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Effect of Silica Fume Addition on the Behavior of Silty-Clayey Soils

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Abstract

The aim of this research is to investigate the effect of silica fume addition on the behavior of soil subgrades which has inadequate natural stability. Natural silty-clay soil and silty-clayey soil-silica fume mixtures were compacted at the optimum moisture content and subjected to various laboratory tests.. The test results showed a significant improvement on swelling pressure and compressive strength of composite samples with silica fume. The swelling pressure decreased by 87% with increasing silica fume contents from 5% to 15% for all samples and the compressive strength of clay samples increased by 4% with increasing silica fume contents from 5% to 10% and after that it decreased. It is observed that the permeability of soil increased with increasing silica fume content. The coefficient of permeability increased by 100% with increasing silica fume content to 15%. Also, the results show that the silica fume decreases the development of cracks on the surface of compacted clay samples through reducing crack width by 75%. The investigation showed that the silica fume is a valuable material to modify the properties of soil subgrade to make them suitable for construction.

الخلاصة

إن الهدف من هذا البحث هو تحري تأثير إضافة غبار السيليكا على الترب ذات الثبات الطبيعي غير الكافي . إن الترب الطينية الغرينية الطبيعية أو خليط التربة الطينية الغرينية مع غبار السيليكا تم رصها باستعمال محتوى الرطوبة المثلى لإجراء مجموعة من الفحوصات المختبرية. إن نتائج الفحوصات أظهرت تحسن في ضغط الانتفاخ وقابلية الانضغاط للتربة المضاف لها غبار السيليكا. أن ضغط الانتفاخ يقل بمقدار ٨٧ % عند زيادة محتوى غبار السيليكا من ٥ % الى ١٥ % لكافة النماذج بينما تزداد قابلية انضغاط نماذج التربة الطينية بمقدار ٤ % بزيادة محتوى مادة السيليكا الفعالة من ٥ % الى ١٠ % وبعدها تقل قابلية الانضغاط. تم ملاحظة زيادة نفاذية التربة بزيادة محتوى غبار السيليكا . حيث يزداد معامل النفاذية بمقدار ١٠٠ % عند زيادة محتوى السيليكا الى ١٥ % . كذلك فلقد اظهرت النتائج ان غبار السيليكا يقلل من انتشار التشققات لنماذج الترب المرصوصة من خلال تقليل سمك الشق بمقدار ٧٥ %. لقد اظهر التحري ان غبار السيليكا هي مادة قيمة في تحسين خصائص التربة لملائمة أعمال الإنشاء عليها.

1. Introduction

A difficult problem in civil engineering work exists when the subgrade is found to be clay. Clay soils have a tendency to swell when their moisture content is allowed to increase [1]. This moisture may come from rains, floods, leaking sewer lines, or from the reduction of surface evaporation when an area is covered by a building or pavement. Frequently, these clayey soils cause the cracking and breaking up of pavements, railways, highway embankments, roadways, foundations and channel or reservoir linings [2, 3].

When civil engineers are faced with possible construction damage, a need for improving the engineering properties of the soil is justified using some sort of stabilization methods. Stabilization of pavement subgrade soils has traditionally relied on treatment with lime, cement, and special additives such as pozzolanic materials. Pozzolanic materials, such as Fly Ash, Silica Fume, and Rice Husk Ash, which are regarded as wastes may be used for soil improvement [4, 5, 6]. The Silica Fume is found to be 40% cheaper than that of Portland cement[4].

Very little data is available to prove the correlation between the compressive shear of clay and silica fume additive material. Therefore, Kalkan and Akbulut in 2004 [7] examined the suitability of silica fume, which is an abundantly available product, for the construction of hydraulic barrier in landfill. They conducted experiments on a membrane composed of the clay and silica fume with different contents. The performance of silica fume-clay composite liners with the optimum moisture content was evaluated to develop an alternative liner material with low permeability, low swelling pressure and high compressive strength for landfills. Kalkan and Akbulut in 2004 [7] proved that a higher bonding strength between clay and silica fume particles led to higher internal shear strength in the clay–silica fume mixture. Therefore, in order to evaluate the interaction between silica fume and silt or clay particles in composed samples, the samples were magnified 5000 times by means of a scanning electron microscope (SEM). Observations of scanning electron microscope showed that silica fume particles settle in the pore space among the silt-clay grains, then the settled silica fume particles react to form hydration products (flocculation products) in the surrounding of soil grains. This textural event caused a significant improvement in permeability, swelling pressure and compressive strength. For this reason, the obtained experimental results have also released a possibility that a chemical reaction with silica fume and clay particles may occur [7].

The main objective of this study is to investigate the effect of silica fume on swelling pressure, compressive strength, permeability and cracks of silty-clayey soil.

2. Chemical Modification of Silica Fume -Clay Mixture

It is difficult to give a reaction of silica fume with clay under normal conditions. However, interpretation of chemical reactions must be explained to understand silica fume–clay modification. To produce the modification of silty-clayey soil, the important two effects are the quality and quantity of silica fume added to clay and the chemical composition of clay. The silty-clayey soil used in this research have significant quantity of calcium compounds, which form Ca^{2+} ions and hydroxyl ions by reacting water molecules. The active silica reacts with calcium hydroxide and forms calcium silicate hydrate gels ($CaSiO_3.H_2O$). The basic reaction of silica fume–calcium in clay could be indicated as:

$$Ca^{2+} + OH^{-} + \text{soluble silica} \rightarrow \text{calcium silicate hydrate}$$

It was found out that the material from this reaction became stronger and more brittle than previous form. There are findings similar to these concepts [8, 9].

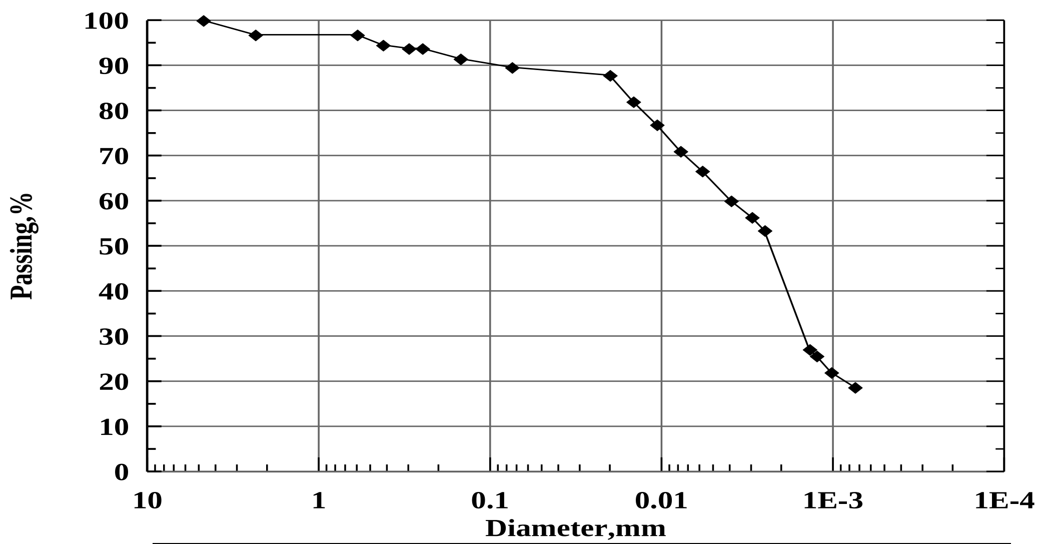
3. Materials

3.1 Clay

The silty-clayey soil used in this research was brought from Baghdad, Iraq. The physical characterization of clay sample is presented in Table 1. The soil is classified as silty-clay according to the ASTM D422 [10] with a specific gravity of (G_s = 2.73). The grain size distribution of soil is shown in figure 1.

Table1. Physical Properties of soil.

Index properties		Index value
Atterberg Limits	Liquid limit, L.L, (%)	49
	Plastic limit, P.L, (%)	24
	Plasticity Index, P.I, (%)	25
Grain size analysis	% Sand (0.075-4.75)mm	10.3
	% Silt (0.005-0.075) mm	25.3
	% Clay (< 0.005) mm	64.5
Specific gravity G_s		2.73
Compaction test	Max. dry unit density, gm/cm^3	1.69
	Optimum moisture content, %	19



GSD(ASTM D422)	Sand	Silt	Clay
	4.75-0.075	**0.075-0.005**	**<0.005**
Soil Sample	**10.2**	**25.3**	**64.5**

Figure 1 Grain size distribution.

3.2 Silica Fume

Silica fume (SF), also known as micro-silica, is a by product of the reduction of high-purity quartz with coal in electric furnaces in the production of silicon and ferrosilicon alloys. SF is also collected as a by product in the production of other silicon alloys such as ferrochromium, ferromanganese, ferromagnesium, and calcium silicon (ACI Committee 226. 1987) [11]. It consists of very fine vitreous particles with a surface area on the order of 20,000 m^2/kg (215,280 ft^2/lb) when measured by nitrogen absorption techniques, with particles approximately 100 times smaller than the average cement particle. Because of its extreme fineness and high silica content, Silica Fume is a highly effective pozzolanic material [11, 12]. Silica Fume is used in concrete to improve its properties. It has been found that SF improves compressive strength, bond strength, and abrasion resistance; reduces permeability; and therefore helps in protecting reinforcing steel from corrosion. The chemical composition of silica fume used in the present study which is applicable to the ACI Committee 226 requirements [11] is given by the manufacturer and shown in Table 2.

Table 2. Chemical composition of silica fume used in the tests

Composition	**Silica fume (%)**
SiO_2	98.87 %
Al_2O_3	0.01%
Fe_2O_3	0.01 %
CaO	0.23 %
MgO	0.01 %
K_2O	0.08 %
Na_2O	0.00 %

4. Preparation of Silty-Clay Soil-Silica Fume Mixtures

The soil brought from the field to the soil mechanic laboratory at the University of Baghdad was dried in an oven at approximately 105 °C before grinding process. The soil and silica fume mixed together in the dry state. The amounts of silica fume were selected to be 5%, 10% and 15% of the total dry weight of the clay soil-silica fume mixtures. The dry soil and silica fume were then mixed with the required amount of water for optimum moisture content. All mixing was done manually, and proper care was taken to prepare homogeneous mixtures at each stage of mixing.

5. Experimental Study

The experimental study was carried out at the soil mechanic laboratory/University of Baghdad. The liquid limit, plastic limit, and plasticity index of the natural and stabilized soil samples were determined by Atterberg tests in accordance with ASTM D 4318 [13]. The compaction parameters such as the maximum dry unit weight and the optimum moisture content were obtained by Standard Proctor tests in accordance with ASTM D 698 [14]. The samples of modified natural clays were all initially compacted at their optimum moisture content in a Standard Proctor mold ASTM D 1557 [15] then, the unconfined compression tests were carried out to determine the unconfined compressive strength values in accordance with ASTM D 2166 [16].

The swelling behavior of natural clayey soil and clayey soil-silica fume mixtures were assessed from one dimensional consolidation tests. These samples were subjected to Standard Consolidation test in accordance with ASTM D 2435 [17].

The specific gravity of soil was estimated according to standard test methods for specific gravity of soil solids by Water Pycnometer ASTMD 854 [18].

The development of desiccation cracks in the laboratory prepared samples representing natural clayey soil and clayey soil-silica fume mixtures was observed by cracking tests[20]. All of the samples were compacted at the optimum moisture content using Standard Proctor efforts before the cracking tests. In this stage, compacted samples were kept in laboratory conditions for 48 h to allow saturation of samples. At the end of 48 h, saturated samples were extruded from the Standard Proctor molds using a hydraulic jack. These samples were kept under laboratory conditions for 28 days to allow for their desiccation and the development of desiccation cracks was observed on the surface of samples. There are similar approaches to these concepts such as Kalkan in 2009 [20].

6. Results and Discussions

6.1 Effects of Silica Fume Content on the Consistency Limits

The effects of silica fume on the consistency limits are given in figure 2. Liquid limit, plastic limit and plasticity index values increased with increasing silica fume content for all stabilized samples. The reason of this could be explained depending on the soil type, the relative amount of silicate clay mineral in the samples and associated exchangeable cat-ions [8, 21]. While in reference [6], the physical properties such as consistency limits show improvements when mixed with the lime and silica fume blend.

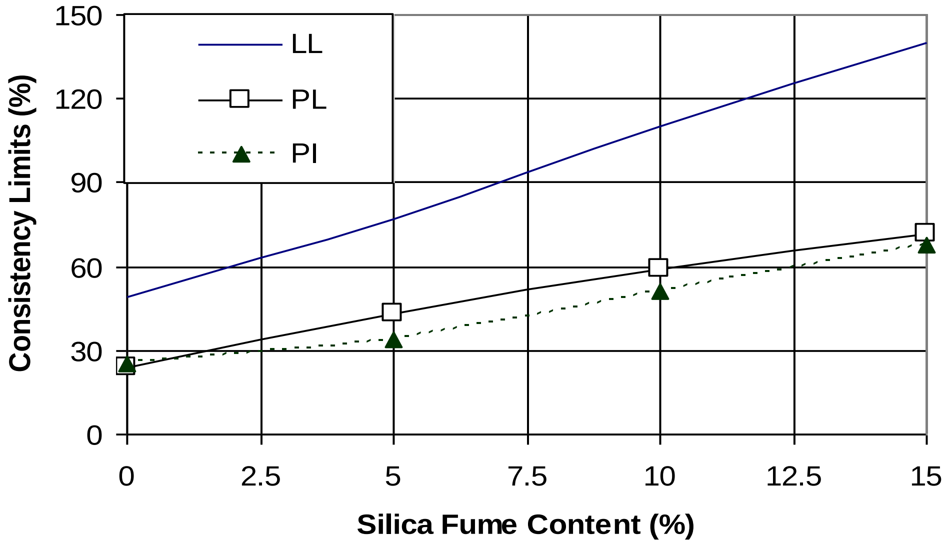


Figure 2 Consistency limits for different soil-silica fume mixtures.

6.2 Specific Gravity

The effect of silica fume content on specific gravity is presented in figure 3. Figure 3 shows that as the silica fume content increases, the specific gravity of soil decreases .This indicates that the soil-silica fume mixture is lighter than that of the natural conditions because the silica fume fills the voids between soil particles. Similar results were obtained by reference [6] in which lime and silica fume blend was used.

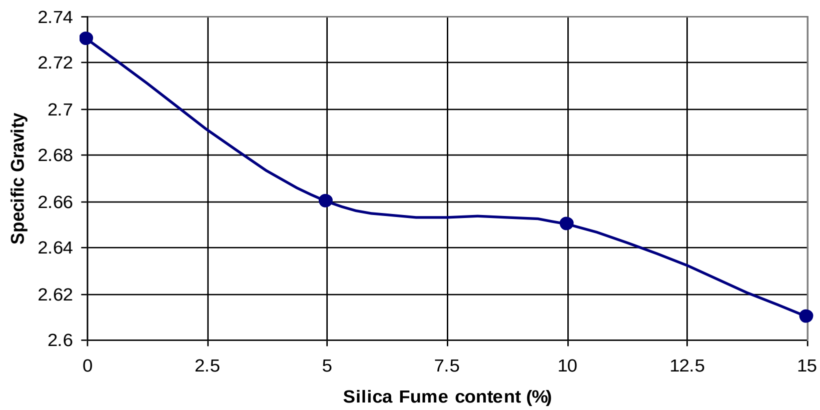


Figure 3 Effect of silica fume content on specific gravity of soil.

6.3 Effects of Silica Fume Content on Compaction Parameters

Figure 4 shows the variation of moisture content and dry unit weight values of stabilized samples with silica fume. There are an increase in the optimum moisture content and a decrease in the maximum dry unit weight due to the addition of silica fume. The reason for increase in the optimum moisture content is due to the change in surface area of composite samples. The silica fume changes the particle size distribution and surface area of the stabilized soil samples. In the same way, the reason for the decrease in the maximum dry unit weight is the addition of higher amounts of silica fume with low density, which fills the voids of the composite samples. The similar conclusion was obtained by references [7, 22, 23].

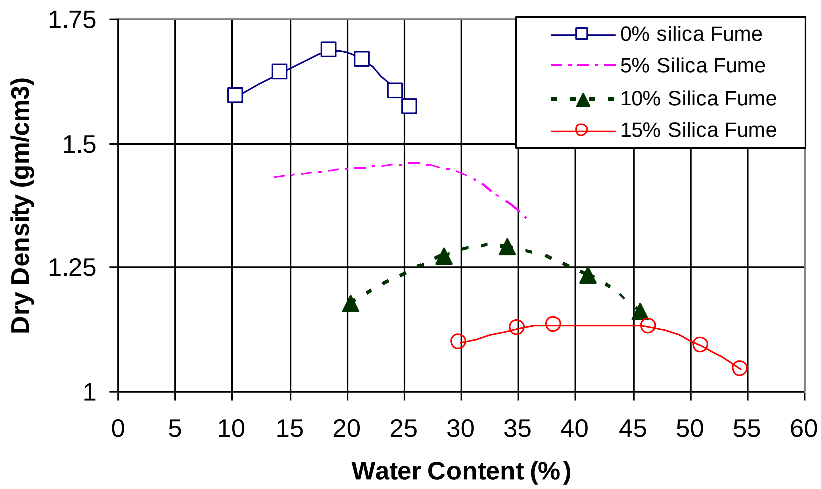


Figure 4. Variation of moisture content and dry unit weight values of stabilized samples with different silica fume content.

6.4 Effects of Silica Fume Content on Unconfined Compressive Strength

The effects of silica fume contents on the unconfined compressive strength for stabilized silty-clayey soil samples are presented in figure 5. The unconfined compressive strength of stabilized samples significantly increases with increasing silica fume content from 5% to 10% (increase from 403.732 to 419.712 kPa (4%)). However, after that, the unconfined compressive strength is slightly affected by additional silica fume content. The maximum unconfined compressive strength of the stabilized silty-clayey soil samples is found to be at the 10% silica fume content. The increase in the unconfined compressive strength is attributed to the internal friction of silica fume particles and chemical reaction between silica fume and soil. An increase in silica fume content in soil has made the stabilized soil samples more brittle than the natural soil samples, which is ductile as compared to all the stabilized samples. The unconfined compression test is widely used as a quick, economical method of obtaining the approximate compressive strength of the cohesive soils. In reference [7], the compressive strength increased by 37% for all samples with increasing silica fume content up to 25%. However, after that, compressive strength was slightly affected by silica fume content rise.

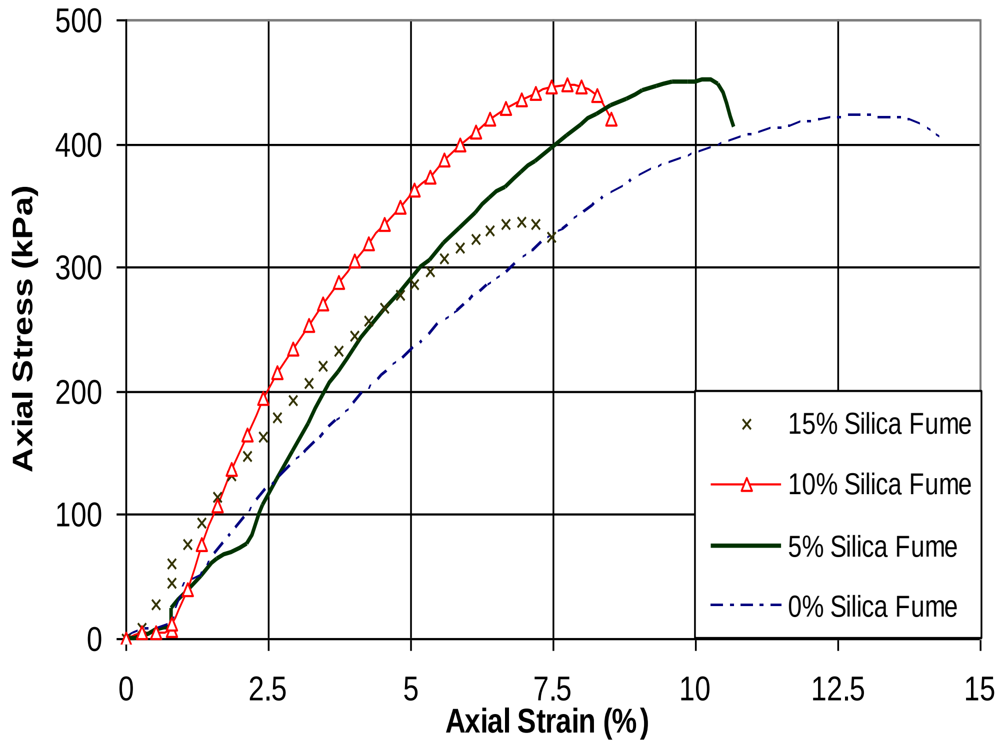


Figure 5 Compressive stress-strain curve for soil with different silica fume content.

6.5 Effect of Silica Fume Content on Permeability

The test results are given in figure 6. There is a significant increase in the permeability of soil with increasing the silica fume content. The results show that the coefficient of permeability increases from 0.141 mm/sec to 0.256 mm/sec and from 0.214 mm/sec to 0.284 mm/sec for the samples of natural and stabilized soil containing from 0% to 5%, and from 10% to 15% respectively. While in reference [7], the permeability decreases with increasing silica fume content. The increase in the permeability in this research is attributed to the changes in soil sample structure due to particle rearrangements and the initiation of cracks.

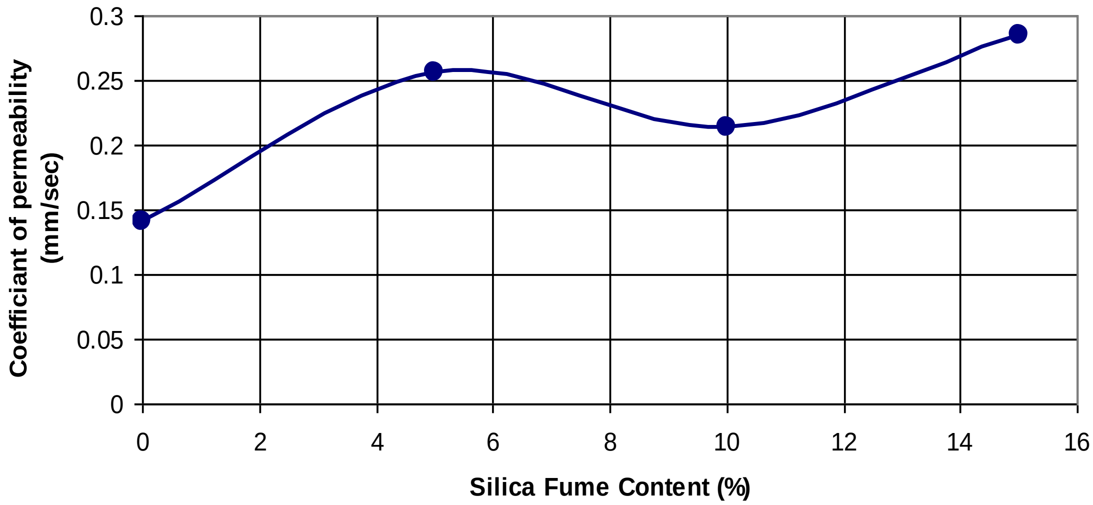


Figure 6 Variation of coefficient of permeability with silica fume content.

6.6 Effect of Silica Fume Content on Swelling

It was observed that improvement in swelling pressure was obtained using silica fume contents. The swelling pressure in composite samples was decreased with increasing silica fume content as shown in figure 7. It was observed that the decrease in the swelling pressure occurred with rising silica fume contents, which ranged from 5% to 15%. The composite samples with 5% , 10% and 15% silica fume contents decrease the swelling pressure by 18%, 48% and 87% respectively.

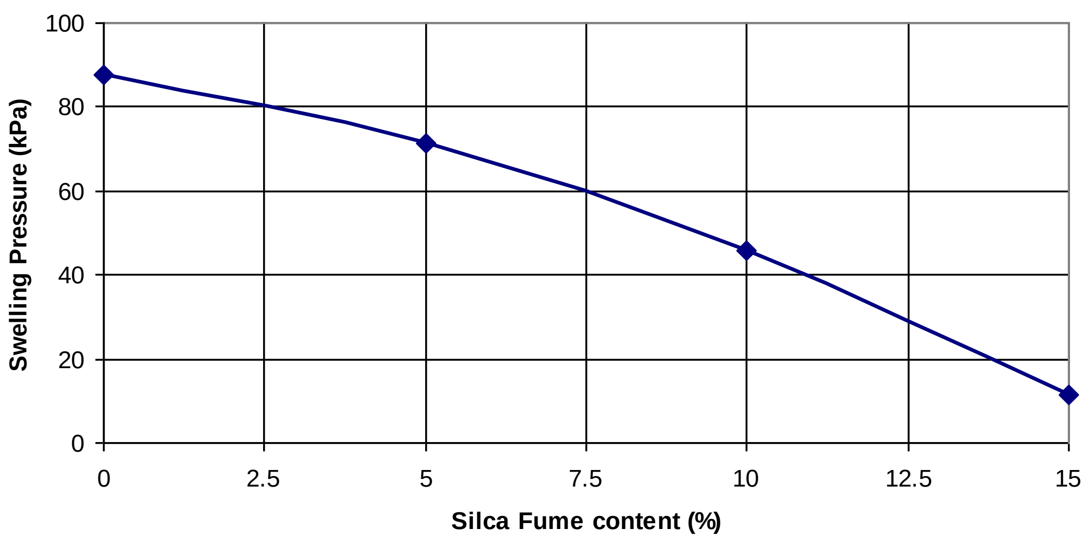


Figure 7. Effect of silica fume on swelling pressure.

The amount of swelling of natural soil and composite soil samples containing silica fume is shown in figure 8 and figure 9 . As can be seen in these figures, silica fume decreased the vertical swelling of soil-silica fume mixtures. The vertical swelling percentages of soil- silica fume mixture samples decreased from 12% to 2% for the soil-silica fume mixtures containing 0% and 15% silica fume contents. While in reference [20] the vertical swelling percentage of soil- silica fume mixture samples decreased from 19% to 3% for the soil-silica fume mixtures containing 0% and 50% silica fume contents. The decrease in the swelling of composite samples is due to the interaction between silty-clayey minerals and silica fume particles.

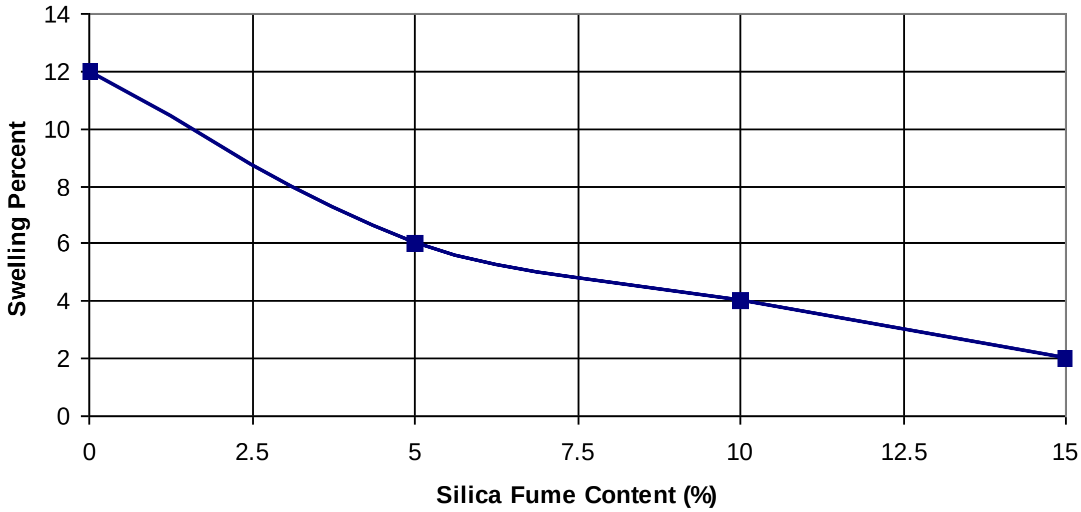


Figure 8 Effect of silica fume content on swelling percent.

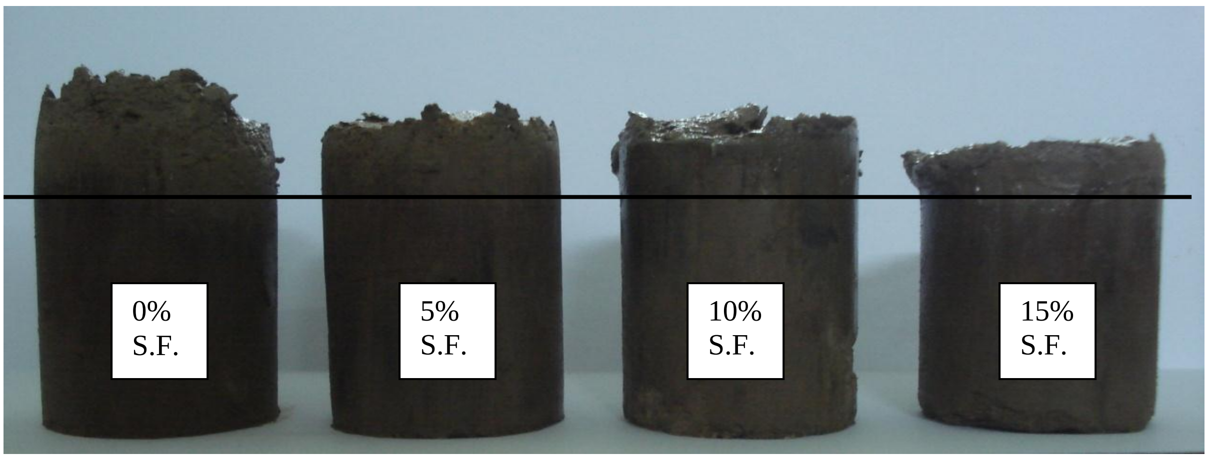


Figure9. The Variation in Extent of swelling with increasing of silica fume content.

6.7The Effect of Silica Fume Content on the Desiccation Crack Development

In Table 3 and figure 10, the test results showed that, the natural clayey soil cracked severely, whereas the samples of soil-silica fume mixtures suffered little cracking. In each sample, it was observed that reduction in the development of desiccation cracks with 75% occurred with increasing silica fume content between 0 and 15%. While in reference [20] it was observed that reduction in the development of desiccation cracks by 88 % occurred with increasing silica fume content between 0 and 25%. So, the addition of silica fume minimized the effects of volumetric shrinkage strain.

Table 3. Effect of silica fume on crack width.

Silica Fume, content %	0	5	10	15
Crack width, mm	0.4	0.3	0.2	0.1

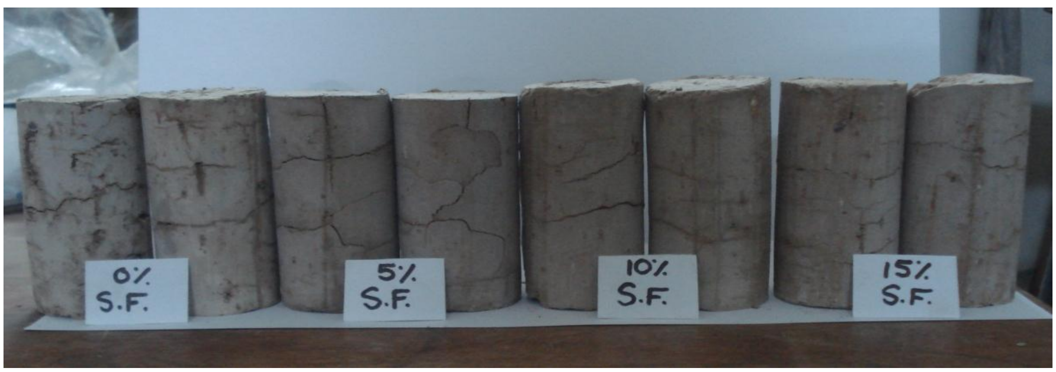


Figure 10 Effect of silica fume on the desiccation crack development.

7. Conclusions

The following conclusions are derived from this investigation:

1- Silica fume increased liquid limits, plastic limits and plasticity index by 1.8 times and decreased the specific gravity in all clay samples by 4%.

2- Silica fume increased the optimum water content and decreased the maximum dry unit weights of the samples by about 31% for all the composite samples in the same compaction effort.

3-A significant improvement on swelling pressure and compressive strength of composite samples was obtained using silica fume. The swelling pressure decreased by 87% with increasing silica fume contents from 5% to 15% for all samples and the compressive strength of clay samples increased by 4% with increasing silica fume contents from 5% to 10% and after that it decreased.

4- It is observed that the permeability of soil increased by with increasing silica fume content. The coefficient of permeability increased by 100% with increasing silica fume content up to 15%. The increase in permeability is attributed to the changes in soil sample structure due to particle rearrangements..

5- It is concluded that silica fume can be used to minimize the development of desiccation cracks and the swelling behavior of clayey soils as it decrease crack width by 75%.

6-The investigation showed that the silica fume is a valuable material to modify the properties of soil subgrade to make them suitable for construction.

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