# Enhancement of Expansive Soil Properties Using Lime Silica-Fume Mixture

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Abstract: Expansive clayey soils are generally found in arid and semiarid regions where they cover vast areas around the world. Due to the presence of some clay minerals such as montmorillonite, these soils exhibit significant volume changes upon wetting or drying. They are considered potential natural hazard, which can cause extensive damage to civil engineering structures if not adequately treated especially to lightly loaded structures such as single to double storey houses, pavements, walkways, floors, canal linings etc.This study investigates the effect of adding Lime-Silica Fume Mixture (LSFM) to expansive clayey soil in order to enhance its engineering properties. LSFM has been added in different percentages 0%, 4%, 8% and 12% for lime with 0%, 8%, 13% and 18% for silica fume by soil weight and consequently (16) specimens of treated soil were obtained by mixing these percentages. The X-ray diffraction analysis was conducted on natural soil, prepared soil, lime and silica fume. Chemical composition analysis was also conducted on silica fume and lime. The results of tests show that the addition of LSFM reduces the liquid limit (LL), plasticity index (PI), specific gravity (Gs), maximum dry density (MDD), free swell%, compression index (Cc) and increases plastic limit (PL), optimum moisture content (OMC), Unconfined Compression Strength (UCS) especially with increasing curing time and California Bearing Ratio (CBR).

The results show a significant effect of LSFM on the results of unconfined compression strength with increasing curing period .The unconfined compression strength is increased by 12 times when adding 12% lime with 13% silica fumes. The reduction in swell% reaches 92.93% when adding 4%lime with 8%silica fume, this reduction in swell% can be considered as a best result for swell% reduction compared with the effect of other additives used in the previous studies. The effect of wetting-drying cycles on swell% has been studied as well and it has been found that swell % decreases with increasing number of cycles. It can be concluded that adding LSFM can be used effectively to overcome the problems of expansive soils. The optimum improvement in the physical properties such as consistency limits and swell potential can be achieved by adding lime in the range of 4-8% combined with 8-13% silica fume, while the optimum enhancement in the shear strength parameters and CBR value can be attained by adding 8-12% lime to 8-13% silica fume.



## 1. Introduction

Expansive soils are generally found in arid and semiarid regions where they cover vast areas around the world. Due to the presence of some clay minerals such as montmorillonite, these soils exhibit significant volume changes upon wetting or drying. Principally, swelling occurs when water infiltrates between the clay particles, causing them to separate. Foundations of light weight structures, floors, pipelines, and roads that are built on such soils are often subjected to severe structural damages. The cost associated with damage due to swelling soils is more than twice as much as the cost associated with damage from floods, hurricanes, tornadoes, and earthquakes **(Jones and Holtz,1973).**

Based on the economics and practicality of the operation, there are many methods which can be used to minimize swell of a particular soil and enhancement other engineering properties. These methods may include compaction control, pre-wetting, maintaining constant water content and chemical stabilization techniques. Chemical stabilization of expansive soil means altering the chemical or mineralogical structure of swelling clay skeleton by blending lime, cement, fly ash or silica fume.

Chemical stabilization of soils is one of the available answers for the geotechnical engineering problems and it may be used to reduce the settlement of structures, improve the shear strength of soil and thus increase the bearing capacity of shallow foundation, increase the factor of safety against possible slope failure of embankment and earth dams, and reduce the shrinkage and swelling characteristics of soils **(Das, 1990)**.
Soil stabilization has grown widely in recent years, especially in developing countries, where the need for expansive techniques to improve the engineering properties of soil is necessary **(AL-Ashou and AL-Khashab, 1993)**.

## 2. Materials
### Soils

Because of the aim of the present study is to investigate the effect of lime –silica fume mixture (LSFM ) on expansive soil properties specially the swell% ,and the swell% of natural soil was 6% which classified this soil under CL and to study the swelling behavior clearly when adding LSFM , the expansive clayey soil was prepared in laboratory by mixing 25% of bentonite with 75% of natural soil. Several tests are made on the prepared soil to obtain its engineering properties, swell% of the prepared soil reaches to 15.9% and its classified under CH (according to plasticity chart). A summary of the tests results for the natural and prepared soil used are given in Table (1).
The grain size distribution of natural soil, bentonite, and prepared soil is shown in Fig. (1).

### 2.2 Silica Fume

The silica-fume was used as an additive material by mixing it with lime to obtain a

Table (1) Engineering properties of the natural and prepared soil

| Property | Natural soil | Prepared soil |
|---|---|---|
| Liquid limit, LL (%) | 49 | 90 |
| Plastic limit, PL (%) | 25 | 38.5 |
| Plasticity index, PI (%) | 24 | 51.5 |
| Specific gravity, Gs | 2.7 | 2.68 |
| Gravel | 0 | 0 |
| Sand | 0 | 0 |
| Silt% | 40 | 32 |
| Clay% | 60 | 68 |
| Maximum dry density, g/cm$^3$ | 1.62 | 1.405 |
| Optimum moisture content % | 20 | 24.7 |
| Swelling% | 6 | 15.9 |

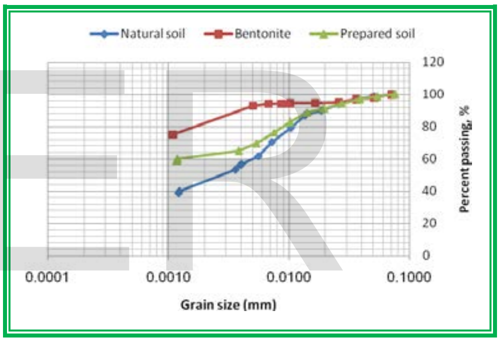


Figure (1) The grain-size distributions of natural soil, bentonite and prepared soil

mixture to use in enhancement of the prepared expansive soil properties. It was produced by Sika Company from EGYPT as a waste material from manufacturing of silicon or ferrosilicon. It was supplied as a powder packed in 5 Kg bags.
The chemical composition and physical properties of silica-fume used is as shown in Tables (2) and (3), respectively. The results show that it conforms to the chemical requirements of **ASTM C1240 – 03.** The test was carried out at the laboratories of State Company of Iraqi Geological Survey (IGS).

Table (2) Chemical composition of silica fume used

| Chemical | Content | Requirement of |
|---|---|---|

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| Component | (%) | ASTM C1240-03 |
|---|---|---|
| $SiO_2$ | 97.88 | ≥ 85 |
| $Fe_2O_3$ | 0.41 | - |
| $Al_2O_3$ | 0.11 | - |
| CaO | 0.12 | - |
| MgO | 0.24 | - |
| $Na_2O$ | 0.22 | - |
| $K_2O$ | 0.49 | - |
| Moisture | 1 | 3≤ |
| L.O.I | 0.53 | 6≤ |

Table (3) Physical properties of silica fume used

| Physical properties | Value of SF used | Requirement of ASTM C1240-03 |
|---|---|---|
| Percent retained on 45-µm (No. 325) | 2% | 10% |
| Accelerated pozzolanic strength activity index with Portland cement at 7 days | 115% | 105% |



**2.3 Lime**

The lime used in this study was produced in Iran. Table (4) shows the chemical composition for this product.

Table (4) Chemical composition of Lime

| Chemical Component | Content (%) |
|---|---|
| CaO | 66.52 |
| MgO | 2.57 |
| $Na_2O$ | 28.93 |
| IR | 1.52 |

Figures (2), (3),(4) and (5) show the results of X-Ray diffraction test (XRD). This test was carried out on natural soil, prepared soil, lime and silica fume to identify the minerals existing in these materials. The montmorillonite peak in natural soil is lesser than that in prepared soil. The tests were carried out by the Department of Chemistry and Physics, Ministry of Sciences and Technology.

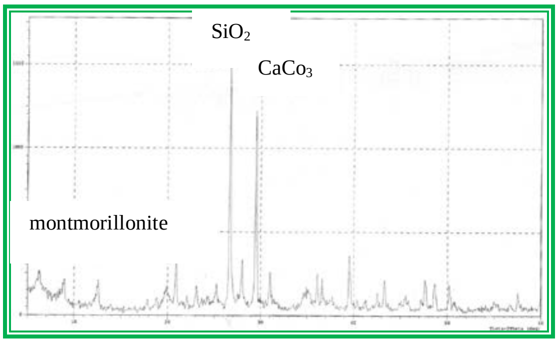


Figure (2) X-ray diffraction pattern for natural soil

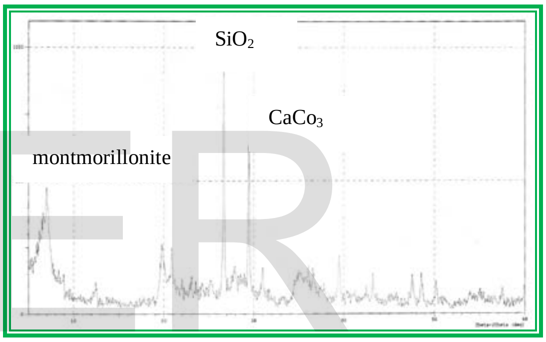


Figure (3) X-ray diffraction pattern for prepared soil

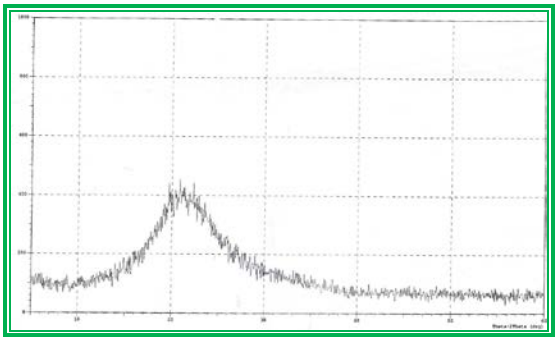

Figure (4) X-ray diffraction pattern for Silica fume used

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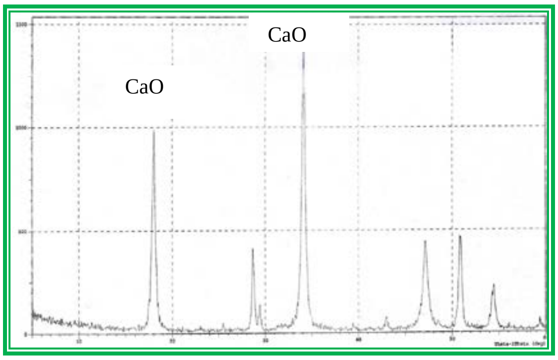


Figure (5) X-ray diffraction pattern for Lime used

## 2.4 Preparation of Samples

After bringing 200 kg of the natural soil from Al-Ghazaliya region the soil was dried in the oven at 105 ˚C for 24 hours to ensure dried soil and then pulverized by Los Angeles machine. Then 75% of dried natural soil was mixed with 25% of dried bentonite to get clayey soil with high plasticity index. Prepared soil was mixed by mixer with the various percentages of silica-fume and lime. The mixture for each percent of lime-silica fume mixture was mixed carefully until a homogeneous color was obtained and then put into nylon bags.

## 2.5 Testing Program

Sixteen samples of LSFM used resulting from mixing 0, 4, 8 and 12% of lime with 0, 8, 13 and 18% of silica fume as shown in Fig. (6) . For each of the mentioned percentages, several tests were made to obtain the behavior of expansive soil after adding the lime-silica fume mixture.

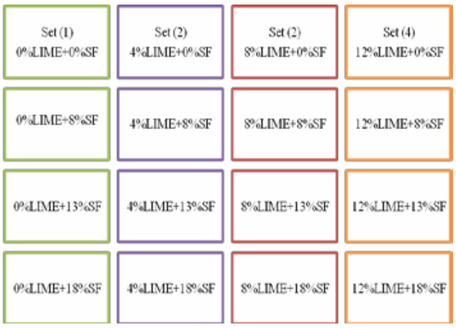


Figure (6) Percentages of lime and silica-fume mixture

## 2.6 Classification Tests

### 2.6.1 Grain Size Distribution

The grain size distribution of coarse grained soil is generally determined by means of sieve analysis but if the soil sample contains appreciable amounts of fines (silt and clay), then the soil sample can be washed through No.200 sieve until the water passing through the sieve is clean and this was obtained according to **ASTM D421-00.**

For a fine-grained soil, the grain-size distribution can be obtained by means of hydrometer test, which provides data on the grain size of soil particles finer than those retained on the No.200 sieve, and is based on the principle of sedimentation of soil particles in water. This test involves the use of 50 grams of dry, pulverized soil and this was obtained according to **ASTM D422-00.**

### 2.6.2 Consistency Limits

The liquid and plastic limit tests were carried out on soil passing sieve No. 40 (0.425mm). Liquid limit test is carried out in accordance with **ASTM D4318-00,** using Casagrande method. The plastic limit test is determined according to **ASTM D4318-00.**The difference between the liquid limit and the plastic limit of a soil is defined as the plasticity index (PI).

**P.I=L.L-P.L**

The Consistency limits of all samples were determined after a maturing time of two hours.

## 2.7 Specific Gravity (Gs)

The specific gravity for soil used is determined according to **ASTM D 854-00**. These test methods cover the determination of soil solids that pass the 4.75 (No.4) sieve, by means of a water pycnometer.

## 2.8 Compaction Characteristics

In order to obtain the moisture density relations for the untreated expansive soil and treated expansive soil with different percentages of LSFM, standard Proctor compaction test was carried out according to **ASTM D 698-00.**

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The oven- dried samples passing sieve No.4 were compacted in three layers by 25 blows per layer with 5.5 Ib hammer from 12 in.

### 2.9 Unconfined Compression Test (UCS)

The unconfined compression strength ($q_u$) is determined by applying an axial stress to cylindrical soil specimen with no confining pressure and observing the axial strains corresponding to various stress levels **(Das, 2002)**.

The specimens were compacted statically according to the maximum dry density and optimum moisture content values inside the mold of 35 mm internal diameter and 85 mm in height using a manual hammer as shown in Plate (1), then the samples were extruded by hydraulic jack and each sample was sealed by double nylon bags as shown in Plate (2) to prevent loss in sample moisture and to allow samples to cure for 2 hours, 7 days and 28 days, in order to study the influence of lime and silica-fume on development strength for different percentages of mixture and different curing period.

At the end of the curing time, the nylon bags were removed off the specimens, the specimens were tested under load with a strain control of rate equal to (1.52 mm/min). The test was terminated when strain continued to increase under constant loading or when a peak in principal stress difference occurred.

Plate (1) Mold & manual hammer used in UCS

Plate (2) Samples sealed by double nylon bags

Samples were weighted before and after seal to check the percentage of water content loss during the curing period. The obtained density was always checked from the known weight and the obtained volume in order to ensure the reproducibility of the compaction procedure. The average of two specimens was used for each unconfined compressive strength value. A total of 96 unconfined compression tests were conducted. The testing procedure was conducted according to the **ASTM D 2166-00**.

### 2.10 Free Swelling and Swelling Pressure Tests

The preparation of test specimens was carried out as described by **Head (1984)** on untreated and treated prepared soil .The specimens were statically compacted (at their maximum dry density and optimum moisture content) inside the consolidation ring of 50 mm internal diameter and 20 mm in height using a manual hammer as shown in Plate (3).

Plate (3) Sample preparation for swelling and consolidation tests

The specimen height was made to be 4 mm less than the height of the consolidation ring to ensure that the specimen would remain laterally confined during swelling. This was done using a disk of metal of thickness equal to the difference in height between the consolidation ring and the specimen, i.e. (4mm); the disc diameter was (1mm) less than the internal ring diameter.

The inner surface of the ring was oiled to minimize the frictional effect. Then, specimen and ring were installed into the consolidation apparatus following the standard method described by **Head (1984)**. Sample was inundated with water and allowed to swell at seating pressure 1kPa. The final swell which the specimen reached before adding load is called the swell percent, while the pressure required to bring the specimen into its original height is defined as the swell pressure. The increase in sample thickness was recorded using dial gauge of 0.002mm/division. This test was conducted according **to ASTM D4546-96.**

The free swell percent is calculated as:

$$\text{Free swell } (\%) = (H-Ho/Ho) \times 100$$

where: H= the final thickness of sample (after end of swelling), mm.

Ho= the initial thickness of sample, mm.

## 2.11 Consolidation Test

The tests were carried out according to **ASTM D2435-96**. The samples were prepared according to the same procedure followed for free swell test. The consolidation test starts by adding weights to the hanger, the loads were applied at increments of 50, 100, 200, 400, 800, and 1600 kPa and unloaded at increments of 800, 400 and 200 kPa. The load duration was 24 hours as recommended by **Head (1984)**.The compression index (Cc) was determined from the results of this test.

## 2.12 California Bearing Ratio Test (CBR)

According to **ASTM D1883-87**, the CBR test method is used to evaluate the potential strength of prepared soil (0% Lime+0% Silica-fume) and prepared soil treated with different percentages of LSFM.

The CBR test is a penetration test that can be carried out both in the laboratory as well as in-situ (Kezdi, 1980). However, only the laboratory CBR test is of interest in this work.

The CBR is computed as the ratio of the load required to force the standard piston into the soil to a certain depth of 0.1 in. (2.54 mm) and 0.2 in. (5.08 mm) to that required for similar penetrations into a standard sample of compacted crushed rock as shown by Equations as follows:

$$CBR_{0.1''} = (P_{0.1''} / P_{S\,0.1''}) \times 100$$

$$CBR_{0.2''} = (P_{0.2''} / P_{S\,0.2''}) \times 100$$

where:

$CBR_{0.1''}$ , $CBR_{0.2''}$ = California Bearing Ratio at 0.1″ (2.54 mm) and 0.2″ (5.08 mm) piston penetration respectively.

$P_{0.1''}$ , $P_{0.2''}$ = Load required to force a standard piston 0.1″ (2.54 mm) and 0.2″ (5.08mm) into the soil sample, respectively.

$P_{S\,0.1''}$ , $P_{S\,0.2''}$ = Load required to force a standard piston 0.1″ (2.54 mm) and 0.2″ (5.08 mm) into a standard sample of crushed stone respectively ($P_{S\,0.1''}$ =3000 lbs. =13.34kN, $P_{S\,0.2''}$ =4500 lbs. =20.01 kN).

## 2.13 Chemical Tests

Chemical tests on Lime and Silica-fume which were used in the present study were carried out at the laboratories of State Company of Iraq Geological Survey.

## 2.14 X-Ray Diffraction Test (XRD)

X-Ray diffraction analysis device (XRD-6000, SHIMADZU, JAPAN, Cu tube radiation BF 2.7 KW, power 60 kV & 80 mA) as shown in Plates (4 and 5) was used on a natural soil, prepared soil, silica-fume and lime to identify the minerals existing in these materials. The test was carried out by the Department of Chemistry and Physics, Ministry of Sciences and Technology.

Plate (4) Preparation of sample for XRD test

Plate (5) XRD device

2.15 Wetting and Drying Cycles

The effect of lime-silica fume mixture on the swelling percent and of a compacted untreated and treated soils during the wetting–drying cycles was investigated in this study with simple method using tins as shown in Plate (6).

Sixteen samples were compacted in the tins according to optimum moisture content and maximum dry density by manual hammer. All samples were submerged in distilled water and allowed to swell fully over seven days, the increase in sample height was measured using an electronic vernier. Water was then drained and the tins with wetted samples were transferred into an oven at (45-50) ˚C for three days.

The decrease in sample height was recorded after the full drying has been reached (i.e, no further change in the height of sample). After dried, all samples height were carefully measured using an electronic vernier, the tin dried samples were again wetted and allowed to swell fully over seven days.

A wetting–drying cycle test was completed with the saturation of samples and then drying them in an oven. In these tests, the samples were subjected to six wetting and drying cycles.

Plate (6) Sample swelling in tin

It was observed that there was no significance change in the test results after the sixth cycle of wetting–drying , therefore the wetting–drying procedure was terminated after six cycles. Plate (7) shows the samples after six wetting-drying cycles.



Plate (7) Samples in tins after six cycles of wetting-drying

3. Results and discussion

3.1 Consistency Limits

Figures (7), (8) and (9) show the effect of adding different percentages of LSFM on the consistency limits values of the prepared expansive clayey soil. In general liquid limit (LL) and plasticity index (PI) decrease with increasing amount of LSFM, while plastic limit (PL) increases with increasing LSFM.

The maximum decrease in liquid limit is found with the addition of (4% Lime+0%SF), (8%Lime+0%SF) and (12%Lime +0%SF) .These additions reduced the liquid limit by 38.9%, 38.3% and 31.3%, respectively.

The maximum decrease in plasticity index is found with the addition of (8% Lime+8%SF), (12%Lime+8%SF) and (8%Lime+0%SF).These additions reduced the plasticity index by 64.3%, 59.9% and 58.9%, respectively.

The maximum increase in plastic limit is found with the addition of (12%Lime+18%SF), (4%Lime+18%SF) and (8%Lime+8%SF).These additions increased the plastic limit by 35%, 30.4% and 30.1%, respectively.

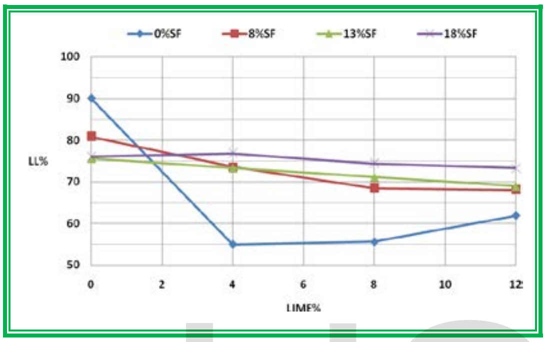


Figure (7) The effect of adding LSFM on Liquid Limit of Expansive clayey soil

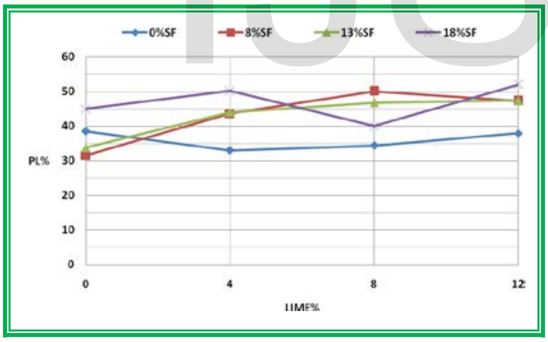


Figure (8)The effect of adding LSFM on Plastic Limit of Expansive clayey soil

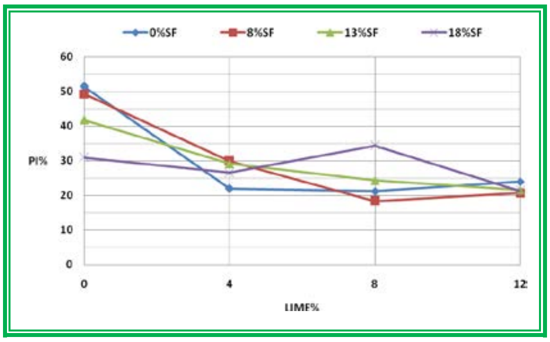


Figure (9)The effect of adding LSFM on Plasticity Index of Expansive clayey soil

The results show the pronounced effect of LSFM on consistency limits and consequently, on swelling % which depend on these results.

These changes in the values of consistency limits are due to flocculation process and pozzolanic reaction occurs when lime, water, soil, and silica fume react to form various cementing compounds. Flocculation and agglomeration produce a change in the texture of clay soils, clay particles tend to clump together to form larger particles, these reacts tend to decrease the liquid limits , increase the plastic limits, and decrease plasticity index **(Das, 1990).**

## 3.2 Specific Gravity (Gs)

Figure (10) shows the effect of adding different percentages of LSFM on the specific gravity (Gs) values of the prepared soil. The figure shows the decrease in specific gravity of soil with increasing LSFM content. This indicates that the lime and silica fume are lighter than the prepared soil and thus the composite samples of treated soils with lime and silica fume become lighter than the prepared soil.

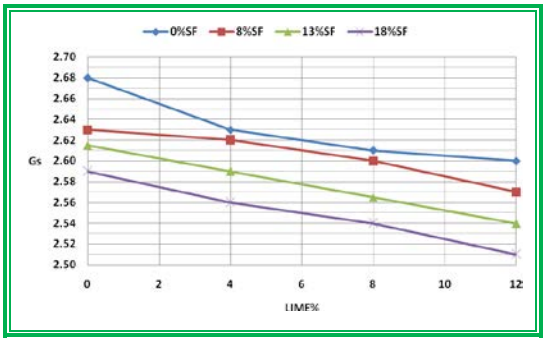


Figure (10)The effect of adding LSFM on Specific Gravity of Expansive Clayey Soil

## 3.3 Compaction Characteristics

Figures (11), (12), (13) and (14) show the effect of adding different percentages of LSFM on the dry density-water content relationships of prepared expansive clayey soil. Figure (15) shows the relationship between maximum dry density (MDD) with different percentages of addition LSFM on expansive clayey

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soil used, for all percentages of LSFM the maximum dry density decreases with the increase in adding LSFM except with addition of 4%lime alone. Figure (16) shows the effect of adding different percentages of LSFM on the optimum moisture content (OMC).It has been indicated that the optimum moisture content decrease with increasing percentage of adding LSFM.

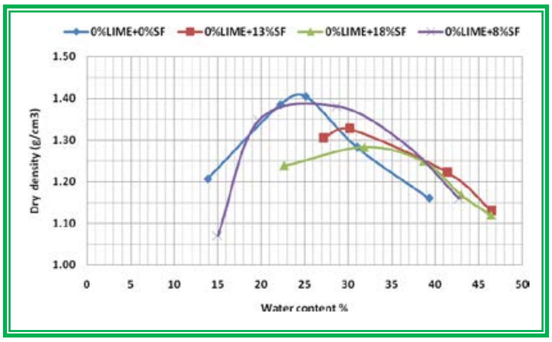


Figure (11) The effect of adding different percentages of SF on dry density-water content relationship

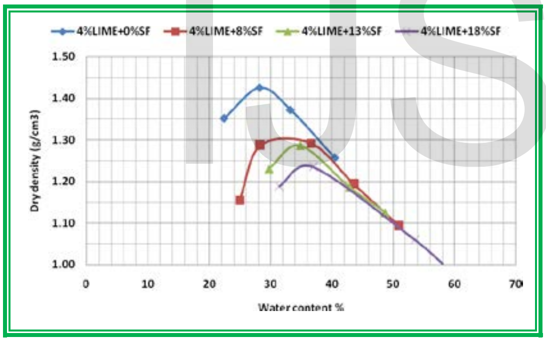


Figure (12) The effect of adding 4%Lime with different percentages of SF on dry density-water content relationship

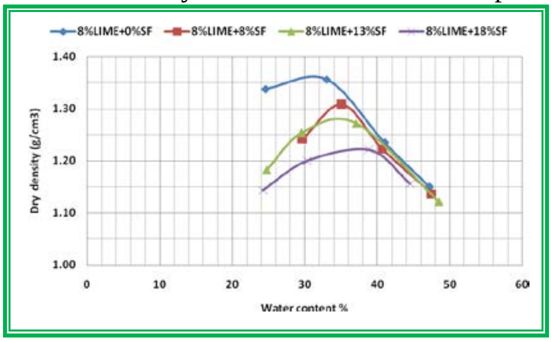


Figure (13) The effect of adding 8%Lime with different percentages of SF on dry density-water content relationship

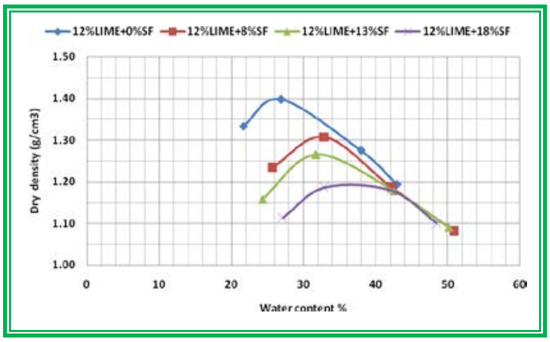


Figure (14) The effect of adding 12%Lime with different percentages of SF on dry density-water content relationship

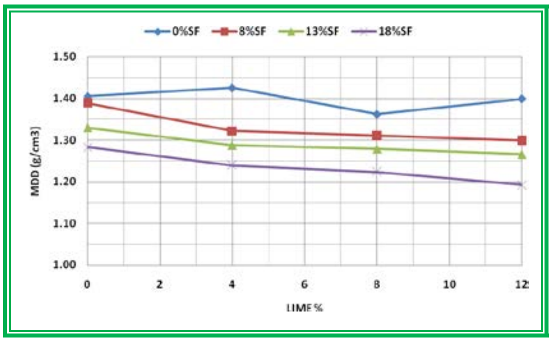


Figure (15) Effect of adding LSFM on MDD of expansive clayey soil

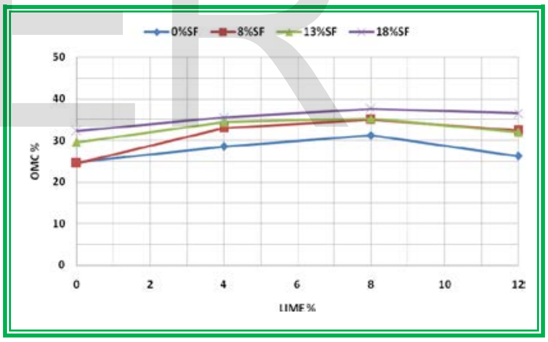


Figure (16) Effect of adding LSFM on OMC of expansive clayey soil.

This reduction may be due to the immediate reactions between LSFM and soil particles (flocculation and agglomeration) which form further voids and make more open structure and hence, reduce the maximum dry density. The increase in optimum moisture content with increasing LSFM is due to the consumption of water during LSFM–clay reaction and/or the increase in water necessary to lubricate the new established particle skeleton of LSF-clay system and finally due to evaporation of water as a result of the borne high temperature during reactions **(Rajasekaran,2002)** .

where: T.a. =Total additive %( Lime%+SF %), S% =swell%, S%.r.=swell% reduction.

### 3.4 Free Swell Percentage

Table (5) and Fig. (17) show the effect of adding different percentage of LSFM on the free swell% values , total additive% and values of free swell% reduction , which can be represented by Equation below:

$$\text{Free swell\% reduction} = \left[\frac{\text{Swell\%(untreated soil)} - \text{Swell\%(treated soil)}}{\text{Swell\%(untreated soil)}}\right]$$

Table (5) Effect of adding LSFM on free swell of expansive clayey soil

| Sample no. | LIME % | SF % | T.a. | S%. | S%.r. | Sample no. | LIME % | SF % | T.a | S% | S%.r. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 16.09 | 0 | 9 | 8 | 0 | 8 | 4.45 | 72.35 |
| 2 | 0 | 8 | 8 | 1.79 | 88.86 | 10 | 8 | 8 | 16 | 2.43 | 84.90 |
| 3 | 0 | 13 | 13 | 4.82 | 70.08 | 11 | 8 | 13 | 21 | 1.86 | 88.43 |
| 4 | 0 | 18 | 18 | 2.56 | 84.07 | 12 | 8 | 18 | 26 | 1.35 | 91.62 |
| 5 | 4 | 0 | 4 | 4.76 | 70.43 | 13 | 12 | 0 | 12 | 5.47 | 66.01 |
| 6 | 4 | 8 | 12 | 1.14 | 92.93 | 14 | 12 | 8 | 20 | 2.64 | 83.57 |
| 7 | 4 | 13 | 17 | 1.55 | 90.35 | 15 | 12 | 13 | 25 | 3.37 | 79.04 |
| 8 | 4 | 18 | 22 | 1.47 | 90.84 | 16 | 12 | 18 | 30 | 2.01 | 87.50 |



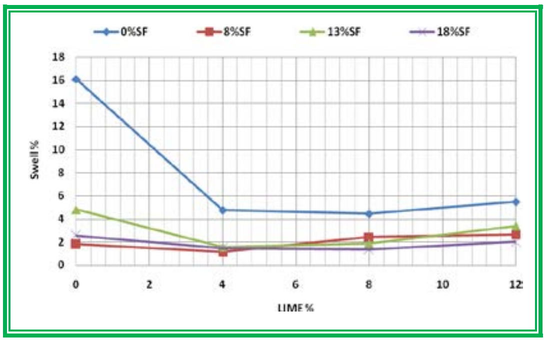


Figure (17) The effect of adding different percentages of LSFM on free swell % of expansive clayey soil

Figures (18), (19), (20) and (21) show the relationship between free swell% and time for different percentages of LSFM. It can be indicated that the prepared expansive soil (0%Lime+0%SF) needs a long time to complete its expansion and the time required to reach a steady state condition is reduced due to the addition of LSFM. Also, the results show that the swelling values may follow different paths with respect to time for different LSFM contents.

In general, the swell% decreases as the LSFM increases and reaches about (65%-80%) of maximum value of free swell after one day .The time required reaching a steady value varies considerably depending upon the LSFM content.

Samples which were treated with silica-fume only reached to a steady value in a short time approximately one day, while the samples which were treated with lime only needed more time. This is may be due to different size particles of silica fume and lime, different permeability between these samples and thus different time for absorption of water to complete the swelling. Differentiations in swell time behavior are also pronounced by Seed et al. **(1962) and Al-Omari and Oraibi (2000).** They attribute such behavior to the differences in permeability.

The percent of free swell reduction reached 88.86%, 70.08% and 84.07% due to adding 8%, 13% and 18% of silica-fume only, respectively and 70.4%, 72.35% and 62.01% when adding 4%, 8% and 12% of lime only, respectively.

Free swell reduction increased when adding lime to silica-fume, this indicates that silica-fume becomes too effective in the presence of lime.

Addition of silica fume only is more effective in reduction of the free swell% when compared with addition of lime only. The optimum percentage of LSFM on free swell reduction was found at 4%

lime when it was mixed with 8%, 13% and 18% of SF which was decreased the free swell% by 92.93%, 90.35% and 90.84% respectively and when mixed 8% lime with 18%SF, the reduction in the free swell will be 91.62%.
This improvement in the swelling percent reduction in the prepared expansive soil due to adding LSFM may be attributed to the following reasons as referred to by McKennon et al. 1994 ; significant increase in the soluble calcium, promoting formation the silicate calcium hydrate over silicate aluminum hydrate which in turn is stronger and increases the pH of mixture to a point at which clay silica and clay alumina are liberated from the silica bearing tetrahedral sheets and the alumina bearing octahedral sheets respectively. As a result, high improvement in pozzolanic reaction emerges.

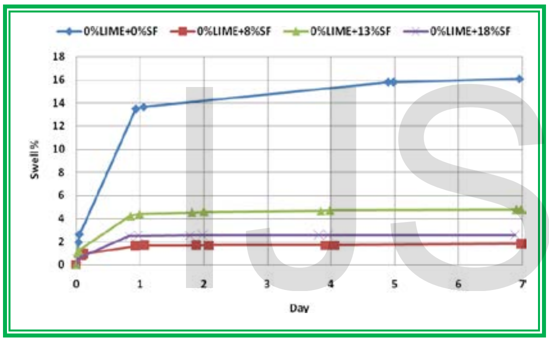


Figure (18) The effect of adding different percentages of SF on relationship between free swell and time

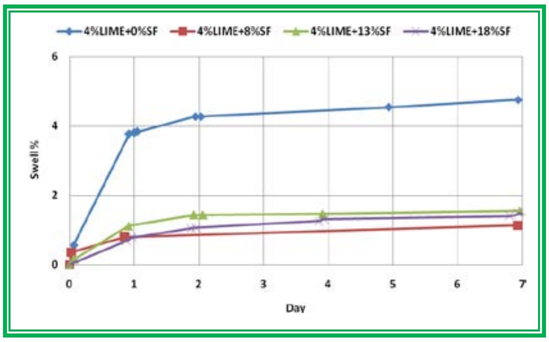


Figure (19) The effect of adding 4%Lime with different percentage of SF on relationship between free swell and time

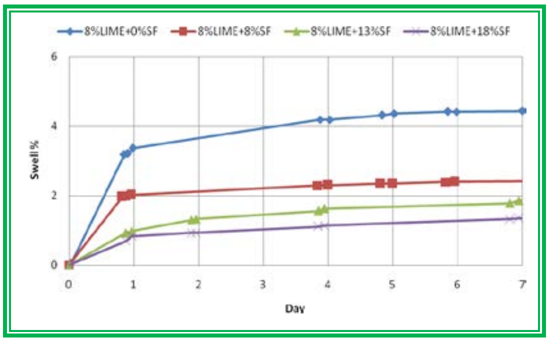


Figure (20) The effect of adding 8%Lime with different percentage of SF on relationship between free swell and time

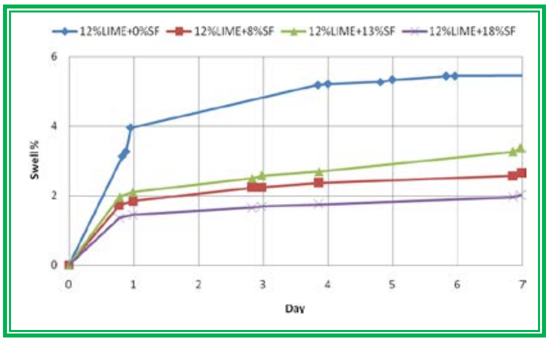


Figure (21) The effect of adding 12%Lime with different percentage of SF on relationship between free swell and time



The relationship between swell% and sum of additive can be approximated by Equation as below with a good degree of correlation as shown Fig. (22).

$$\text{Swell\%} = -\ 0.014X^3 + 0.360X^2 - 3.667X + 16$$

where:
X =sum of additive% (lime%+SF %).

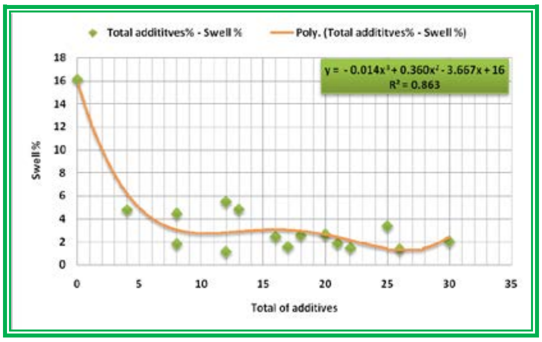


Figure (22) Relationship between total additive and swell%

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### 3.5 Swelling Pressure

Table (6) show the effect of adding different percentages of LSFM on swell% - applied pressure relationship. The results show that the amount of swell pressure is decreased by 57.4% ,43.2% ,68.3% and 55.2% with addition of (0%lime+8%SF),(0%lime+13%SF),(0%lime+18%SF) and (4%lime+8%SF) respectively ,then swelling pressure increases significantly with the increase in the percentage of LSFM content especially with increase in lime percent.

Table (6)The effect of adding LSFM on swelling pressure (kPa)

| | | | LIME% | | |
|---|---|---|---|---|---|
| | | 0 | 4 | 8 | 12 |
| | 0 | 161.1 | 747.4 | 2489.4 | 1979.3 |
| SF% | 8 | 68.6 | 72.2 | 897.4 | 1894.5 |
| | 13 | 91.5 | 311.1 | 870.3 | 1187.7 |
| | 18 | 51.1 | 419.1 | 550.9 | 813.9 |

Such behavior (i.e., increase in swelling pressure) may be attributed to the hydration of LSFM during the long time consumed for swelling to be completed. The hydration process highly increases the specimen strength and decreases compressibility, which requires very high load to get back to its original height. Therefore, this type of test (ASTM D4546-96, Method A) is not recommended for soils in which LSFM or any other hardening additives are used. Okca (1999) reported that the increases in swell pressure can be attributed to the reduction in water adsorption tendency of the samples due to the addition of pozzolanic materials particles to the samples and the development of a cementation matrix that can resist expansion.

Despite these results, it has been noted that the swelling pressure decreases with increasing the silica fume content with each lime percentages, which is an indication that lime- silica-fume mixture can be used in reduction the swelling pressure.



### 3.6 Compression Index (Cc)

Figures (23) show the effect of addition of different percentages of LSFM on compression index (Cc).

Figures (24), (25), (26) and (27) show the effect of addition different percentage of LSFM on void ratio-log applied pressure (e-log *p*) relationship.

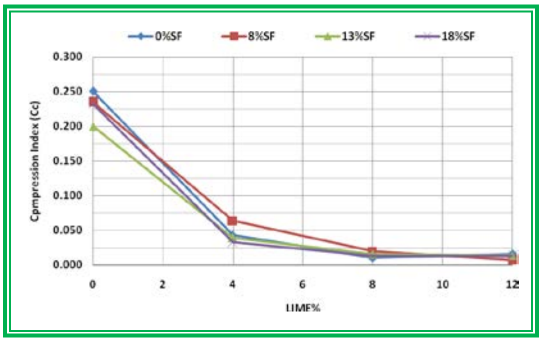


Figure (23) The effect of adding different percentages of LSFM on compression index (Cc)

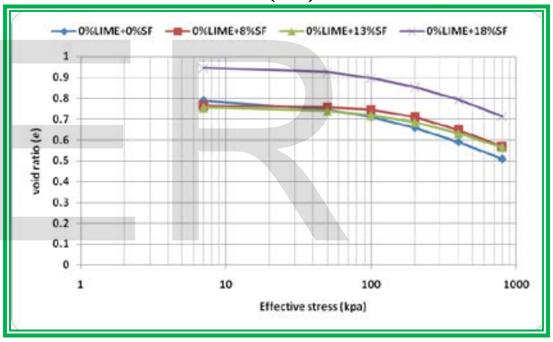


Figure (24) The effect of adding different percentages of SF on e-log *p* relationship

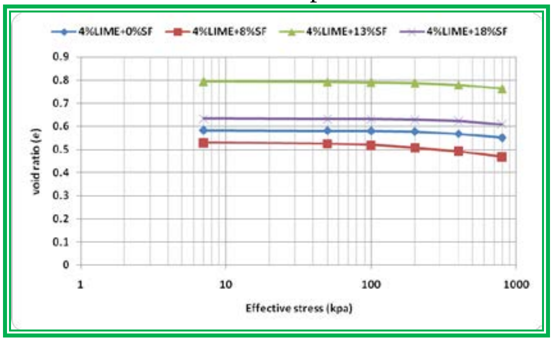


Figure (25) The effect of adding 4%Lime with different percentages of SF on e-log *p* relationship

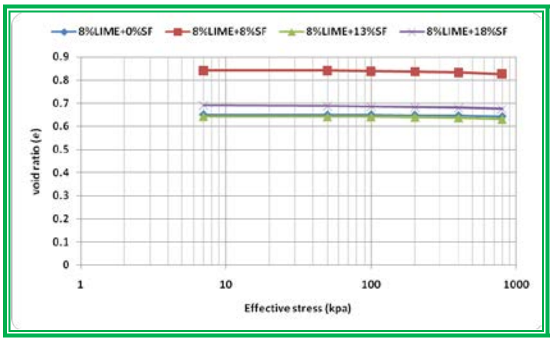


Figure (26) The effect of adding 8%Lime with different percentages of SF on e-log *p* relationship

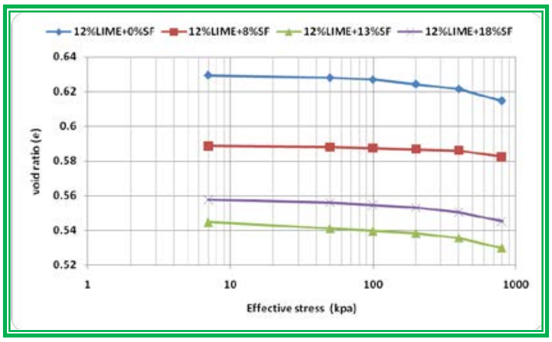


Figure (27) The effect of adding 12%Lime with different percentages of SF on e-log *p* relationship

In general the compression index (Cc) decreases with increasing LSFM percentage. Maximum decrease is found with addition of 8% lime and 12% lime with all percentages of silica-fume .The optimum percentage of LSFM which causes the higher reduction in Cc is found with the addition of (12%Lime+8%SF).This addition reduces the compression index by 97.11%. It has been also noted that the influence of adding lime on the reduction in the values of Cc is more pronounced than the influence of adding silica-fume.

The results indicate that addition of LSFM is a good method to reduce the compressibility of expansive soil. This effect can be attributed to the reduction in water adsorption tendency of the samples due to the addition of pozzolanic materials particles to the samples and the development of a cementation matrix that can resist expansion (Okca, 1999).

3.7 Unconfined Compressive Strength (UCS):

The effects of curing period on the unconfined compressive strength (UCS) values of the prepared and treated expansive soil with different percentages of LSFM are shown in Figs. (28), (29), (30) and (31).

Also, the influences of adding LSFM on the unconfined compressive strength after 2hour, 7 days and 28 days curing time are shown in Figs (32),(33) and (34), respectively. As illustrated in these figures, the increase in LSFM and curing period has improved the unconfined compressive strength. The optimum percent for LSFM that achieves the maximum strength was obtained to be (12%lime+13%SF) and (12%lime+18%SF) for 28 days which increased the UCS up to 2669.61and 3162.52 kPa respectively.

The addition of SF alone with 2hour curing had a negligible effect on UCS, with increasing curing period; at 8%SF a marginal increase in UCS was observed at 28 days curing which increased UCS up to 340.11 kPa.

The addition of lime alone with 2hour curing had a negligible effect on UCS, with increasing curing period a significant increase in UCS was observed especially when adding 12%lime which increased UCS up to 2500 kpa at 28 day curing.

Kalkan (2012), has reported that the increase in the compressive strength may be due to:

1- Soil type, composition, mineralogy, particle shape and particle size distribution
2- Internal friction of LSFM particles and the chemical reaction between SF and lime particles. In addition to being a highly pozzolanic material, the extremely fine SF particles improved the packing of the soil matrix, resulting in a denser stabilized soil.
3- The hydration and hardening that occurred between the silica fume, lime and soil.

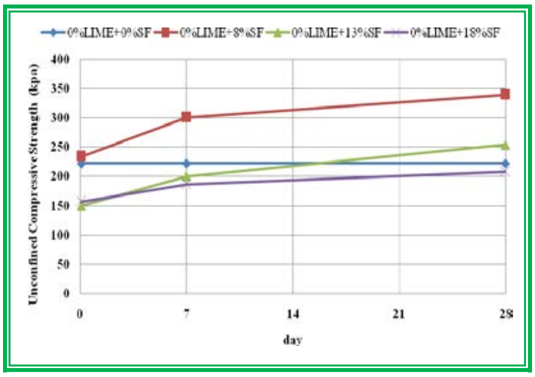


Figure (28) Effect of curing period on UCS when adding different percentages of SF

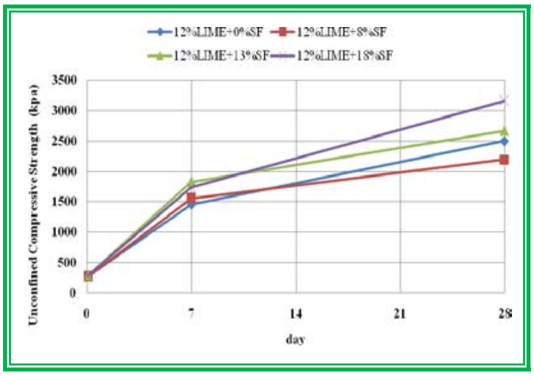


Figure (31) Effect of curing period on UCS when adding 12%lime with different percentages of SF

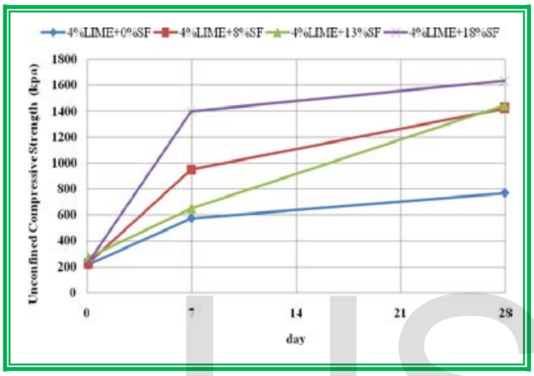


Figure (29) Effect of curing period on UCS when adding 4%lime with different percentages of SF

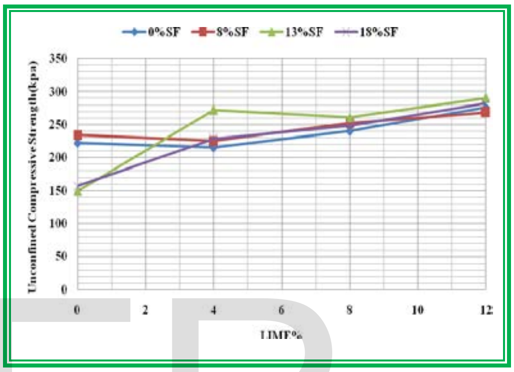


Figure (32) Effect of adding LSFM on UCS for 2 hour curing period

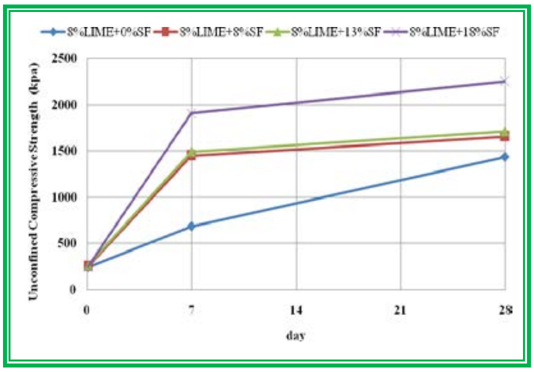


Figure (30) Effect of curing period on UCS when adding 8%lime with different percentages of SF

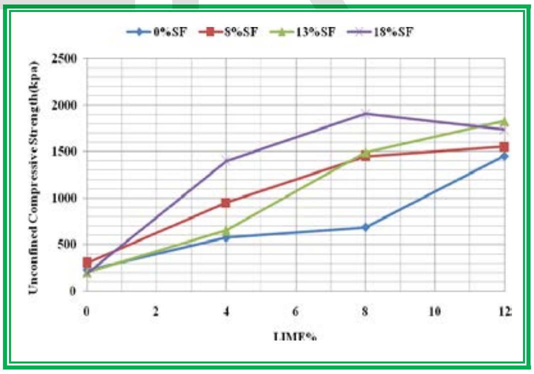


Figure (33) Effect of adding LSFM on UCS for 7 days curing period

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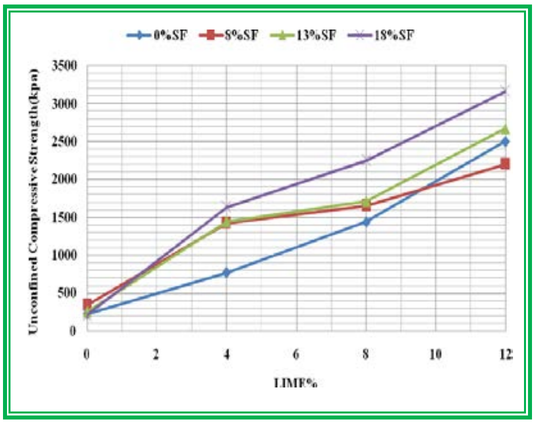


Figure (34) Effect of adding LSFM on UCS for 28 days curing period

### 3.7.1 Strength development

Table (7) shows the values of unconfined compressive strength at 2hour, 7day, 28 day curing and the value of strength development factor (s.d.) for all samples at 7 day with respect to strength at 28 day which can be evaluated by Equation as shown bellow:

$$(s.d.) = \frac{UCS\ 7day}{UCS\ 28\ day} \times 100$$

where:

s.d. = Strength development factor

UCS7day = Unconfined compressive strength at 7day curing (kPa).

UCS28day = Unconfined compressive

| Sample no. | Lime % | SF % | UCS for 2 hour curing | (S.I.)* 2hour curing | UCS for 7 day curing | (S.I.)* 7day curing | UCS for 28 day curing | (S.I.)* 28day curing | s.d.% |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 222.28 | 0.0 | - | - | - | - | - |
| 2 | 0 | 8 | 234.23 | 5.4 | 301.43 | 35.6 | 340.11 | 53.0 | 88.6 |
| 3 | 0 | 13 | 149.59 | -32.7 | 200.25 | -9.9 | 254.15 | 14.3 | 78.8 |
| 4 | 0 | 18 | 157.09 | -29.3 | 186.82 | -16.0 | 207.99 | -6.4 | 89.8 |
| 5 | 4 | 0 | 215.33 | -3.1 | 573.50 | 158.0 | 767.36 | 245.2 | 74.7 |
| 6 | 4 | 8 | 225.36 | 1.4 | 950.58 | 327.6 | 1422.52 | 540.0 | 66.8 |
| 7 | 4 | 13 | 272.53 | 22.6 | 650.70 | 192.7 | 1445.37 | 550.2 | 45.0 |
| 8 | 4 | 18 | 228.87 | 3.0 | 1399.14 | 529.4 | 1633.30 | 634.8 | 85.7 |
| 9 | 8 | 0 | 240.31 | 8.1 | 684.01 | 207.7 | 1437.20 | 546.6 | 47.6 |
| 10 | 8 | 8 | 252.12 | 13.4 | 1448.88 | 551.8 | 1655.50 | 644.8 | 87.5 |
| 11 | 8 | 13 | 261.25 | 17.5 | 1493.80 | 572.0 | 1712.76 | 670.5 | 87.2 |
| 12 | 8 | 18 | 248.22 | 11.7 | 1908.43 | 758.6 | 2250.44 | 912.4 | 84.8 |
| 13 | 12 | 0 | 275.89 | 24.1 | 1455.00 | 554.6 | 2500.24 | 1024.8 | 58.2 |
| 14 | 12 | 8 | 268.34 | 20.7 | 1554.44 | 599.3 | 2197.74 | 888.7 | 70.7 |
| 15 | 12 | 13 | 290.25 | 30.6 | 1831.02 | 723.7 | 2669.61 | 1101.0 | 68.6 |
| 16 | 12 | 18 | 282.07 | 26.9 | 1736.85 | 681.4 | 3162.52 | 1322.7 | 54.9 |

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strength at 28day curing (kPa).

From the results, the values of s.d. reach 88.6%, 78.8% and 89.8% with addition of 8%, 13% and 18% of silica fume respectively, while s.d. value reaches 74.7%, 47.6% and 58.2% with addition of 4%, 8% and 12% of lime respectively, which gives an indication that development strength at 7 days by addition of silica fume is more of lime, with a value of s.d. average approximately 80% with addition of silica fume and 60% with addition of lime. In general, the results predict that the addition of lime to silica fume delays the development of strength for all samples and the maximum delay was found with addition of 4%lime and 12%lime to other percentages of silica fume. The reason for these results of development strength are because of the pozzalanic reaction acceleration of lime is less than the pozzalanic reaction acceleration of silica fume.

3.8 California Bearing Ratio (CBR)

Table (8) and Fig. (34) show the effect of adding LSFM on California Bearing Ratio (CBR) values of the expansive clayey soil.

Table (8) Effect of addition of LSFM on CBR

| | | LIME% | | | |
|---|---|---|---|---|---|
| | | 0 | 4 | 8 | 12 |
| SF% | 0 | 4.42 | 5.75 | 5.86 | 9.67 |
| | 8 | 5.36 | 7.78 | 6.93 | 8.73 |
| | 13 | 4.05 | 9.51 | 7.74 | 13.92 |
| | 18 | 4.22 | 8.99 | 8.02 | 11.40 |

In general CBR increases with increasing LSFM and the results show that the addition of lime alone is more effective than adding silica-fume alone on CBR values. CBR values slightly increase with adding 8%SF alone then decrease with addition 13%SF and increase with addition 18%SF.While CBR value increases with increasing lime alone for all percentages used in the present study. This indicates that lime is more effective in increasing CBR value compared with silica fume.

Also, CBR values increased with the addition of lime up to 4% and then decreased at 8%lime and again increased at 12%lime with all percentages of silica fume used in the present study.

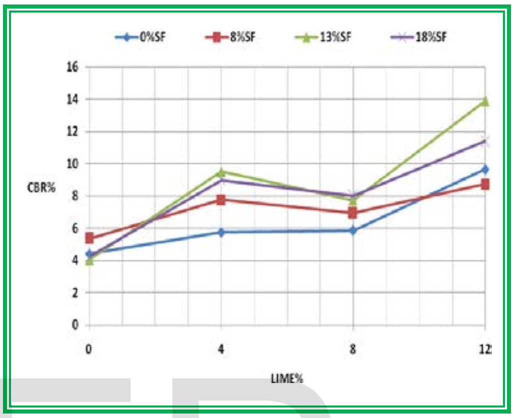


Figure (34) Effect of addition of different percentages of LSFM on California bearing ratio (CBR)

CBR increased when adding silica-fume to lime, this indicates that lime becomes very effective in the presence of silica-fume as compared with addition silica-fume or lime alone. The optimum percent of LSFM which gives a higher improvement of CBR value was found when adding (12%lime+13%SF) and (12%lime+18%SF) which are compatible with results obtained from unconfined compressive strength tests with 2 hours curing period, so a good relationship obtained between CBR and unconfined compressive strength can be approximated by Equation below with a good degree of correlation as shown Figs. (35).

$$Y=96.105 \ln(X) + 49.26$$

where:

Y= Unconfined compressive strength tests with 2 hours curing period (kPa).

X= California Bearing Ratio (CBR).

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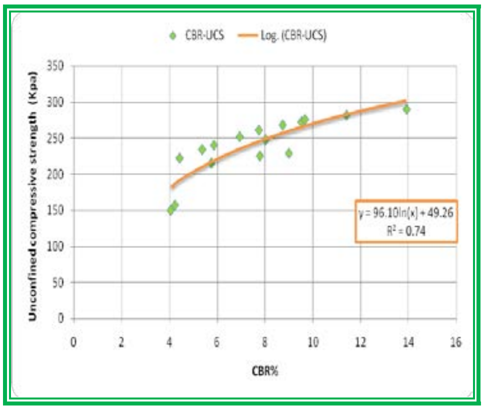


Figure (35) Relationship between CBR and UCS.

## 4. Conclusions

In this study, the effect of adding LSFM on the engineering properties of expansive clayey soil was investigated and the following conclusions can be drawn:

1- LL and PI decrease with addition of LSFM, while PL increases with increasing LSFM content. The maximum decrease in liquid limit is found with the addition of (4% Lime+0%SF) which reduces the liquid limit by 38.9%.The maximum decrease in plasticity index is found with the addition of (8% Lime+8%SF) which reduces the plasticity index by 64.3% .The maximum increase in plastic limit is found with the addition of (12%Lime+18%SF) which increases the plastic limit by 35%.The results show pronounced effect of LSFM on consistency limits.

2- Specific gravity decreases with increasing LSFM content.

3- The LSFM changes compaction parameters of expansive clayey soil. The maximum dry unit weight decreases with the increase of the LSFM content except with the addition of 4%lime only, while optimum moisture content increases with increasing LSFM content.

4- The swell% decreases as the LSFM increases. The optimum percentage of LSFM that influences on free swell reduction was found at 4% lime when it was mixed with 8%, 13% and 18% of SF which decrease the free swell% by 92.93%, 90.35% and 90.84% respectively and when 8% lime is mixed with 18%SF the reduction of the free swell will be 91.62%.Also the addition of SF only was found to be more effective in reduction the free swell% when compared with addition of lime only.

5- The results of the swell pressure test according to (ASTM D4546-96, Method A) do not give reasonable values of swell pressure; therefore, this test is not recommended for soils in which LSFM or any other hardening additives are used. Despite these results, it has been noted that the swelling pressure decreases with increasing the SF content with each lime percentages, which is an indication that LSFM can be used in reduction of the swelling pressure.

6- The compression index (Cc) decreases with increasing LSFM percentage. Maximum decrease is found with addition of 8% lime and 12% lime with all percentages of SF. The optimum percentage of LSFM causes the higher reduction in Cc found with the addition of (12%Lime+8%SF).This addition reduces the compression index by 97.11% .It has been also noted that the influence of adding lime on the reduction in the values of Cc is more pronounced as compared with the influence of adding SF.

7- The increase in LSFM and curing period improves the unconfined compression strength (UCS). The optimum percentages of LSFM that achieved the maximum strength were obtained to be (12%lime+13%SF) and (12%lime+18%SF) for 28 days which increases the UCS from 222.28 to 2669.61and 3162.52 kPa respectively.

The addition of SF or lime only with 2hour curing has a negligible effect on UCS. The strength development (s.d.) at 7 days with addition of SF is more than that with addition of lime, with a value of average s.d. approximately 80% with addition of SF and 60% with addition of lime. In general, the results predict that the addition of lime to SF delays the development strength for all samples and the maximum delay was found with addition of 4%lime and 12%lime to other percentages of SF.

8- CBR increases with increasing LSFM and the results show that the addition of lime only is more effective than adding SF on CBR values. CBR values increase with the addition of lime up to 4% and then decrease at 8%lime and again increase at 12%lime with all percentages of SF used in the present study. CBR increased when adding SF to lime, this indicates that lime becomes more effective in the presence of SF as compared with addition SF or lime only. The optimum percent of LSFM which gives a higher improvement in CBR value is found when adding (12%lime+13%SF).Thus, there is an enhancement in CBR values with addition LSFM and finally a good relationship (i.e,Equation,4-4) between the values of UCS and CBR is obtained.

9- From the results of improvement percent obtained in order to study the effect of wetting – drying cycles, it has been observed that swell% decrease with increasing LSFM content and number of wetting-drying cycles .The highest decrease in swell% appears when mixing 4%lime with 13% and 18% of SF.

10- From the results and according to the engineering use of LSFM, it can be concluded that the engineering properties of expansive clayey soil can be improved by adding lime in the range of 4-12% combined with 8-13% SF. Note that the optimum improvement in the physical properties such as consistency limits and swell potential can be achieved by adding lime in the range of 4-8% combined with 8-13%SF,while the optimum enhancement in the shear strength parameters and CBR value can be attained by adding 8-12% lime to 8-13%SF.

Acknowledgment

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