Performance of soft clay stabilized with sand columns treated by silica fume

Zeena Samueel¹, Hussein Karim^{1,*}, and Mohammed Mohammed¹

¹Department of Building and Construction Engineering, University of Technology, Baghdad, Iraq

Abstract. In many road construction projects, if weak soil exists, then uncontrollable settlement and critical load carrying capacity are major difficult problems to the safety and serviceability of roads in these areas. Thus ground improvement is essential to achieve the required level of performance. The paper presents results of the tests of four categories. First category was performed on saturated soft bed of clay without any treatment, the second category shed light on the improvement achieved in loading carrying capacity and settlement as a result of reinforcing with conventional sand columns at area replacement ratio = 0.196. The third set investigates the bed reinforced by sand columns stabilized with dry silica fume at different percentages (3, 5 and 7%) and the fourth set investigates the behavior of sand columns treated with slurry silica fume at two percentages (10 and 12%). All sand columns models were constructed at (R.D= 60%). Model tests were performed on bed of saturated soil prepared at undrained shear strength between 16-20 kPa for all models. For all cases, the model test was loaded gradually by stress increments up to failure. Stress deformation measurements are recorded and analyzed in terms of bearing improvement ratio and settlement reduction ratio. Optimum results were indicated from soil treated with sand columns stabilized with 7% dry silica fume at medium state reflecting the highest bearing improvement ratio (3.04) and the settlement reduction ratio (0.09) after 7 days curing. While soil treated with sand columns stabilized with 10% slurry silica fume provided higher bearing improvement ratio 3.13 with lower settlement reduction ratio of 0.57 after 7-days curing.

1 Introduction

Stabilization of soil has become one of the useful solutions to treat the soft soils to achieve the required engineering properties and specification so that the structures can be placed safely without undergo large settlements. The problematic soil is removed and replaced by a good quality material or treated by using mechanical and/or chemical stabilization. Geotechnical properties of such soils may be improved by various techniques. These techniques include compaction, electro-osmosis, ground freezing, chemical stabilization, grouting use of reinforcement such as stone and geotextile waste materials or nontraditional stabilizers, such as silica fume and fly ash, are also applied sometimes for stabilization. Good improvement in engineering properties of soft clay has been noticed by Abd El- Aziz et al. (2014) [1] and Al-Jobouri (2013) [2] when adding mixture of lime and silica fume for stabilizing soft clay. Kalkan (2009) [3] examined the suitability of silica fume to reduce the development of desiccation cracks in compacted clayey liner and over systems. Kalkan (2011) [4] found that silica fume decreases the deformation of expansive clayey soils subjected to cyclic drying and wetting. Karim et al. (2016) [5] studied the behavior of sand columns (R.D=15%) stabilized with dry silica fume as an additive with different percentages (3, 5 and 7%) and driven in soft clay with c_u between 16-20 kPa. The results showed

that the best possible addition of silica-fume in sand-silica fume column is 7% giving bearing improvement ratio and settlement reduction ratio of 1.56 and 0.5 respectively.

Sand and stone columns, known as column-type technique, are most widely adopted approaches for improving soft and compressible soils due to their high compressive strength and stiffness to the soft soil. The degree of improvement in carrying capacity and reduction in settlement of a soft soil by sand columns is due to two factors: the first one is inclusion of a stiffer sand column in the soft soil. The second factor is the compaction of well graded sand at high relative density. In recent years, many studies and attempts have been carried out to increase the stiffness of stone columns as well as sand columns by mixing additives with backfill materials or by using different patterns of encasement (Abbawi, 2013) [6]. Good improvements in load carrying capacity of sand columns and significant reduction in settlement have been noticed by Al- Saoudi et al. (2014) [7] who used lime as an additive to increase the stiffness of sand columns.

This research focuses on studying the feasibility of improving geotechnical properties of soft clay soil with implemented sand columns (mixed with silica fume using different percentages) and evaluates the degree of improvement in load carrying capacity and settlement reduction ratio.

* Corresponding author: husn_irq@yahoo.com

2 Materials used

2.1 Soil

Soil samples used in this study were obtained from Al-Nahrawan area. The soil consists of 16 % sand, 34 % silt and 50 % clay as shown in the grain size distribution (Fig. 1). Atterberg's limits revealed L.L = 37 and P.L = 16. According to the Unified Soil Classification System (USCS), the soil classified as CL (clay of low plasticity). Other physical and chemical properties of the soil are summarized in Table 1. From vane shear test, the cohesion of the soft soil (c) is 35 kN/m².

Fig. 1. Grain size distribution curve.

Table 1. Physical and chemical properties of natural soil used.

Index Property	Index Value
Liquid Limit (L.L) (%)	37
Plastic Limit (P.L) (%)	16
Linear Shrinkage (SL) (%)	12
Plasticity Index (P.I) (%)	21
Activity (At)	0.81
Specific Gravity (Gs)	2.69
Gravel (larger than 2mm) (G) %	0
Sand (0.06 to 2mm) % (S)	16
Silt (0.005 to 0.06) (M)%	34
Clay (less than 0.005mm) (C)%	50
Classification (USCS)	CL
Organic Material (O.M) (%)	0.39
Calcium Oxide (CaO) (%)	0.36
SO ₃ Content (%)	0.52
Total Dissolved Salt (TDS) (%)	1.02
pH Value (%)	9.17

2.2 Sand

The sand used as a backfill material was brought from Al-Ekhaidhir area. The grain size distribution showed 4% gravel, 94% sand and 2% fines classified as well graded sand as shown in Figure 2. The physical and chemical properties of sand are shown in Table (2). The

internal friction (ϕ) is 44° obtained from direct shear test at dry unit weight 16 kN /m³.

Fig. 2. Grain size distribution for the sand used.

Table 2. Physical and chemical properties of sand used.

Index Property	Index Value
Max. Dry Unit Weight (kN/m ³)	20.8
Min. Dry Unit Weight (kN/m ³)	16.25
D ₁₀ (mm)	0.24
D ₃₀ (mm)	0.7
D ₆₀ (mm)	1.7
Coefficient of Uniformity (C _u)	7.13
Coefficient of Curvature (C _c)	1.19
Gravel (G %)	4
Sand (S %)	94
Fines (%)	2
Classification	SW
Specific Gravity (Gs)	2.65
Organic Material (O.M) (%)	0.09
Total Dissolved Salt (TDS) (%)	0.3

2.3 Silica fume

The American concrete institute (ACI, 1995) [8] defines silica fume (S.F.) as a "very fine no crystalline silica produced in electric arc furnaces as a byproduct of production of elemental silicon or alloys containing silicon". It is usually a grey colored powder, somewhat similar to Portland cement or some fly ashes. It can exhibit both pozzolanic and cementations properties. Silica fume has been recognized as a pozzolanic admixture that is effective in enhancing the mechanical properties to a great extent. By using silica fume along with super plasticizers, it is relatively easier to obtain compressive strengths of order of 100-150 MPa in laboratory. The physical and chemical properties of silica fume are shown in Table 3.

Table 3. Physical and chemical properties of silica fume used.

Chemical and physical properties	Composition
Chemical composition (%)	
SiO ₂	> 85
Fe ₂ O ₃	< 2.5
Al ₂ O ₃	< 1
CaO	< 1
K ₂ O + Na ₂ O	< 3
C (free)	< 4
Cl ⁻¹	< 0.2
L.O.I	< 6
Physical Properties	
Specific Gravity (Gs)	2.25
Density (gm/cm ³)	0.75
Moisture content (%)	< 2%
Specific Surface (m ² /gr)	~ 20

3. Experimental work

3.1 Steel Container

The model test were carried out by using a steel container with plate thickness of 4mm and internal dimensions 600 mm*600 mm*500 mm.

3.2 Model footing

For all model tests, a circular steel model footing with diameter of 64.6mm and thickness 10mm was used.

3.3 Loading Assembly

The loading assembly consists of two main parts; a loading frame and a steel container. The loading frame consists of a steel rod with several attachments that host the loading weights. The whole assembly is capable to apply static vertical loads on the footing. Details of the main parts of the loading assembly are shown in Figure 3.

Fig. 3. Steel container and loading assembly.

4. Sampling and soil mixture preparation

Before stages of preparation of the soil bed, control tests were carried out to obtain a relationship between the shear strength and water content. The undrained shear strength was determined by the Vane shear device. The shear strength of soil decreases with increasing value of water content as shown in Figure 4.

Fig. 4. Variation of undrained shear strength with water content.

Following this stage, the natural soil was left for air drying and crushed by a hammer to small sizes and then crushed by using a crushing machine. The air-dried soil was divided into groups, each weight 20 kg. Then, each group was mixed in mixer with sufficient amount of water corresponding approximately to the water range of (27-29%) to get undrained shear strength (c_u) between (16-20 kN/m²). After through mixing with water, the soft soil lumps were spread into the container in 5 layers, and tamped with a specially tamping tool to remove any entrapped air. The procedure continued until the required thickness of bed was achieved, the top surface was scraped, level and covered with a polythene sheet and a wooden board of the same size was placed with 5kPa seating pressure. Then, the soil was left for a period of two days to regain its strength by self-weight consolidation. The top surface of the soft soil bed was marked into 4 equal zones and a column was constructed in the center of each quarter by inserting a vertical hollow plastic PVC pipe with external diameter of 50 mm to a depth of 300 mm. The soil inside the column was carefully removed by a hand auger. Later, the sand and sand-silica fume mixture was then poured into the hole in layers. After pouring all the specific amount of the mixture, the full depth of the hole was filled with sand with slight tamping to achieve unit weight of 18.7 kN/m³ at medium state ($D_r = 60\%$). After the completion of the preparation of the bed of soil, a seating load 5 kN/m² was placed for 24 hours, it was covered with a nylon sheet to prevent any loss of moisture and left for curing period at seven days. Following the curing days for the columns, the static loading system was placed and fixed in position and the footing was incrementally loaded with continuous measurements of the footing up to failure. The same procedure for preparation soft clay was presented in Al-Gharbawi (2012) [9] and Rajab (2013) [10].

5. Experimental results

Prior to the discussion of the model test results, it is important to clarify that the failure is considered as the load corresponding to settlement 10% of the footing diameter. Results and discussion are subdivided into two sections; the first is devoted for discussing the results concerning the improvements in bearing capacity due to the presence of sand columns and sand-silica fume columns. The increase in bearing capacity is determined using the term “bearing improvement ratio” which represents the bearing ratio (q/c_u) of the treated soil to that of untreated soil, simply given the notation $(q/c_u)_t/(q/c_u)_u$. The second section of the discussion is devoted to the reduction in settlement gained by each improvement pattern. The term “settlement reduction ratio” is explained as the ratio of the settlement of the treated soil to the settlement of the untreated soil and given the notation S_t/S_{unt} .

5.1 Untreated soil

The first set of model tests was performed on untreated soil to determine the relationship between the applied stresses versus settlement. This relationship is considered as benchmark for comparison purposes of different patterns of improvement. Typical results are shown in Figure 5 which relates the settlement ratio ($S/D_{footing}$) versus bearing ratio (q/c_u). The bearing ratio at failure is 4.18 corresponding to 10% settlement ratio.

Fig. 5. Bearing ratio versus settlement ratio of untreated soil.

5.2 Soil treated with sand columns

Figure 6 demonstrates the relationship between q/c_u and $S/D_{footing}$ for soil reinforced with sand column at relative density 60% corresponding to medium state. At initial stress increments up to $q/c_u \approx 2$, the untreated and treated models exhibited approximately the same settlement ratio indicating insignificant influence for the presence of sand columns. At this stage, the applied stress was evenly distributed over the contact area of the composite soil and no sign of stress concentration was noticed. The influence of the sand column becomes noticeable when the bearing ratio exceeding 2 and reaching maximum

value at stress levels close to failure with bearing ratio (q/c_u) at failure equal to 7.75.

Fig. 6. Bearing ratio versus settlement ratio of soil reinforced with sand columns.

The bearing improvement ratio $(q/c_u)_t/(q/c_u)_u$ versus settlement ratio $S/D_{footing}$ at failure is 1.83 as shown in Figure 7.

Fig. 7. Bearing improvement ratio versus settlement ratio of soil reinforced with sand columns.

Variation of bearing ratio q/c_u versus settlement reduction ratio S_t/S_u is shown in Figure 8. Settlement ratio exhibits a decreasing trend then increasing bearing ratio revealing a settlement reduction ratio of (S_t/S_u) equal to 0.29 at failure.

Fig. 8. Settlement reduction ratio versus bearing ratio of soil reinforced with sand columns.

5.3 Sand column treated with dry silica fume

Six model tests were performed on sand column stabilized with silica fume at medium state (R.D 60%) and tested after curing for seven days. Figure 9 presents the q/c_u versus S/D_{footing} for all percentages (3, 5 and 7%) of silica fume used. At initial stress increments, the results of sand column stabilized with the silica fume showed no deformation compared with untreated sand models. The columns provided sufficient stiffness that led to improve the surrounding soil. The bearing ratio q/c_u at failure are 10.35, 11.15 and 12.7 for 3, 5 and 7% silica fume respectively.

Fig. 9. Bearing ratio versus settlement ratio of soil reinforced with sand columns stabilized with silica fume.

The bearing improvement ratio $(q/c_u)_t / (q/c_u)_{\text{unt}}$ versus settlement ratio S/D_{footing} is presented in Figure 10. It is shown that q_t/q_{unt} increases with increasing silica fume content. The bearing improvement ratio $(q/c_u)_t / (q/c_u)_{\text{unt}}$ at failure = 2.48, 2.66 and 3.04 for 3, 5 and 7% silica fume respectively.

Fig. 10. Bearing improvement ratio versus settlement ratio of soil reinforced with sand columns stabilized with silica fume.

Relation between settlement reduction ratio S_t / S_{unt} and bearing ratio q/c_u is shown in Figure 11. It can be

shown that 7% silica fume is more efficient in providing the lowest settlement ratio of 0.09. The settlement reduction ratio S_t / S_{unt} are 0.168, 0.121 and 0.09 for 3, 5

and 7% silica fume respectively at $q/c_u = 5$.

Fig. 11. Settlement ratio versus bearing ratio of soil reinforced with sand columns stabilized with silica fume.

5.4 Sand column treated with slurry silica fume results

Four model tests were performed on sand column stabilized with silica fume at medium state (R.D 60%) and tested after 7-days curing. Figure 12 presents the q/c_u versus S/D_{footing} for all percentages 10 and 12 % by weight slurry silica fume used. At initial stress increments, the results of sand column stabilized with silica fume showed marginal difference deformation as compared with untreated sand models. These columns provided significant stiffness that led to improve the composite soil. The bearing ratio q/c_u at failure ($S/D_{\text{footing}} = 10\%$) are 13.12 and 12.02 for 10% and 12% by weight

silica fume respectively.

Fig. 12. Bearing ratio versus settlement ratio of soil reinforced with sand columns treated with slurry silica fume.

The relationship between bearing improvement ratio $(q/c_u)_t / (q/c_u)_{\text{unt}}$ and settlement ratio S/D_{footing} (%) is

presented in Figure 13. Results show that the initial peak is about $S/D_{\text{footing}} = 1.5\%$ followed by decreasing then increasing to second peak close to failure. The bearing improvement $(q/c_u)_t / (q/c_u)_{\text{unt}}$ at failure = 3.13 and 2.88

for (10% and 12%) by weight slurry silica fume respectively.

Fig. 13. Bearing improvement ratio versus settlement ratio of soil reinforced with sand columns stabilized with slurry silica fume.

Settlement reduction ratio S_t/S_{unt} versus bearing ratio q/c_u are shown in Figure 14. It is shown that at $q/c_u = 1$ settlement reduction ratio is equal to zero indicating that there is no settlement in this stage, but then it starts to increases gradually. The settlement reduction ratio $S_t/S_{\text{unt}} = 0.057$ and 0.144 for (10% and 12%) by weight slurry silica fume at $q/c_u = 5$ respectively. Up to 10% of the liquid, the voids are still not filled with liquid. When adding the liquid, the density increases, the percent of voids decreases and the soil strengthens. By increasing the liquid percent more than 10%, the liquid starts to displace (or remove) the soil particles which in turn leads to increasing the percentage of voids and weakness of the soil.

Fig. 14. Settlement reduction ratio versus bearing ratio of soil reinforced with sand columns stabilized with slurry silica fume.

5.5 Comparison between sand columns reinforced with dry and slurry silica fume

Figure 15 presents the q/c_u versus S/D_{footing} of sand column for dry and slurry. No significant difference was noticed between dry and slurry sand columns at medium state. However, the slurry sand columns provided significant increase in bearing ratio as compared to dry type. Table 4 shows a summary of results for sand columns treated with dry and slurry silica fume types.

Fig. 15. Bearing ratio versus settlement ratio of sand columns treated with dry and slurry silica fume.

Table 4. Summary results of sand columns stabilized with dry and slurry type.

Type of soil treated	q/c_u	$(q/c_u)_t / (q/c_u)_{\text{unt}}$	S_t/S_{unt}
Sand Column +3% Silica Fume	10.35	2.48	0.168
Sand Column +5% Silica Fume	11.15	2.66	0.121
Sand Column +7% Silica Fume	12.7	3.04	0.09
Sand Column+10% (slurry silica fume)	13.12	3.13	0.057
Sand Column+12% (slurry silica fume)	12.02	2.88	0.144

6 Conclusions

In the light of experimental tests, the following conclu-

sions can be drawn:

1. The bearing improvement ratio and settlement reduction ratio exhibited by the sand columns only are 1.83 and 0.229 respectively.
2. The results analysis of the model tests indicated an encouraging improvement in load capacity of the sand columns stabilized with silica fume and considerable reduction in the settlement compared to the conventional stone columns.
3. It is worth mentioning that the values obtained for bearing improvement ratio and settlement ratio are limited to type of silica fume used in the test. The best possible addition of silica fume content in sand-silica fume columns is 7% at dry state, giving bearing improvement ratio and settlement ratio of 3.04 and 0.09 respectively. While addition 10% slurry silica fume to sand columns shows bearing improvement ratio and settlement ratio of 3.13 and 0.057 respectively.
4. In general, the use of silica fume as a stabilizing agent with sand provided improvements in terms of bearing improvement ratio and settlement reduction ratio due to increase in stiffness of the columns.

References

1. M.T. Abd El-Aziz, M.A. Abo-Hashema and M. El-Shoubagy, *The effect of lime-silica fume stabilizer on engineering properties of clayey subgrade, Engineering conference, Faculty of Engineering, Mansoura University, Sharm El-Sheikh, Egypt, April (2004)*
2. M.M. Al-Jobouri, M.Sc. Thesis, Civil Engineering Department, University of Baghdad, Iraq, (2013)
3. E. Kallkan, J Appl Clay Sci, **43** (2009)
4. E. Kallkan, J Appl Clay Sci, **52** (2011)
5. H.H. Karim, Z.W. Samueel and M.S. Mohammed, Eng Tech J **34**, Part A (2016)
6. Z.W. Abbawi, Ph.D. Thesis, University of Technology, Baghdad, Iraq, (2010)
7. K.S. Al-Saoudi, M.M. Al-Ksissi and N.A.A. Rajah, Eng Tech J **32**, Part A (2014)
8. ACI Committee 234, ACI Mater J, **92** (1995)
9. A.S.A. Al-Gharbawi, M.Sc. Thesis, University of Technology, Baghdad, Iraq, (2013)
10. N.A.A. Rajab, M.Sc. Thesis, University of Technology, Baghdad, Iraq, (2013)