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# Effect of Optimum Utilization of Silica Fume and Lime On the Stabilization of Problematic Soils

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**Abstract:** Chemically stabilized soil studies have revealed that the efficiency of stabilization is primarily depends on the natural environment of the soil. Problematic soils such as silt and clay do not satisfy the standards for structural applications at this stage because under relatively mild stress conditions, the soils can expand, collapse, disperse, settle excessively, or even fail which can lead to structural failure. Moreover, the improvement of kaolin soil stays a test because of the significant expense and non-eco-accommodating material such as concrete. This study aims at the kaolin soil stabilization by utilizing 4% and 6% of silica fume and several percentage inclusion of lime. The lime percentages of 3%, 5%, 7%, and 9%, whereas the ratio of silica fume is set at 4% and 6%. The primary goal of this study is to increase the shear strength of soft kaolin soil blended with 4% and 6% of silica fume (SF) and varying amounts of lime (L). The soil parameters were evaluated for kaolin soil alone and for 4% and 6% of silica fume blended with varying percentages of lime. The findings disclose that the optimal percentages of silica fume and lime in terms of maximum shear strength at 176.91 kPa of improvement were 4% and 7% respectively due to the pozzolanic reaction between silica fume and lime was more successful with soil particles. The combination of silica fume and lime blended with the kaolin soil can highly enhanced the strength of the soil up to 88.10% compared to the lime and silica fume mixed alone with the optimal proportion of 4% of silica fume and 7% of lime which can reduce the environmental pollution with the reduction in carbon dioxide emission during production and provides economic benefits due to the low cost of materials.

**Keywords:** Soil stabilization, kaolin soil, silica fume, lime, undrained shear strength, permeability

## 1. Introduction

In recent years, the main issues that geoscientists have had to face have been the building and implementation of land development initiatives in areas of the world with a heavy proportion of swelling clayey soils and soft soil such as silt [1]- [5]. Due to the great porosity and low shear strength of expansive clay and soft soils, ignoring infrastructural and building development is extremely dangerous [3], [6]. Among such soil conditions, silt soil is noted for its troublesome qualities due to its inherent ability to undergo dynamic environments in reaction to variations in the moisture regime [3]- [5], [7], [8]. The small particle size combined with a relatively large surface area causes the kaolin to have a strong ability to retain water, resulting in sagging behavior when subjected to humidity fluctuations [3], [9]. Because of its expansive qualities, kaolin soil has become a difficult material that necessitates specific management during construction [10]. As a result, it is critical to increase and maintain soil qualities through the use of stabilizing measures that can respond to extreme demand scenarios. Soils having a high clay or silt percentage are challenging to work with. Before constructing on this topsoil, a detailed design analysis should be conducted to account for the soil's low strength and high compressibility [11]. Kaolinite is classified as a clay mineral. This is a modified epoxy mineral

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made up of individual fragments that can also be differentiated. One tetragonal sheet of alumina is joined to one octahedral of alumina by oxygen molecules in this layered silicate mineral.

Soil settlement is a significant difficulty when coping with subsoil construction projects such as roadways, housing, and slope projects. Buildings often collapse significantly owing to the increase in porosity and weak shear strength caused by the lacking characteristics of soft soil [12]- [15]. A certain amount of settlement is unavoidable when constructions are constructed on expansive soil. This propensity can lead to problems in practical applications, causing a bothersome disturbance that should be handled. Various problems may occur in lands that are mostly comprised of soft clay. Asphalt, railroads, roads, retaining structures, and many other infrastructures suffer from fracturing and degradation as a result of these difficulties. Pozzolanic materials can be optimized to quantify the engineering characteristics of soft soil for building (SF). Expansive soils concerns include limited load carrying capacity, severe projected settlement, and generally poor structural stability of buildings made on such soil. Soils that are weak, moist, and fine-grained have such a weak shear strength and a high porosity [12]- [15].

Soil adjustment interaction is commonly employed to enhance the real qualities of the soil. The most current strategy for soil correction is to replace contaminated soil with more stable materials such as cement, geotextiles, and geo-lattices [16]. According to previous studies, a few more chemicals were used as settling specialists. A fraction of these stabilizer additives includes various types of bitumen, pozzolanic additives, lime, and concrete. Soil modification, also known as a soil treatment, is a well-informed and incredibly clever process that has been used to increase the sturdiness and mechanical qualities of large soils [5]. Soil enhancement is frequently used to treat soil issues instead of adopting consequently improving such as building shear structures or buttress hardening road pavements or enlarging foundation. Chemical enhancement is typically more successful in subsoil since it can be used to alter the properties of the sample. To reinforce the soil and remove its vulnerability to water, and the stress cycle that occurs, chemical methods might be used. Chem-stabilizer technologies are used to enhance the strength of the soil, relieve vertical and lateral settlement, minimize time production and expenses, and handle other problems that may affect particular weak soil projects. The faults are investigated in this work by performing lab tests on soft kaolin clay, kaolin blended with lime, kaolin blended with silica fume, and kaolin blended with silica fume and lime [17], [18].

When compared to other sources, cement has historically been used in large quantities as a soil stabilizer [19], [20]. However, the considerable creation has a substantial effect on the environmental quality. Concrete manufacturing in the construction mix is a substantial source of $CO_2$ emissions and the emission of pollution chemicals [20]-[22]. For every tonne of liquid concrete produced, the concrete assembly process can emit between 700 and 1300 kg of $CO_2$ into the surrounding [7], [20], [23]- [25]. As a result, a reduction in concrete formation on the natural result has begun by replacing with another sustainable material, such as pozzolan [26], [27]. Concrete replacement with waste materials has been widely used effectively to reduce economic challenges. Nonetheless, due to the massive supply of organic waste from this industry, agricultural waste materials have recently received attention [28].

Silica fume debris can be employed successfully to lessen the danger of proteolysis concrete cracking in crushed clayey soil and covering systems. Thus, soil improvement has consistently been used as economical, sustainable, and offers a quality enhancement approach that can be tailored to meet the needs of individual engineering goals for unique projects [29]- [31]. Concrete with structural applications can be manufactured by employing silica-fume (SF) as a substitute for coarse or by adding an addition [32], [33]. SF was previously acclimated to soft soil with the inclusion of many other substances including lime, cement, dust, wood slag, and so on, and the findings indicated that the introduction of SF can affect the characteristics of the material and enhance the compression strength of soil sample [33]- [35]. Owing to the porous and pozzolanic impact of silica fume, the addition of SF resulted in better strength properties conduction value ratios, and stronger strength properties compared to fly ash [34], [35].

Yilmaz and Demir [36] investigated the effects of silica fume and lime addition on soil samples explained by changes. In a laboratory testing for specimens collected, the relevant proportions were utilized: for silica fumes, 5%, 10%, and 15%, and for lime, 1%, 3%, 5%, 7%, 9%, and 11%. The findings suggest that adding lime in the 5% to 9% range mixed with 10% silica fume enhanced the soil’s physical properties. Whenever the soil was treated to an 11% to 15% silica fume and lime blend, the plasticity index reduced from 40% to 19%. Internal friction angle rose from 5.80° to 24.75° at LSF 5% and 10%, and soil cohesion improved from 55.52 $kN/m^2$ to 157.54 $kN/m^2$. The compressibility index (c), on the other hand, dropped from 0.025 to 0.007. In conclusion, mixing silica fume and lime improves the engineering characteristics of subgrade soil.

The impacts of applying silica fume, lime, and lime–silica fume as stabilizers on kaolin soil were examined and considered in 2015 [14], [15]. This study used a foppish, greyish silica fume (SF), a cementitious material with a heavy proportion of crystalline silicon dioxide and very fine spherical fragments. Lime interacts with subsoil, causing it to lose flexibility while increasing strength and durability. During the test, three percentage values were employed for each substance: lime 2, 4, and 6%, and SF 2.5, 5, and 10%, with the optimum SF percent combined with the lime proportions. Many tests were conducted after the inclusion of the lime or SF to evaluate soil characteristics. As the lime and SF proportions grow and the soil becomes coarser, the soil sample curves shift substantially to the coarser side. The unconfined compression test found that 5% of SF and 4% of lime were the optimal SF and lime calculated values. It was also revealed that while the strength enhancement is modest, there is an optimal lime content beyond the limit. In other cases, it was found that the growth of strength was too sluggish to meet the norms [14].

As a result, due to the poor qualities, kaolin soil was selected as a specimen in this investigation. The technical qualities of such soils vary depending on different geological processes occurring under various conditions. Kaolin soils contain compressibility, weak strength, and low permeability in all circumstances, and they are frequently compacted, resulting in poor construction quality. The possibility of using the mixture of SF and lime in kaolin soil as a soil stabilization agent and a substitute way to increase the strength properties of kaolin soils is picking up the slack. Previous research found that adding silica fume to compacted samples reduces the development of exterior proteolysis fissures. The optimal blend of SF and Lime with kaolin not just increases the strength characteristics of the silt soil but also lowers the relative density, plasticity index (PI), maximum dry density (MDD), and optimum moisture content (OMC). As a result, the silica fume-lime combination is an environmentally acceptable, and economical solution for weak soil stabilizing agents.

## 2. Materials and Methods

## 2.1 Materials

### 2.1.1 Kaolin Clay

Kaolin S300 from Kaolin (M) Sdn. Bhd. Bhd. In this study, was employed as a soil specimen. Kaolin with a fine-sized also referred to as kaolinite, can be found naturally or manufactured in a lab [10]. Kaolin is fine in size and is a white color in the natural state as shown in Fig. 1. Kaolin is delicate, has a low thickness at high solids content, is promptly wet and scattered in water and some natural frameworks, and can be created with a controlled molecule size dispersion [8], [10]. A watery suspension is formed when a greater amount of water is added to it. Due to its availability, cost-effectiveness, and expansive characteristics with the variation in moisture content [10], kaolin was selected to be the sample soil in this study. Table 1 describes the fundamental engineering features of Kaolin S300. Table 2 lists the chemical properties of this soft kaolin.

**Fig. 1 - White kaolin**

**Table 1 - Fundamental properties of kaolin**

| **Properties** | **Unit** | **Result** |
| --- | --- | --- |
| Gravel | % | 0 |
| Sand | % | 46 |
| Clay and Silt | % | 51 |
| USCS classification | | ML |
| AASHTO classification | | A-5 |
| Group index | | 11 |
| Int. moisture content | % | 0.98 |
| SG$^{a*}$, $G_s$ | | 2.62 |
| LL$^{b*}$ | % | 40.6 |
| PL$^{c*}$ | % | 31.4 |
| PI$^{d*}$ | % | 9.3 |
| MDD$^{e*}$, $\rho_{d(max)}$ | g/cm$^3$ | 1.606 |
| OMC$^{f*}$, $W_{opt}$ | % | 19 |
| UCS$^{g*}$, $q_u$ | kN/m$^2$ | 42.11 |
| USS$^{h*}$, $S_u$ | kN/m$^2$ | 21.06 |

$^{a*}$Specific gravity, $^{b*}$Liquid limit, $^{c*}$Plastic limit, $^{d*}$Plasticity index, $^{e*}$Max. Dry Density, $^{f*}$Opt. Moisture Content, $^{g*}$Unconfined Compression Stress, $^{h*}$shear strength

### 2.1.2 Silica Fume

Silica fume, which is produced as a byproduct in the production of silicon and ferrosilicon alloys in the electrometallurgy industry, is a substance with high pozzolanic value due to its high content of amorphous silica. A grey color-densified SF was bought from Xiamen All Carbon Corporation, Malaysia with a specific gravity of 2.33, LL of 90.5%, PL of 80.5%, and PI of 10.0% was adopted in this present research. Scanfume, a permeable SF for cement with a relatively large average of approximately 15000 $m^2/kg$, was employed in this investigation. The entire surface area of the SF influences the reactivity of the pozzolanic activity. The pozzolanic reaction becomes more reactive as the overall surface morphology increases [10]. Scan-fume is a grey colored powder shown in Fig. 2. The specific gravity of the SF is around 2.0 to 2.4 and the bulk density of it is 550 $kg/m^3$ to 650 $kg/m^3$. Table 2 exhibits the chemical characteristics of SF.

**Fig. 2 - Grey color-densified silica fume**

### 2.1.3 Lime

Lime comes in a variety of forms that are used in the construction industry. They are produced through the calcination of the natural process at temperatures of up to 900°C. Lime, along with SF and lime, was utilized as a soil stabilizing ingredient. All the lime that was used in the research was bought from CAO Industries Sdn. Bhd. which is situated in Selangor, Malaysia. The lime (Fig. 3) utilized in this study was a laboratory-grade hydrated lime. The chemical composition of the lime that was tested at the laboratory is shown in Table 2. The details of the hydrated lime are shown in Table 3.

**Fig. 3 - Laboratory-grade hydrated lime.**

**Table 2 - Chemical properties of kaolin, SF, and lime**

| Composition | Unit | Kaolin | SF | Lime |
|---|---|---|---|---|
| $SiO_2$ | % | 66.11 | 74.02 | 1.70 |
| CaO | % | 0.08 | 0.00 | 70.60 |
| $Al_2O_3$ | % | 19.25 | 0.45 | 0.80 |
| $K_2O$ | % | 2.85 | 4.27 | 0.10 |
| MgO | % | 1.23 | 3.73 | 0.71 |
| $Fe_2O_3$ | % | 0.73 | 0.71 | 0.30 |

**Table 3 – Details of hydrated lime used in the study**

| Product Info | Details |
|---|---|
| Synonym | Quicklime/ Lime |
| Formula | CaO |
| Weight of Molecule | 56.08 g/mol |
| Product Number | 248568 |
| No.-CAS | 1305-78-8 |
| No.-EC | 215-138-9 |
| Quality Level | 200 |
| Grade | Reagent Grade |
| Assay | ≥68.0% Ca basis (EDTA titration) |
| Form | Powder |
| Loss | 10% loss on ignition, 1000°C (absorbed $H_2O$ and $CO_2$) |
| pH | 12.6 (20 °C) |
| Boiling Point | 2850 °C (lit.) |
| Density | 3.3 g/mL at 25 °C (lit.) |
| SMILES String | O=[Ca] |
| InChl | 1S/Ca.O |
| InChl Key | ODINCKMPIJJUCX-UHFFFAOYSA-N |

## 2.2 Methods

The mentioned experimental studies were used to define the necessary engineering characteristics of all other substances. To regulate the standardization of the experiment, Kaolin S300 was utilized instead of a soil sample. Following that, the kaolin was mixed with 2%, 4%, 6%, and 8% SF by dry weight of the soil, and the influenced by the physical, strength, and compaction characteristics of the soil were investigated. The sampling used in this investigation is shown in Table 4. The optimal SF percentage was measured as the fraction of SF correlated to the maximum undrained shear strength (USS). This optimal SF concentration had been combined with soft kaolin and 3%, 5%, 7%, and 9% lime by dry weight of the soil specimen. The mechanical properties of the combination of the soil were then determined, as well as the optimal lime percentage refers to the maximum strength. The percentages of SF and lime utilized in this investigation were chosen based on the literature review [10].

**Table 4 – Percentage of sample usage**

| Sample | Content (%) | | |
|---|---|---|---|
| | Kaolin | Silica Fume | Lime |
| K | 100 | - | - |
| K2SF | 98 | 2 | - |
| K4SF | 96 | 4 | - |
| K6SF | 94 | 6 | - |
| K8SF | 98 | 8 | - |
| K4SF3L | 93 | 4 | 3 |
| K4SF5L | 91 | 4 | 5 |
| K4SF7L | 89 | 4 | 7 |
| K4SF9L | 87 | 4 | 9 |
| K6SF3L | 91 | 6 | 3 |
| K6SF5L | 89 | 6 | 5 |
| K6SF7L | 87 | 6 | 7 |
| K6SF9L | 85 | 6 | 9 |

The mechanical sieve analysis is conducted in line with BS 1377: Part 2: 1990 [37]. The particle size distribution of kaolin soil specimen and stabilized SF and lime kaolin soil sample was determined in the test. The hydrometer test was conducted in line with BS 1377: Part 2: 1990 [37]. The purpose of this lab test is to assess the particle size distribution of the sample that passes through the 63 µm sieve. In this laboratory test, 50 g of the sample in the pan after sieving was employed.

The soil samples' specific gravity was calculated using the small pycnometer method in line with BS 1377: Part 2: 1990 [37]. The test employed 10 g of the oven-dried sample that passed through a 2 mm BS sieve and was done twice until the findings differed by no more than 0.03 $Mg/m^3$. Distilled water is used for the testing.

The soil sample's Atterberg limit was determined by BS 1377: Part 2: 1990 [37]. A liquid limit (LL) was measured using the cone penetration method with a test specimen weighing at least 300 g and passing through 425 µm, and the plastic limit (PL) was identified by rubbing around 20 g of the prepared specimen collected from the LL sample. The test was performed to differentiate between silt and clay.

A conventional compaction test was conducted to investigate the effect of different lime combinations on the behavior of kaolin soils. The ASTM D1557-12 [38] contains information on the standard compaction test process. These experiments were performed to determine the soils' MDD and OMC. The samples were crushed in a 105-mm-diameter mold. The attained unit weight at the optimum moisture point was used to calculate the dry unit weight and moisture content of each specimen. This weight was calculated by crossing the slopes of the wet-side and dry-side soils of the compaction curve for a total of five compaction tests.

The porosity of fine-grained soils was measured using the falling head permeability test, a common lab procedure. The falling head test applies to fine-grained soils with k values ranging from 105 to 108 cm/s. This method of testing can be used to investigate an undisturbed material. The approach for performing the falling head permeability test is described in ASTM D5084 [39]. The permeability of kaolin samples treated with lime + silica fume was determined using falling head permeability experiments performed in the laboratory. The ASTM D5084 [39] was used to conduct falling head permeability tests. Permeability tests were performed on kaolin samples that had been blended with lime in proportions of 3%, 5%, 7%, and 9%, as well as 4% of SF.

The unconsolidated undrained (UU) triaxial test, the most frequent type of triaxial test, is carried out to measure the increment in shear strength for soft kaolin soils combined with lime and silica fume compared to pure kaolin. The samples for this test were made by compacting samples taken with the soils' optimal moisture content. The instances were prepared and compressed in a barrel-shaped steel form with 100 mm high x 50 mm diameter parts. Furthermore, to maintain reliability and completeness as during the UU test, the densities of the instance are controlled utilizing consistent volume and weight management of the example. The specimen, which was compacted in molds specific to each experiment, were removed from the molds and after being wrapped in stretch film, they were kept in desiccators at approximately 25 ◦C in the laboratory for three (3) days of curing. Then the specimen will be tested for UU tests. In the UU test, the specimen was subjected to a specific all-round (constricting) pressure, and the primary stress differential was instantly delivered, prohibiting drainage at any step of the test. It is critical to identify the shear strength of a certain soil to solve any difficulties concerning soil mass stability, which in turn defines the structural load that may be applied to the soil. The directions for completing the triaxial test are detailed in BS 1377:1990 Part 7 [40].

FESEM tests were also used to examine the morphology of the samples after integrating the kaolin with the SF and lime. The samples used for the FESEM test were kept in desiccators at approximately 25 ◦C in the laboratory for three (3) days of curing. Then the sample was sent to the laboratory for a FESEM test.

## 3. Results and Discussion

### 3.1 Mechanical Properties of Soil Sample

#### 3.1.1 Particle Sieve Analysis

The particle size distribution of kaolin and kaolin stabilized with several percentages of lime and 4% of silica fume is illustrated in Fig. 4. The particle size of fine-grained soil of the materials is classified as silt and clay. Clay is the finest soil with the size of <0.002 mm while silt size is between 0.002 mm to 0.06 mm [41]-[43]. The graph is shifted substantially to the coarser side as the lime content rises. The soil itself becomes more granule with the increasing amount of time due to the immediate pozzolanic reaction which leads to the flocculation of clay particles. The value of the clay percent is not consistent, but it tends to decrease to the lowest value that is 0.3% and after that rise back to 0.4% at 9% lime content. Based on Sharma et al. [44], when there is an increase in lime content, there is a noticeable decrease in silt content and an increased proportion of granular materials. Hence, the results illustrated in the figure are compatible with the research made by Sharma et al. [44]. The reaction of lime and silica fume produces a stronger pozzolanic reaction which causes the silt particles to reduce.

#### 3.1.2 Particle Density

The particle density for Kaolin is 2.62 g/cm$^3$, which identified kaolin as clay minerals as previously indicated by previous scholars who stated that the particle density for kaolinite clay ranges from 2.62 g/cm$^3$ to 2.66 g/cm$^3$ [10], [33]. The addition of SF increased the particle density of the kaolin. A 0.76% increment in particle density was identified with the inclusion of SF up to 8% by dry weight of soil, where it increased to 2.64 g/cm$^3$ from 2.62 g/cm$^3$. The inclusion of the 3%, 5%, 7%, and 9% of lime to the K+4SF mixture reflects an initial reduction of particle density at 3% lime proportion and increased to 2.73 g/cm$^3$. This is due to the reorganization of soil particles caused by the addition of lighter SF and lime. Besides, the inclusion of the 3%, 5%, 7%, and 9% of lime to K+6SF mixture showed an increasing value in particle density value up to 2.69 g/cm$^3$ and it was then reduced to 2.66 g/cm$^3$ when 9% of lime is utilized. As a result, it is possible to conclude that incorporating 4% SF and 7% lime can raise the particle density of the kaolin. The particle density of the materials examined is shown in Table 5.

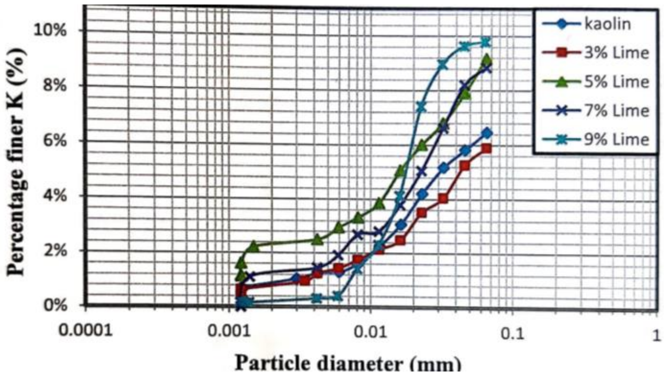



**Fig. 4 - PSD of the kaolin soil mixed with 4% of SF and various percentages of lime**

**Table 5 - Particle density of the kaolin soil and treated soil samples**

| Sample | Weight of Dry Soil (g) | Weight of Water (g) | Weight of Soil + Water (g) | Particle Density (g/cm$^3$) |
|---|---|---|---|---|
| K | 9.94 | 99.62 | 95.83 | 2.62 |
| K2SF | 10.02 | 99.72 | 95.93 | 2.33 |
| K4SF | 10.02 | 99.54 | 95.79 | 2.38 |
| K6SF | 10.01 | 99.82 | 96.06 | 2.64 |
| K8SF | 10.02 | 99.89 | 96.10 | 2.66 |
| K4SF3L | 7.01 | 99.90 | 96.12 | 2.66 |
| K4SF5L | 7.01 | 99.73 | 97.07 | 2.64 |
| K4SF7L | 7.00 | 99.67 | 97.11 | 2.60 |
| K4SF9L | 7.00 | 99.12 | 96.36 | 2.54 |
| K6SF3L | 7.00 | 98.89 | 96.10 | 2.51 |
| K6SF5L | 7.00 | 99.92 | 97.34 | 2.50 |
| K6SF7L | 7.00 | 99.85 | 97.25 | 2.69 |
| K6SF9L | 7.00 | 99.94 | 97.30 | 2.72 |

### 3.1.3 Atterberg Limit

The humidity of the passage was measured using the Liquid Limit (LL) test at 15 mm, 20 mm, and 25 mm. The LL and Plastic Limit (PL) of kaolin are 40.7% and 31.4 %, correspondingly, with a PI of 9.3%. The LL and PL of SF are large, 90.5% and 80.5%, correspondingly, owing to the SF's high water adsorption properties, which makes the SF exceedingly thermally conductive. The LL and PL reported for lime are 27.4% and 21.6%, correspondingly, with a PI value of 5.8%. The LL and PL were originally lowered by 7.4% and 5.1%, respectively, from 40.7% to 37.7% and 31.4% to 29.8 percent, with 2% of SF incorporated. Then, when the SF content climbed by up to 8%, so did the LL and PL values. The PI of the specimens reduced from 0% to 8% with the inclusion of SF, demonstrating that the silt content of the material examined dropped with the application of SF. With a lime capacity of up to 9%, the LL and PL values were lowered by 17.0% and 15.4%, correspondingly. The addition of lime enhanced the LL and PL of the specimen. The PI showed a declining trend with increasing lime, which is due to lime's capacity to stiffen the undisturbed soil. With a rise in SF concentration (from 9.3% to 6.6%), the PI of the kaolin was lowered by 29.0%, while a rise in lime led to a 27.3% drop of PI (from 6.6% to 4.8%). Fig. 5 depicts the link between types of samples and Atterberg limits.

According to the results in Fig. 5, both stabilizers can attach and disperse the kaolin, resulting in coarse aggregates and a decline in silty soil via ion exchange activity and cementitious processes. These findings are consistent with earlier studies undertaken by other scientists, as mentioned in the previous section [41], [45]. The decrease in PI after the inclusion of SF and lime indicates that the expansive properties of kaolin are diminished.

### 3.1.4 Standard Compaction Test

Fig. 6 depicts the interrelation between the MDD and OMC of kaolin and kaolin combined with 4% of SF and various concentrations of lime. According to the results, the standard compaction strain was reduced as a result of a reduction in alignment, particularly the corresponding alignment concerning the soil particles. There are many MDD values, and a stabilizer, such as SF and lime can reduce the MDD from 1.62 g/cm$^3$ to 1.49 g/cm$^3$. The MDD reduces because the soil becomes lighter than it was before being replaced with SF and lime composite particles. According to Sharma et al. [44], the particles coat the specimen, resulting in big particles with extra vacancies and, as a result, a reduction in density. The voids in the modified soil samples are filled with the stabilizing agent [46].

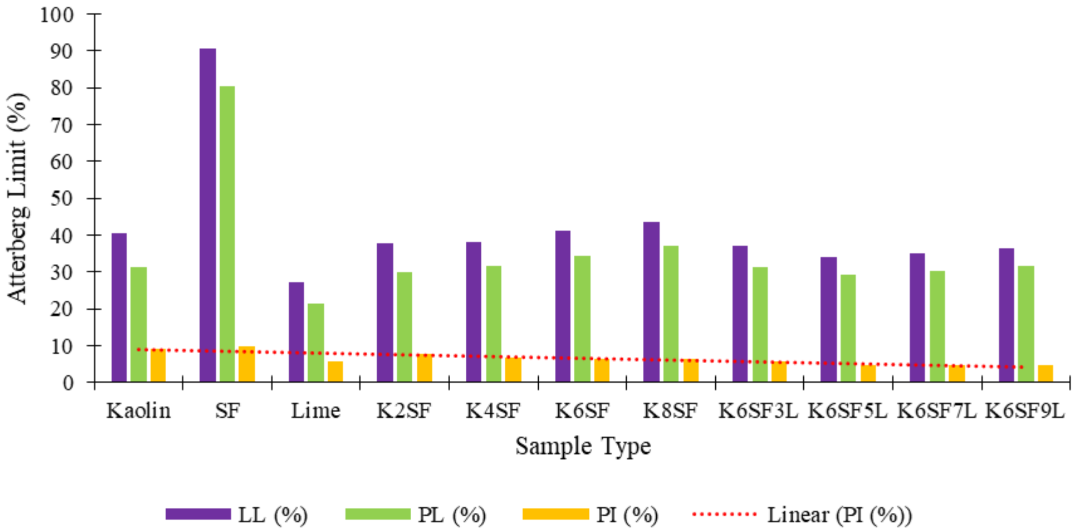



**Fig. 5 - Atterberg limits of the various percentages of inclusion of raw and treated kaolin**

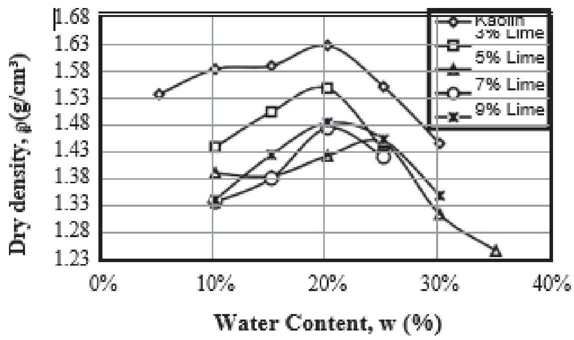



**Fig. 6 - Relationship of MDD and OMC of raw and treated kaolin**

Fig. 7 illustrates an increase in the OMC since the total area is reduced when SF and numerous lime particles cover and link the soils via coagulation and aggregation owing to the free radical's lime demands more liquid for pozzolanic reaction to take place, this procedure necessitates more liquid. An increment in lime proportion from 5% to 7% may result in increased water absorption by lime. According to Yarbaşi et al. [46], a modification in the particles size and porous structure of silica fume-stabilized clayey samples collected leads to an increase in OMC. Furthermore, with the addition of silica fume, the free silt clay proportion can be reduced, resulting in a coarser material with a greater surface area. According to Harichane et al. [30], this technique needs more energy, suggesting that even more water is needed to compress the specimens.

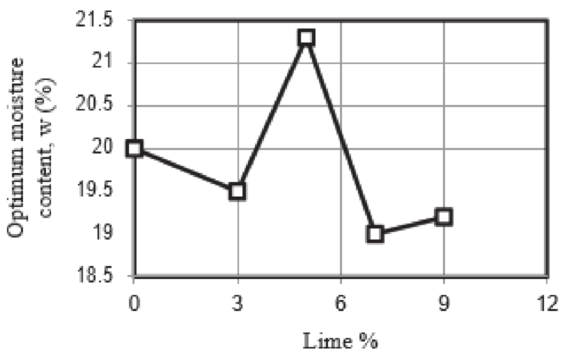



**Fig. 7 - Effect of utilization of 4% SF with several contents of lime on the OMC**

The OMC has decreased slightly, owing mostly to the substitution of soil with SF that has a lower density of about 2.2 g/cm$^3$ [31]. The results show that the SF and lime treatments reflected a gradual decline in the MDD, whilst the stabilizers somewhat increase this value for the OMC. Fig. 7 and Fig. 8 depict the impacts of multiple quantities of lime with 4% silica fume on the OMC and MDD, correspondingly. Table 6 lists the moisture content and bulk density of the samples obtained in the study.

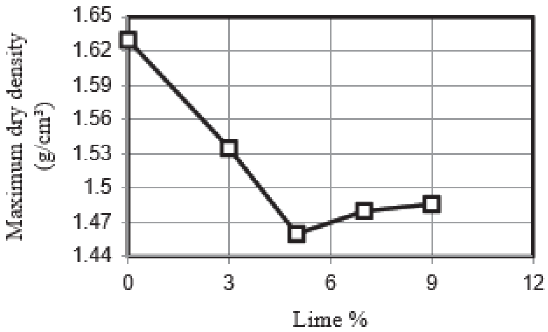



**Fig. 8 - Effect of utilization of 4% SF with several contents of lime on the MDD**

**Table 6 - Moisture content and bulk density of the samples obtained in the study**

| Sample | Moisture Content (%) | | | | | Bulk Density ($g/cm^3$) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 5% | 10% | 15% | 20% | 30% | 5% | 10% | 15% | 20% | 30% |
| K | 4.325 | 7.225 | 12.790 | 16.940 | 29.045 | 1.577 | 1.704 | 1.800 | 1.910 | 1.872 |
| K2SF | 3.190 | 7.770 | 12.680 | 17.600 | 28.375 | 1.514 | 1.662 | 1.767 | 1.893 | 1.851 |
| K4SF | 4.015 | 7.605 | 12.900 | 18.275 | 29.065 | 1.493 | 1.641 | 1.767 | 1.872 | 1.851 |
| K6SF | 4.395 | 8.915 | 13.180 | 18.420 | 29.305 | 1.493 | 1.641 | 1.767 | 1.872 | 1.830 |
| K8SF | 3.780 | 7.952 | 13.140 | 18.510 | 28.410 | 1.430 | 1.577 | 1.704 | 1.830 | 1.830 |
| K4SF3L | 4.137 | 8.645 | 12.810 | 18.470 | 28.100 | 1.514 | 1.662 | 1.746 | 1.872 | 1.851 |
| K4SF5L | 4.925 | 6.935 | 11.575 | 16.740 | 26.795 | 1.514 | 1.641 | 1.767 | 1.872 | 1.893 |
| K4SF7L | 4.395 | 5.980 | 121.650 | 17.000 | 28.320 | 1.491 | 1.598 | 1.767 | 1.872 | 1.851 |
| K4SF9L | 3.515 | 6.972 | 11.480 | 16.780 | 28.545 | 1.472 | 1.620 | 1.740 | 1.850 | 1.851 |
| K6SF3L | 4.662 | 9.830 | 14.460 | 19.060 | 28.130 | 1.483 | 1.510 | 1.670 | 1.810 | 1.770 |
| K6SF5L | 5.076 | 9.320 | 14.664 | 19.532 | 29.330 | 1.359 | 1.614 | 1.561 | 1.683 | 1.734 |
| K6SF7L | 5.034 | 8.710 | 13.77 | 18.59 | 28.930 | 1.415 | 1.490 | 1.610 | 1.790 | 1.730 |
| K6SF9L | 4.761 | 9.125 | 14.395 | 18.679 | 28.759 | 1.440 | 1.483 | 1.703 | 1.805 | 1.764 |

## 3.2 Permeability Test

The falling head permeability test yielded a permeability coefficient of kaolin of approximately 4.82 x $10^{-12}$ m/s for an MDD of 1.63 $g/cm^3$. Based on Head [47], the value obtained for kaolin shows the impervious behavior of kaolin and implicitly shows its inadequate water capabilities, which usually correlate to intact clay. Fig. 9 demonstrates the impacts of 4% silica fume and various lime dosages on hydraulic conductivity. The graph shows that the reduction in permeability values for lime levels up to 5%, which is the appropriate fraction of lime. A low value is the least permeability result derived in stabilized fine particle specimens collected using 5% lime. 3.14 x $10^{-12}$ m/s is the hydraulic conductivity value. Continuing that, as the lime level increases from 7% to 9%, so do the porosity. The permeability values are influenced by an overabundance of lime. Furthermore, for all specimens, these values appear to be a little less impacted by lime. The inclusion of further lime SF reduced permeability of the stabilized fine-grained soil specimens, with extra small particles from the mixture of such molecules clogging the gaps of the prepared specimens and the chemical change between the stabilizing agent (SF and lime) and the fine-grained soft soil. The void ratio decreases as additional stabilizing agents are put into the soil. The increase in permeability of naturally fine-grained soils that follows is due to a change in collected soil stress created by particle reorganization and fracture development [48].

## 3.3 Undrained Shear Strength Analysis

The influence of L–SF on shear strength is shown in Fig. 10, and Table 7 demonstrates the link between the undrained internal friction angles of SF and lime mix content. The soil–L–SF mix improves shear strength and friction angle (Fig. 10) over the soil–lime and soil–SF mixes due to the pozzolanic engagement of lime and SF, which is more efficient with soil. The optimal inclusion for undrained shear strength and friction angle is 4% SF and 7% lime. At 9% and 4% of Lime and SF respectively, shows a drop in shear strength and angle of friction owing to a reduction in one product of the pozzolanic reaction (silicon). According to Fig. 10, shear strength increases with lime concentration, with 5% of lime being the optimal percent. This rise is due to pozzolanic reactions within lime–soil mixes (the liberated silica and alumina combine with the calcium from the lime to make cement), which result in strength increment over time. The shear strength of lime declined at 7% owing to a decreasing value in one component of the pozzolanic process (alumina in the soil). The increase in cohesiveness and internal friction angle values might be attributed to the pozzolanic activity and self-cementitious properties of the soil-lime mixture.

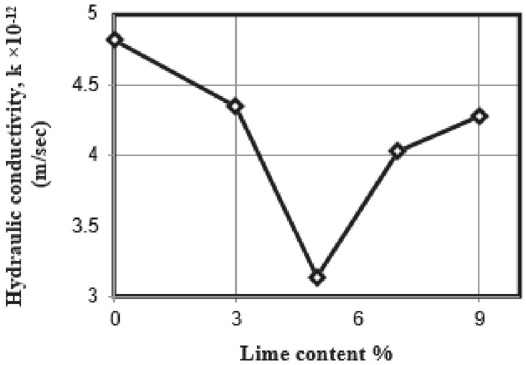



**Fig. 9 - Effect of various dosages of lime on hydraulic conductivity**

**Table 7 - Undrained Shear strength specification for kaolin soil stabilized SF and lime**

| Sample | Control | 4SF3L | 4SF5L | 4SF7L | 4SF9L |
|---|---|---|---|---|---|
| Friction Angle, φ (°) | 22.7 | 19.8 | 24.8 | 24.9 | 23.6 |
| Cohesion, *c* | 17.01 | 44.28 | 17.37 | 28.38 | 38.46 |

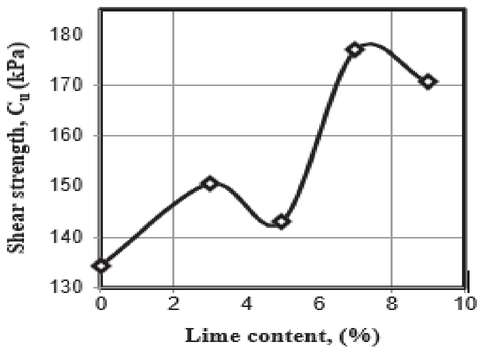



**Fig. 10 - Correlation between the $C_u$ and lime dosage**

## 3.4 Stress-Strain Behaviour

The UU test was used to determine the undrained shear strength of kaolin stabilized with several proportions of lime and SF. Various percentages of SF (2%, 4%, 6%, and 8%) and lime (3%, 5%, 7%, and 9%) and were evaluated, as well as the optimal SF combination with kaolin. To determine the average values of shear strength, tests were performed on the percentages of each of the materials additions. As a result, several specimens were molded and examined. Table 8 lists the undrained shear strength for all samples tested using the UU tests. Table 8 depicts the stress-strain responses of SF percentages (2%, 4%, 6%, and 8%) and lime percentages (3%, 5%, 7%, and 9%). Based on Table 8, it can be concluded that the highest undrained shear strength recorded is at 176.91 kPa with the optimum utilization of SF and lime at 4% and 7% respectively. Fig. 11 presents the Results of the UU test on the untreated sample.

## 3.5 Microstructural Characterization

Fig. 12(a), Fig. 12(b), and Fig. 12(c) show field emission scanning electron microscopy (FESEM) images of untreated kaolin, SF, and lime at x10 000 amplification (c). According to Fig. 12(a), kaolin has a crumbly microstructure. The SF molecule was created in a fine circular form with a molecular size of a few hundred nanometers, as shown in Fig. 12(b). The lime particles seemed to have a rough, uneven shape and a changing atom size apportionment, as seen in Fig. 12(c).

**Table 8 - Undrained shear strength of treated and untreated kaolin**

| Samples | Avg. Max. Deviator Stress, $q_u$ (kPa) | Avg. Axial Strain (%) | Undrained Shear Strength, $C_u$ (kPa) |
|---|---|---|---|
| Control | 271.46 | 17.40 | 134.36 |
| K2SF | 299.32 | 17.90 | 147.33 |
| K4SF | 300.69 | 16.20 | 148.17 |
| K6SF | 320.08 | 16.50 | 157.80 |
| K8SF | 305.04 | 15.20 | 150.43 |
| K4SF3L | 303.42 | 17.86 | 163.49 |
| K4SF5L | 290.91 | 15.13 | 165.23 |
| K4SF7L | 357.61 | 15.54 | 176.91 |
| K4SF9L | 341.89 | 13.82 | 172.11 |
| K6SF3L | 288.29 | 16.10 | 150.32 |
| K6SF5L | 305.98 | 17.63 | 151.69 |
| K6SF7L | 311.59 | 16.11 | 154.89 |
| K6SF9L | 320.64 | 18.17 | 158.99 |

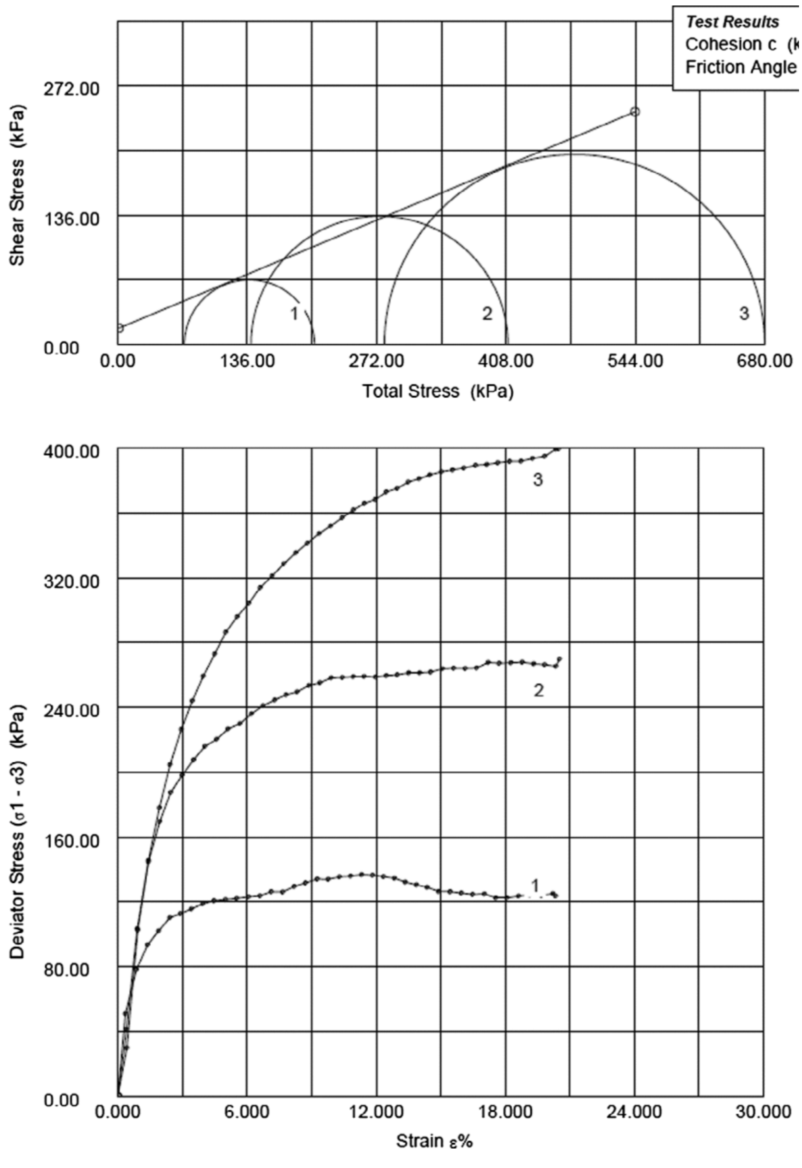
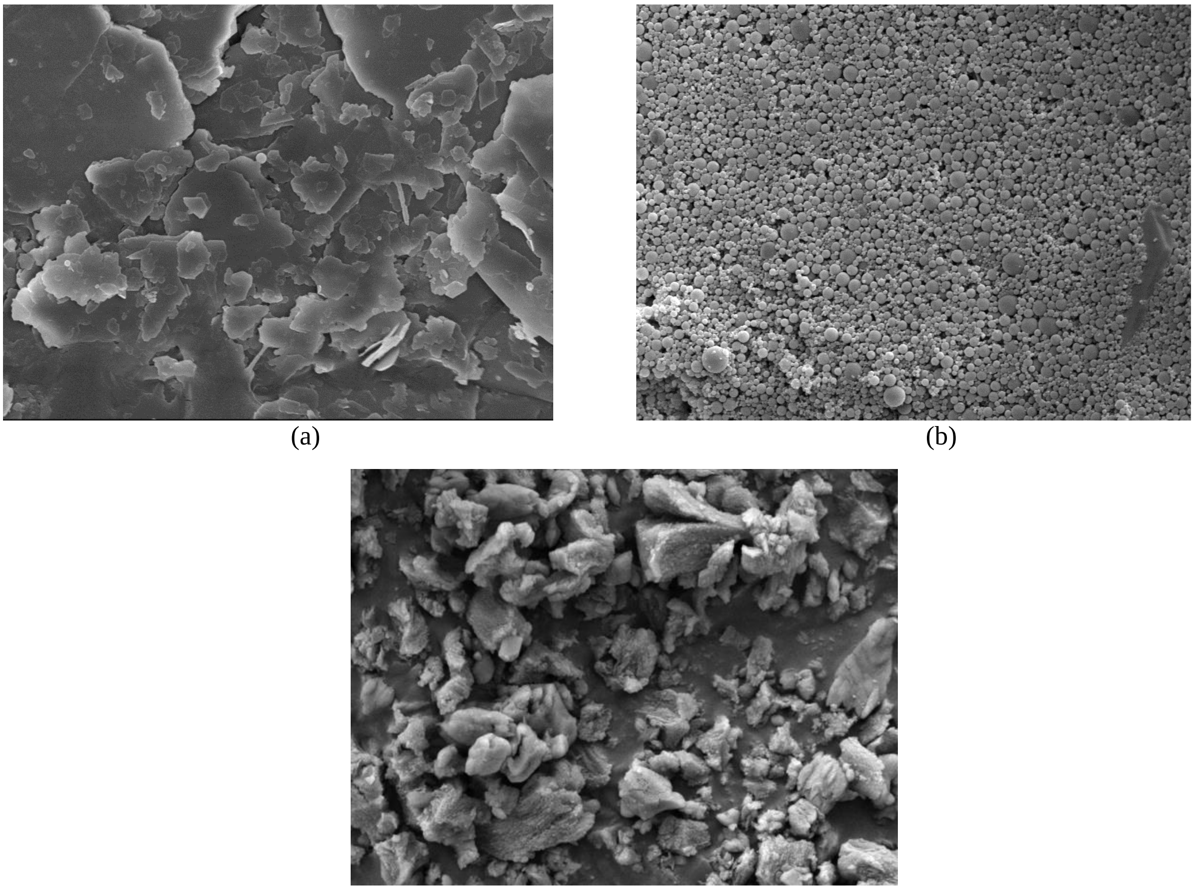



**Fig. 11 - Results of UU test on untreated sample**

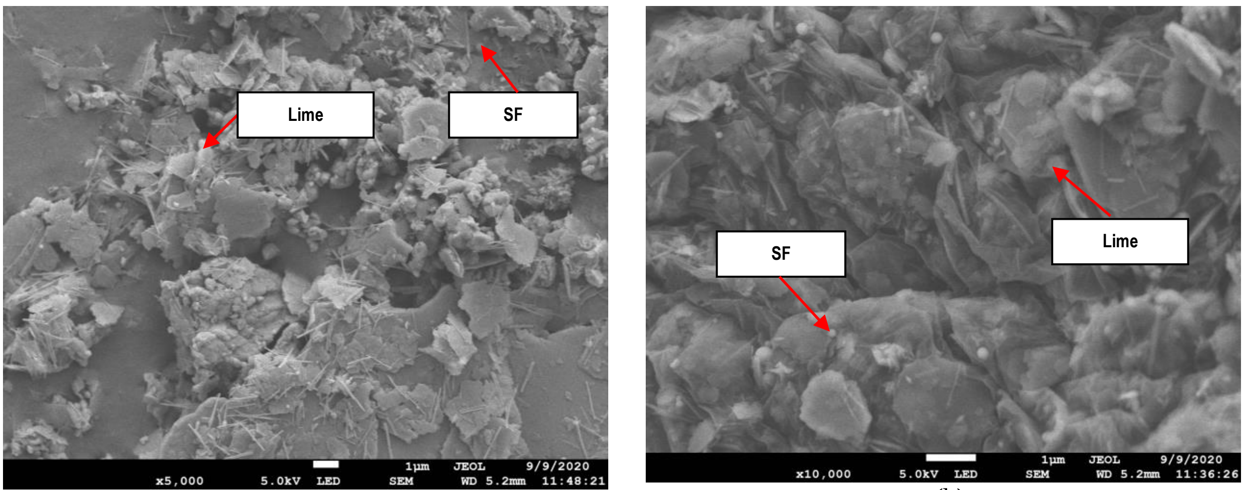


(a) (b)

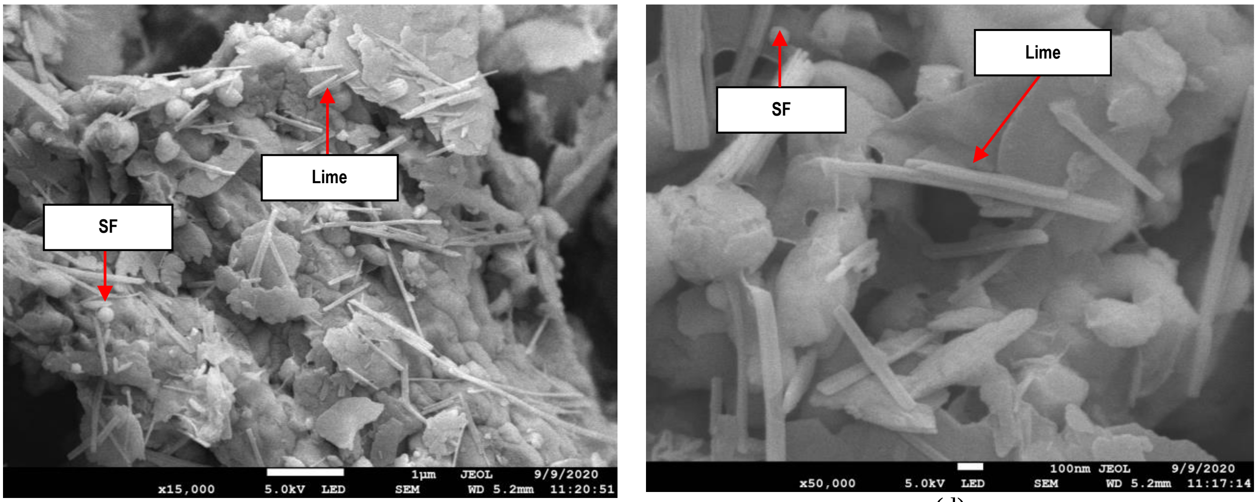
(c)

**Fig. 12 - Microstructural images of (a) kaolin; (b) SF, and; (c) lime**

Fig. 13(a) to Fig. 13(d) show the microstructural image of treated kaolin with 6% SF and 5% lime under x5000, x10000, x30000, and x50000 amplifications, respectively. The figure clearly shows the presence of SF and lime granules in kaolin, as the figures highlight around the state of SF and a rougher and unexpected condition of lime particles, as well as the flaking state of the kaolin. The microstructure seen in this experiment is consistent with earlier researchers' findings that the soil structure changed as a result of the pozzolanic interaction between the soil and the substance utilized as a soil enhancement agent [49]- [51]. As a result, the microstructural image in Fig. 12 and Fig. 13 demonstrate the efficient interaction between the compounds and the kaolin soil, which results in the formation of C–S–H and increased shear strength.




(a) (b)




(c) (d)

**Fig. 13 - Microstructural images of treated kaolin under (a) x10 000; (b) 15000; (c) 30000 and; (d) 100000 magnifications**

## 4. Conclusions

In this work, soft subsoil was mixed with differing quantities of SF and lime stabilizers to investigate the hardness and porosity properties of SF and lime stabilized soils. The following outcomes are possible:

- Based on the compaction test, the dry density of kaolin was determined to be 1.62 g/cm$^3$, and the OMC was determined to be 18.55%. The inclusion of lime reduces the MDD while increasing the OMC. The MDD for 3%, 5%, 7%, and 9% are 1.535g/cm$^3$, 1.46g/cm$^3$, 1.480g/cm$^3$, and 1.486 g/cm$^3$, respectively. The numbers for 3%, 5%, 7%, and 9% for the OMC are 19.50%, 21.30%, 19.00%, and 19.20%, respectively. The drop in MDD happens when the stabilizing agents' composite particles coat the soil, resulting in big particles with greater vacancies and a lower density. Because free lime needs more water for pozzolanic processes to occur, the OMC is growing.
- The findings obtained from the falling head permeability test show adequate results. Kaolin has a hydraulic conductivity of just 4.81 x 10$^{-12}$ m/s. The values for soil stabilized with 3%, 5%, 7%, and 9% percent lime are 4.35 x 10$^{-12}$ m/s, 3.14 x 10$^{-12}$ m/s, 4.03 x 10$^{-12}$ m/s, and 4.28 x 10$^{-12}$ m/s, correspondingly. The reaction of SF and lime decreases the degree of permeability in the treated samples over time; eventually, the specimens rose in strength and become stabilized owing to changes in the soil particles. The hydraulic conductivity is quite low for a lime level of 5%, 3.14 x 10$^{-12}$ m/s. In comparison to the other samples, the soil becomes less permeable at this stage. As a result, a lime concentration of 5% is ideal. Because of changes in the sample soil particles caused by particle rearrangement and crack formation, hydraulic conductivity started to rise significantly between 7% and 9%.

The ideal SF and lime percentages for maximum shear strength are 4% and 7%, respectively. Kaolin mix with SF and lime had a higher undrained shear strength and friction angle than the kaolin treated with SF and lime alone owing to the pozzolanic reaction between SF and lime being more successful with soil particles. When silica fume is added to the mix of lime and kaolin, initially it remains inert. Once lime and water in the mix start reacting with each other (hydrating), the Calcium Silicate Hydrate (CSH), which is the strength producing crystallization, and Calcium Hydroxide (CH) are produced. The pozzolanic reaction occurs between silica fume and the CH, producing additional CSH in many of the voids around the hydrated particles.

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