though with the expansion of water, the CaO will respond with the water and structure calcium hydroxide, $Ca(OH)_2$ as demonstrated in Eq. (1).

$$CaO + H_2O \xrightarrow{Hydration} Ca(OH)_2 \tag{1}$$

Then, the pozzolanic response will occur when the SiO_2 from the SF and dirt soil will respond with $Ca(OH)_2$ to shape CSH. Eq. (2) shows the response when SF, the pozzolan responds with $Ca(OH)_2$. The drawn out interaction of pozzolanic response is known to have a huge effect on the designing properties of the dirt, for example, porosity, penetrability and strength.

$$Ca^{2+} + 2OH^- + SiO_2 \rightarrow x.CaSiO_3H_2O \tag{2}$$

The pozzolanic response relies upon two components which are the greatest measure of $Ca(OH)_2$ that pozzolan can respond with and the surface space of pozzolan. A more prominent surface space of pozzolan prompts the higher pozzolanic reactivity [72]. ESA is essentially comprised of CaO while SF is involved over 85% of SiO_2. The specific gravity was to some degree reduced for eggshell powders due to their penetrable nature. Void openings exist between the calcite valuable stones to allow the trading of gases from the internal to the outside side of the eggshell. The SF is considered a fake pozzolan and is basically contained silica glasses [73]. Based on the past researchers founding, the pozzolans are low in CaO content which is less than 10% [48]. Therefore, a material that contains a high level of CaO ought to be utilized. Along these lines, as previously mentioned in Table 2, the ESA is utilized in this examination as the CaO content in ESA is high (62.50%) and can go about as a settling expert to improve the strength of the untreated kaolin. The high content of CaO in the ESA that helps in the soil improvement were also proven by the previous researchers [45,48]. At first, the $CaCO_3$ of the nature eggshell was changed into CaO through the consuming activity utilizing the heater. This CaO was then added to the development of cementitious parts during soil adjustment. Table 10 shows the substance oxide creations of the untreated kaolin and treated kaolin tests.

3.4. *Mineralogy characteristics*

XRD examination recognized the mineralogical substance of the untreated kaolin admixed with the ideal substance of the

Table 10 – Chemical oxide compositions of the untreated kaolin and treated kaolin samples.

Sample	Compositions (%)					
	SiO_2	CaO	Al_2O_3	K_2O	MgO	Fe_2O_3
Kaolin (Control)	66.11	0.08	19.25	2.85	1.23	0.73
SF	74.02	0.00	0.45	4.27	3.73	0.71
ESA	0.02	62.50	0.01	0.05	0.71	0.02
K2SF	67.59	0.05	18.88	2.88	1.28	0.73
K4SF	69.07	0.05	18.49	2.91	1.33	0.73
K6SF	70.55	0.08	18.12	2.94	1.38	0.73
K6SF3ESA	64.60	1.95	17.54	2.85	1.36	0.73
K6SF6ESA	62.62	3.82	16.97	2.77	1.35	0.69
K6SF9ESA	60.64	5.69	16.39	2.68	1.33	0.66

stabilizer (6% of SF and 6% of ESA). These arrangements of limits were picked to furthermore legitimize the past assessment on compound oxides piece. Fig. 9(a) and (b) delineates the XRD designs got for the untreated kaolin and treated kaolin admixed with the ideal substance of stabilizer (6% of SF and 6% of ESA) individually. In view of Fig. 9(a) and (b), the crude soil showed the presence of high earth minerals (quartz) and low total minerals (muscovite). As the figure depicts there was a reduction in the most zenith forces of offset models particularly for test settled with the substance of the ideal stabilizer.

The power of untreated kaolin that appeared in Fig. 9(a) (>60,000) is decreased when the example was balanced out with 6% of SF and 6% of ESA (<60,000) as demonstrated in Fig. 9(b). Comparable outcomes have been accounted for by past explores [15]. This could be credited to the occasion of the pozzolanic reaction that achieved the lessening of the earth minerals in settled material and lower top forces [15]. Moreover, the vagary of the pozzolanic particle was among the essential segment that will be locked in with the discretionary hydration measure. The movements of power at tops exhibited that the fuse of the SF and ESA affected the plan of the glasslike silica. The crystallinity of silica is lessening the pozzolanic reactivity of the material in light of the limit of the amorphous silica to participate in the hydration cycle to react with the calcium hydroxide [19].

Table 11 – PSD of untreated kaolin, SF, ESA and kaolin stabilised with optimum stabiliser dosage.

Size range (mm)	Cumulative passing (%)			
	Kaolin	SF	ESA	Kaolin + 6% SF + 6% ESA
>4.75	0	0	0	0
0.075–4.75	48	44	74	66
≤0.075	52	56	26	34

3.5. *Morphology analysis*

Table 11 shows the correlation on the molecule size circulation of untreated kaolin test, SF, ESA and treated kaolin test

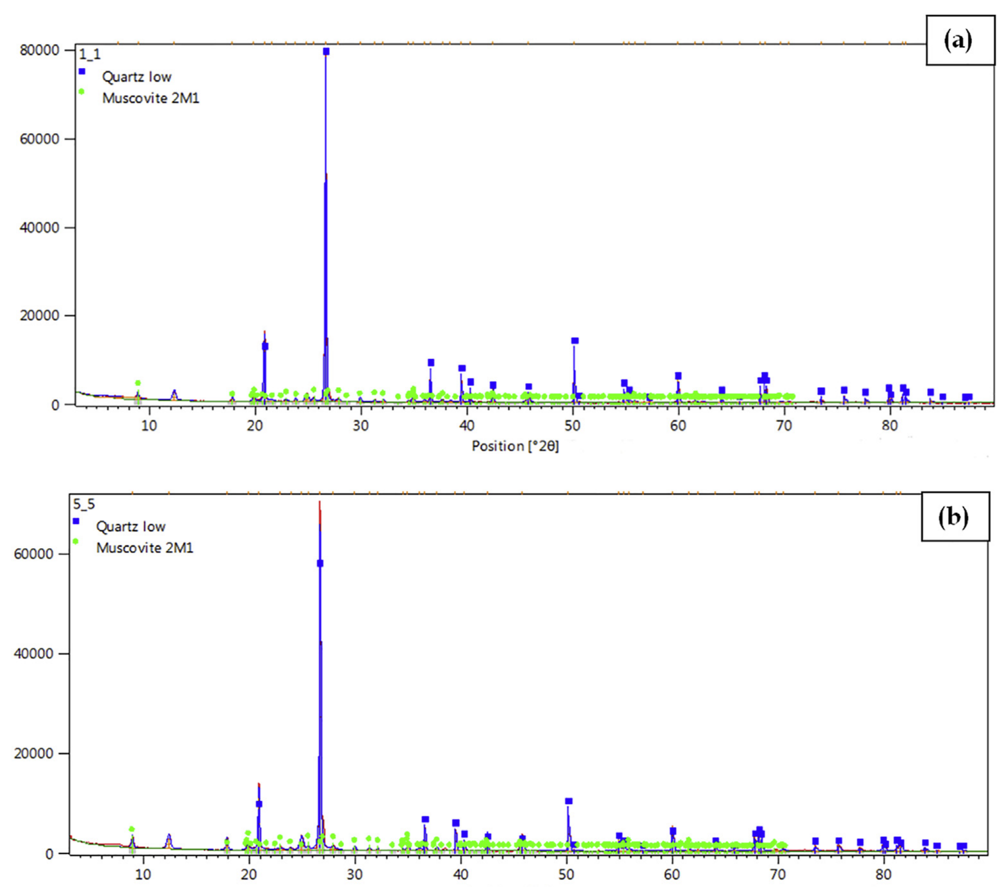


Fig. 9 – The XRD results for (a) untreated kaolin (b) treated kaolin with 6% of SF and 6% of ESA content.

admixed with 6% of SF and 6%. In view of Table 11, for untreated kaolin, there is 52% of particles that are more modest than 0.075 mm, which is named the fine example with molecule size goes from 0.0008 mm to 0.063 mm. Previous researcher stated that the particle size of the kaolin clay is a fine size particles [2] which is coherent with the particle size analysis obtained in the study. The SF is a better material when contrasted with Kaolin and presents in the size going from 0.00008 mm to 0.15 mm due to the 56% of SF particles passed the size of 0.075 mm, where 44% of it held above 0.075 mm which is within the range size of particles investigated by previous researcher [58]. In view of the percent better at 4.75 mm and 0.075 mm, LL and PI, the size of the SF utilized in this investigation can be portrayed as MH (sandy/silty soil) with a high versatility include. As per AASHTO, SF is arranged as A-5 (fine silty) soil because of its LL and PL value. The ESA is a coarser material and exists in the size going from 0.063 mm to 0.3 mm with 26% of the particles passing the 0.075 mm strainer, while 74% of it held above 0.075 mm sifter which is consistent with the result obtained from the previous researcher [45]. In view of the percent better at 4.75 mm and 0.075 mm, LL, and PI, the ESA is named SC (sandy-mud) particles and arranged as A-2-4 dependent on AASHTO classification because of its Atterberg limit qualities.

The incorporation of SF and ESA to the delicate kaolin brief the reshuffling of soil molecule framework, shaping a coarser kaolin–SF–ESA (K–SF–ESA) combination where the PSD bend of the regarded kaolin as demonstrated in Fig. 9 moved somewhat to the coarser right side. The treated delicate kaolin is delegated a sand-silty (SM) and is ordered as sandy-silty (A-2-4) in AASHTO. It comprises 0% rock, 66% sand and 44% mud and sediment (Table 10).

In view of the UCT result, the ideal stabilizer content relating to the most extreme USS is 6% SF and 6% ESA. The treated kaolin test is coarser than untreated kaolin with 34% of particles were more modest than 0.075 mm. In view of the PSD bend plotted in Fig. 10, the treated kaolin moved somewhat to the correct side (coarser sign) which is inferable from the consideration of better SF and coarser ESA that caused the reshuffling of soil particles framework. The treated kaolin is delegated SM (sand-silt) blend and furthermore portrayed in bunch A-2-4 (sandy-silt or sandy-clay) by alluding to the AASHTO characterization. The arrangement results by utilizing USCS and AASHTO characterization for the entirety of the materials are comparable.

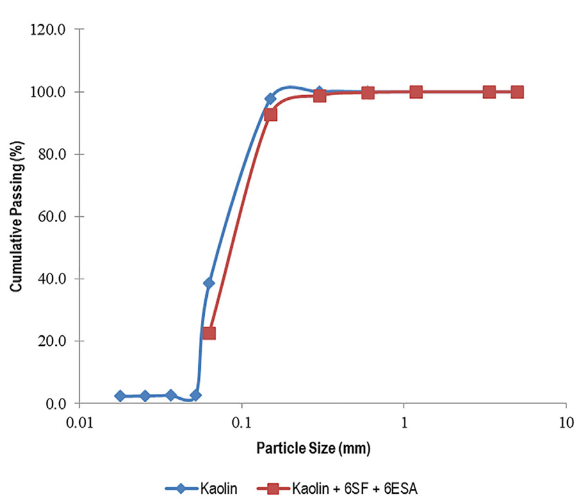


Fig. 10 – PSD curve of untreated kaolin and treated kaolin with an optimum dosage of stabilizers (6% SF & 6% ESA).

3.6. *Shear strength analysis*

As previously mentioned in section 3.1, the ideal level of SF and ESA needed to achieve the greatest shear strength were resolved by means of the UCT. Fig. 11 show the stress–strain diagram of the kaolin treated with 6% of SF and 6% of ESA content. The underlying q_u worth of untreated delicate kaolin is 42.11 kN/m^2. The q_u value expanded with the underlying augmentation of SF content and recorded the most noteworthy improvement at 39.6% by utilizing 6% of SF content by the dry load of the soil. This imprints 6% SF as the ideal substance as being discussed by [12] to be utilized with ESA for additional strength improvement. A 3%, 6% and 9% of ESA were subsequently added to the delicate kaolin admixed with 6% SF to inspect the presentation in balancing out the delicate kaolin. The consolidation of the ESA up to 6% expanded the q_u worth of delicate kaolin to 71.10 kN/m^2, where a most extreme improvement of 68.8% is recorded. The further fuse of ESA substance to 9% diminished the q_u worth of delicate kaolin because of dislodging of soil particles. Moreover, because of the abundance of ESA content, the holding structure between the particles is feeble. The s_u an incentive for each example was determined and arranged in Tables 5 and 6. The consequences of UCT suggests that the expansion of SF and ESA bit by bit expanded the development of CSH and brief the pozzolanic response that adds to the improvement in strength properties of delicate kaolin.

Fig. 12(a) and (b) are the regular disappointment mode that was seen in this examination. Fig. 12(a) is shown the shear disappointment of the compacted soil test, for both untreated and treated examples, where the compacted soil breaks upward from the upper layer to the base upon the utilization of pressure load while Fig. 12(b) embodies the protruding disappointment, where the disappointment happens at the feeble layer of soil. The disappointment in the soil is a muddled condition that can be brought about by different factors and

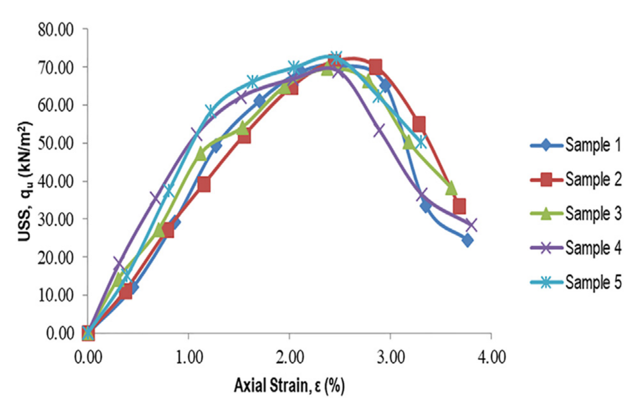
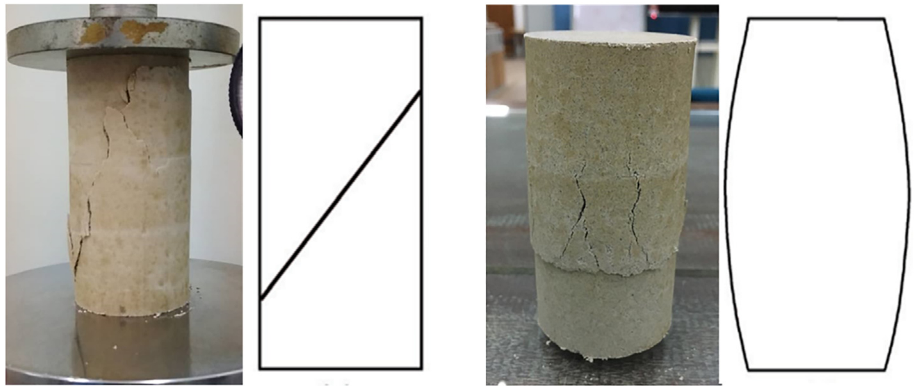


Fig. 11 – Stress–strain graph of the kaolin treated with 6% of SF and 6% of ESA content.



(a) (b)

Fig. 12 – Compacted soil sample of (a) shear failure (b) bulging failure.

have a cosy relationship with the weakness and pliability of the dirt [12]. The factors including the keeping pressure, pore pressure, the pace of strain, temperature, liquid science, modular organization, molecule size, porosity, etc [12].

3.7. *Microstructural characterization*

Field Emission Scanning Electron Microscopy (FESEM) pictures under ×10,000 amplification of untreated kaolin, crude SF, and crude ESA appear in Fig. 13(a)–(c). In view of Fig. 13(a), the kaolin has a flaky shape microstructure. Fig. 13(b) shows that the SF molecule was made out of a fine circular shape with a molecule size of a few hundred nanometers. The ESA powder particles appeared to have a rough, inconsistent morphology and a fluctuating atom size apportionment as a result of the beating treatment coordinated as demonstrated in Fig. 13(c). The eggshell common layer was not recognizable inside the models.

Fig. 14(a)–(d) outline the FESEM picture of treated kaolin with 6% of SF and 6% of ESA under ×10,000 amplification, ×15,000 amplification, ×30,000 amplification and ×100,000 amplification separately. In view of the figure that appeared, it unmistakably shows that the SF and ESA particles are available in the kaolin as the figures outline the round state of SF and a rough and unpredictable state of ESA restricting along with the flaky state of the kaolin. The microstructure observed in this study is coherent to the previous researchers finding which stated that the soil structure changed due to the

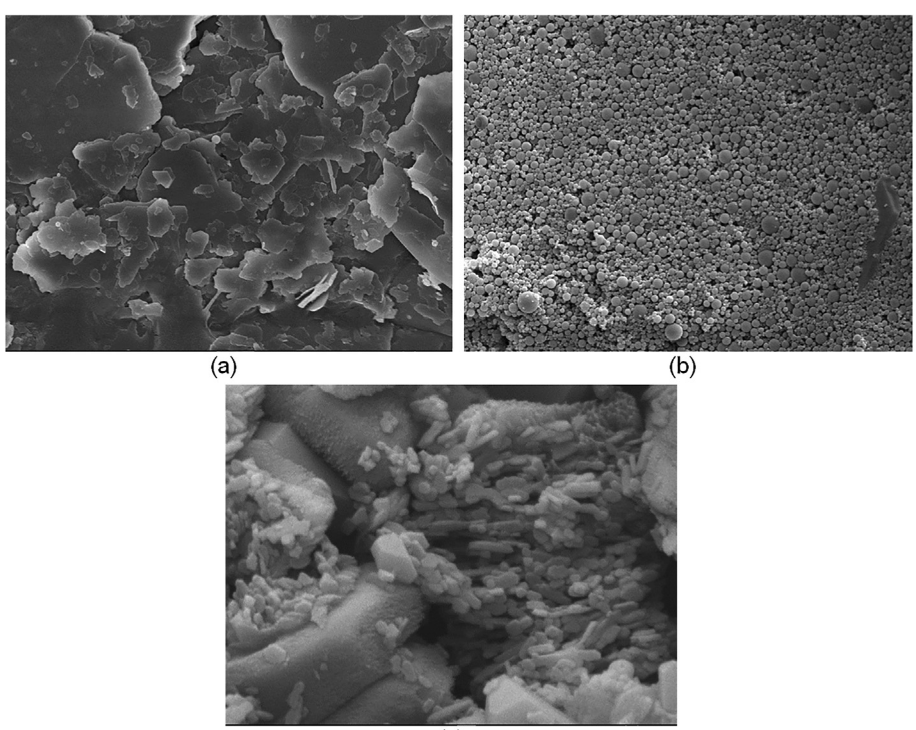


Fig. 13 – FESEM images under ×10,000 magnification of a (a) untreated kaolin, (b) SF, and (c) ESA.

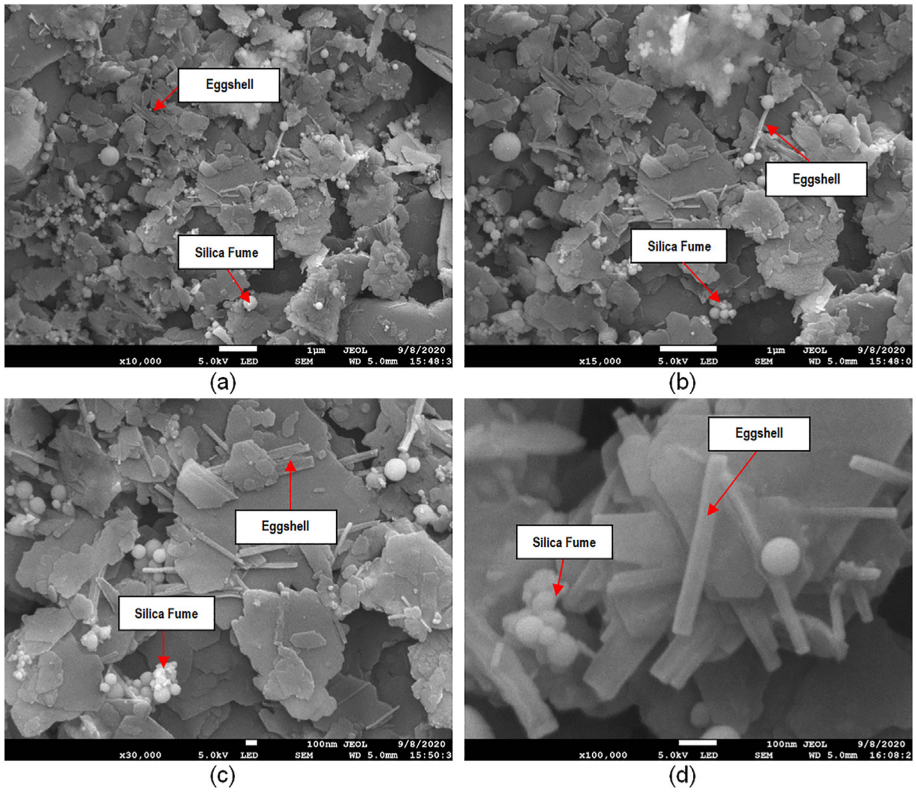


Fig. 14 – FESEM images of treated kaolin under (a) ×10,000, (b) 15,000, (c) 30,000 and (d) 100,000 magnification.

pozzolanic response between the soil and the material used as stabilizing agent [15]. Therefore, FESEM image in Figs. 12 and 13 proves the effective reaction between the additives and kaolin soil and the formation of C–S–H which resulted in higher shear strength.

3.8. *Correlation analysis*

The correlations of the engineering properties (i.e specific gravity, Atterberg limit, Standard Proctor Compaction test and UCT) of delicate kaolin with the fluctuating SF and ESA content were set up in this investigation. The correlation equations of the four (4) parameters researched in this examination is vital to foresee the best model for ideal use of stabilizers of SF and ESA content. Subsequently, the condition will be a huge rule for the soil improvement technique given in this investigation. The correlation equations of the four (4) parameters studied are tabulated in Table 12.

From the correlation equation arranged in Table 12, it tends to be concluded that, with the higher worth of the coefficient of determination (R^2 value), the level of the varieties of the four (4) parameters noticed can be anticipated by the consideration of the SF and ESA as soil stabilizers. In light of the relapse measurements set up in the examination, the coefficient of determination (R^2 value) for all parameters researched is above 0.5. Henceforth, it tends to be

Table 12 – Summary of correlation equation and R^2 value.

Test	Correlation equation	R^2 value	Variation (%)
Specific gravity	$G_s = 0.0225SF^2 + 2.615$	0.8248	82.48
	$G_s = -0.0036ESA^2 + 0.0315ESA + 2.5095$	0.7029	70.29
Atterberg Limit	$LL = 0.3625SF^2 - 2.085SF + 40.63$	0.9887	98.87
	$PL = 0.2813SF^2 - 1.1325SF + 31.285$	0.9770	97.70
	$PI = -0.465SF + 9.02$	0.9033	90.33
	$LL = 0.1456ESA^2 - 1.996ESA + 41.234$	0.9874	98.74
	$PL = 0.1194ESA^2 - 1.5583ESA + 34.625$	0.9798	97.98
	$PI = -0.2019ESA + 6.3728$	0.8913	89.13
Standard Proctor Compaction Test	$\rho_{d(max)} = -0.0128SF + 1.5944$	0.8641	86.41
	$W_{opt} = 0.225SF + 19$	0.9854	98.54
	$\rho_{d(max)} = -0.0011ESA^2 + 0.0088ESA + 1.5263$	0.5908	59.08
	$W_{opt} = 0.0278ESA^2 - 0.1833ESA + 20.3$	0.6923	69.23
Unconfined Compression Test (UCT)	$S_u = 1.4045SF + 20.449$	0.9675	96.75
	$S_u = -0.1642ESA^2 + 1.8405ESA + 28.892$	0.7393	73.93

demonstrated that half of the variety in the parameters contemplated (specific gravity, Atterberg limit, compaction and shear strength) can be clarified by the incorporation of SF substance and ESA content. In this way, the relationship set up is the best model to be utilized to anticipate the ideal measurement use of stabilizers (SF and ESA content). The correlation analysis conducted in this study is not coherent to the previous study due to the different method used to obtain the R^2 value [61,74]. However, the analysis by using R^2 value lead to the same path to accomplish the best plan comparative with a bunch of focused on models.

4. Conclusions

Considering the exploratory results and data examination did in this investigation, the reduction in the specific gravity of the balanced out kaolin blend with SF and ESA shows that the soil particles lattice is reshuffled and a lighter soil combination is shaped. A most extreme decrease of 48.4% in PI of the balanced out kaolin blend with SF and ESA suggests that earth content diminished and broad qualities of delicate soil are successfully decreased. In addition, the decrease in MDD is ascribable to the reshuffling of the soil particles framework while OMC expanded as more water is needed to shape the CSH compounds and to advance the pozzolanic response between the stabilizers and kaolin clay. Besides, the blends of SF and ESA with the kaolin clay resulted to high content of CaO which is needed in increasing the strength of the kaolin clay. This CaO was added to the development of cementitious parts during soil adjustment. Based on the microstructural characterization, SF and ESA is an ideal combination of material to be used together for soil stabilizing agent as both of the materials are incorporated with the kaolin clay. The consideration of SF and ESA coarsen the particles of delicate kaolin blend and the soil arrangement change to SM and A-2-4 with the 15% decrease in fine substance. The blends of SF and ESA as soil adjustment specialists effectively upgrade the undrained shear strength of the kaolin clay soils up to 68.8% of strength improvement with the best percentage of 6% SF and 6% ESA for optimum enhancement of the expansive soil and with the higher worth of the coefficient of determination (R^2 value), the level of the varieties of the four (4) parameters noticed can be anticipated by the consideration of the SF and ESA as soil stabilizers, which can minimize the expenses and as an eco-accommodating materials in soil improvement.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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