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To cite this article: Hayder A. Mahdi *et al* 2024 *IOP Conf. Ser.: Earth Environ. Sci.* **1374** 012035

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Study on Strength Behavior of Expansive Soil Stabilized with Dune Sand and Sodium Silicate

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Abstract. When designing structures constructed on soil that undergoes volumetric changes due to variations in its moisture content, the upward pressure exerted by the soil poses a risk to the safety of the facilities. A significant number of researchers are looking into solutions to either treat these soils or lessen the detrimental consequences they have. One treatment option involves stabilizing these soils by adding low-expansion soil or materials, which can impact their swell characteristics. This study aimed to investigate the effect that the addition of dune sand and sodium silicate material would have on the swellability and strength behaviour of swellable bentonite soil. Soil samples were prepared containing bentonite soil (68, 70, 72, 74, 76, 78, 80, 82), dune sand (11%, 12%, and 15%), and sodium silicate (0%, 4%, 6%, 9, 11, 14, 16, 19, and 21%), to Get different soils with varying swelling capacities. The increased addition rates of sodium silicate significantly affected the soil's swelling qualities. This was evident in the decrease in swelling pressure, as assessed by the free swelling method, from 882 kPa to 38 kPa, despite the drop in the percentage of dune sand. The change also resulted in modifications to the mechanical test results. The value of C_c decreased from 0.29 to 0.21 when sodium silicate was added at a rate of 11%. Similarly, the value of C_s decreased from 0.032 to 0.024 when sodium silicate was added at 14%. Additionally, the shear strength parameter C_u increased from 110 kN/m² to 261 kN/m² when sodium silicate was added at a rate of 4%. Furthermore, the value of Φ increased from 10o to 41o when sodium silicate was added at 11%.The Atterberg limit's swelling indicators also went down. The addition of 10% sodium silicate is an optimal solution for decreasing soil swelling and enhancing the mechanical characteristics of the soil, even at modest rates of dune sand addition.

Keywords: Swellability, bentonite, dune sand, swelling potential, strength behaviour

1. INTRODUCTION

The word "expansive soil" refers, in general, to the soil that can increase in volume in response to an increase in the amount of moisture present in the soil. Because its volume shifts depending on the moisture present, it is also known as problematic soil (1). Soil behaves (shrinks and swells) under a range of changes in moisture content over time (2) and (3). The soil responds (shrinks and expands) to various shifts for moisture it contains over time. Since ancient times, people have been aware of the issue of expansive soil. According to (4), the swelling and shrinking are primarily caused by minerals in the soil called montmorillonite.

The high plasticity of this soil makes it susceptible to causing damage to any structures that are connected to it, particularly those that have low dead weight (such as sidewalks, railways, highway dams, roads, building foundations, canals, reservoir linings, irrigation systems, water lines, sewage lines, and other facilities). Because this type of soil can spread across large areas in various geographic locations, it is of the utmost importance to develop the capacity to recognize it in its earliest stages. The increased liquid limit and plasticity index of the soil is one of the first things that should be considered when considering the likelihood of soil swelling. Clays that can expand have liquid limits higher than 40% and a plasticity index higher than 15% (5).

Constructions built on this soil can have difficulties, so this should be considered. Because these soils cause the structures to be subjected to upward pressure, the specific methods required to reduce or mitigate the effects of each problem are different.

The first approach was to ensure the stability of the structures by ensuring that their weight would be greater than the anticipated swelling pressure. Instead, keeping the soil's moisture level stable and constant can be a treatment; its volume shifts in response to a change in moisture content. Many studies have defined this phenomenon as a chemical condition, so reducing soil swelling can also be accomplished through various additives' strategic and cost-effective use. Ecological and financial factors, as well as geotechnical needs, highlight the significance of using appropriate expanding soil stabilizers to counteract these drawbacks (6).

According to previous research conducted by (7), potential swell soil enhancers include fly ash, bottom ash, polypropylene, and Class Fnylon fibres. Lime was applied in amounts ranging from 0 to 9 or 12% to cure two extremely swollen soils from Jordan. After the experiment, soil performance with and without lime was compared. These evaluations look at chemical composition, the propensity for swelling, and the pressure associated with bloating. Rates of compression and rebound, inflation rates, and consistency are some of the other



factors that are considered. Because of the additive's effect, the swelling value was reduced, which improved the swelling properties (8). Applying emulsified asphalt in the treatment of swelling soils resulted in a significant reduction of 58% in swelling pressure and 78% in swelling potential. Emulsified asphalt stabilization can also be advantageous for expanded clay due to its ability to enhance compressive shear strength (9). Compared to untreated soil, three ratios of lime, cement, and silica fume (5, 7, and 9%) stabilized expansive soil and reduced free swelling and swelling pressure by 65% and 76%, respectively. Based on sprayed soil with 5% and 9% silica fume, foundations have a bearing capacity of 64% to 82% higher than untreated soil (10). Adding nano-silica fume to the soil results in a substantial decrease in compressibility by around 45-50%. Furthermore, treating the soil with nano-silica fume increases its shear characteristics (11). According to (12), incorporating hydrated lime altered the swelling characteristics of the clayey soil. According to (13), the pressure and potential of soil swelling can be reduced by incorporating cement dust at concentrations of 4, 8, 12, 16, and 20%. According to (14), adding polypropylene fibre (PPF) to the soil at rates of 0.5%, 1.0%, and 2% by dry soil weight is beneficial for lowering soil volume expansion. According to (15), methacholine is one of the pozzolanic compounds that improves the properties of the soil by reducing the amount of swelling in the soil. It has been shown that burying a geogrid (or geogrid) is a successful method of treating soil swelling (16) and (17). Utilizing micropiles in soil reinforcement enhanced the bearing capacity of costly soil and mitigated swelling pressure (18). Hence, the study aims to determine the strength characteristics of expansive soil stabilized using dune sand and sodium silicate and compare these findings with prior research.

2. MATERIALS AND METHODS

In the experiments, the materials utilized included bentonite, which served as a swelling soil; dune sand; sodium silicate, added to the bentonite to reduce its swelling; and distilled water—utilizing dune sand as a cost-effective substance for stabilizing expansive soils. The Fallujah Cement Plant was responsible for producing a calcium bentonite variety, which served as the bentonite's source. Tables 1, 2, and 3 detail the mineral composition of bentonite, the outcomes of various chemical tests and the X-ray diffraction analysis performed on the material. The proportion of the mineral montmorillonite contained in bentonite can be utilized to make educated guesses about how much it will swell. A high proportion of montmorillonite is found in bentonite, and the presence of this mineral is interpreted as an indication of a high swelling capacity (5).

Table 1 Bentonite Mineralogical Composition.

Comp	SiO2	Fe2O3	Al2O3	CaO	MgO	Na2O	K2O	TiO2	L.O.I
%	51.92	5.45	14.23	8.24	2.86	0.96	0.69	0.8	10-11

Tested by the Geological Survey and Mining Company, Baghdad-Iraq.

Table 2 Bentonite Chemical Properties.

Components	PH	SO3 %	Gypsum %	T.S.S %	O.M %
value	7.7	1.3	2.64	5.25	0.7

Tested by the Sanitary Laboratory of the College of Engineering at Baghdad University.

Table 3 X-Ray Diffraction of Bentonite.

	Minerals	Percentage
Non-clay minerals	Quartz	16
	Calcite	6
	Feldspar	6
Clay minerals	Montmorillonite	68
	Palygorskite	4

Tested by Geological Survey and Mining Company.

The dune sand utilized for this research was acquired from the Al-Shinafiya desert, 45 kilometres west of Al-Diwaniyah city and 238 kilometres southeast of the Baghdad Governorate. Tables 4 and 5 demonstrate the dune sand's distinct physical and chemical characteristics. The term "non-swelling soil" might be applied to dune sand.

Table 4 Dune Sand Mineralogical Composition.

Components	SiO2	Fe2O3	Al2O3	MgO	CaO	Alkalis (Na2O+k2O)
%	55.55	0.08	0.5	3.9	11.25	1.73

Tested by the Geological Survey and Mining Company, Baghdad-Iraq.

Table 5 Dune Sand Chemical Tests.

Components	PH	SO3 %	Gypsum %	T.S.S %	O.M %
value	7.06	1.33	2.86	0.7	1.3

Tested by the Sanitary Laboratory of the College of Engineering at Baghdad University.

In this particular work, liquid sodium silicate was utilized. Table 6 outlines the many functional attributes of sodium silicate for your perusal. When applied to swelling soil, a high percentage of silica enhances the soil's behaviour (19).

Table 6 Sodium Silicate Chemical Components.

Comp.	SiO2	Fe2O3	Al2O3	CaO	MgO	SO3	TiO2	Na2O	K2O	L.O.I
%	87.67	0.298	0.40	1.40	0.37	1.54	0.031	1.15	3.84	3.30

Tested by the laboratory of the College of Science at Baghdad University.

Table 7 summarizes the physical qualities, tests, and evaluations that can be carried out on the generated models, as well as the standard specifications. Figure 1 illustrates the particle size distribution of the soil utilized.

The appropriate amounts of each component are to be mixed, as shown in Table 8, to prepare the samples for testing. The variation in mixing ratios results in varying degrees of soil swelling, which can be used to analyze soil strength behaviour. The findings of sample number one serve as a benchmark against which the findings of the other samples can be evaluated.

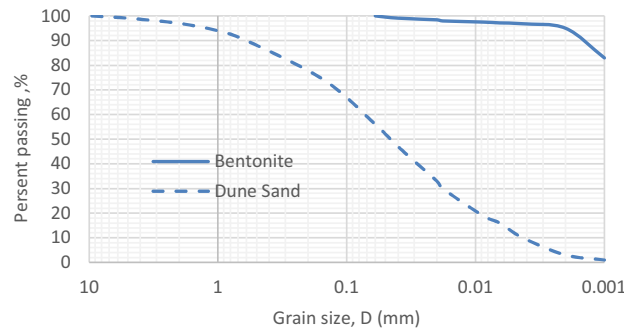


Figure 1: Particle size distribution curves of the soil

Table 7, Physical Properties of the Material Used.

Physical properties	Index properties	Bentonite	Dune Sand	specification
Atterberg limits	Liquid limit, L.L (%)	150	NP	(20)
	Plastic limit, L.L (%)	45	NP	
	Plasticity index, P.I (%)	105	NP	
Grain size analysis	% sand (0.06-2)mm	0	97	(21)
	% silt (0.002-0.06)mm	5		
	% clay (<0.002)mm	95	3	
Specific gravity, Gs	-	2.89	2.63	(22)
Compaction test	Max dry density,(KN/m³)	12.64	15.15	(23)
	Optimum moisture content,%	37	12.5	
USCS	Unified Soil Classification System	CH	SP	(24)

Tested by the laboratory of the College of Science at Baghdad University.

Table 8 Implementation of the Replacement Method for Analysing Specimens.

Soil Sample No.	Bentonite, %	Dune Sand, %	Sodium Silicate, %
1	85	15	0
2	82	14	4
3	80	14	6
4	78	13	9
5	76	13	11
6	74	12	14
7	72	12	16
8	70	11	19
9	68	11	21

3. RESULTS AND DISCUSSION

3.1 Evaluating the Swelling Properties in Soils:

3.1.1 Indirect Methods of Evaluating the Swelling Properties in Soils

According to (5), one way to determine a soil's capacity to swell is to use the single index technique, which relies on a particular soil feature. The subsequent analyses will allow you to learn about these characteristics. **1-Colloidal Particle Content:** Colloidal Particle Content: Table 9 displays the percentage of granules with a diameter smaller than 0.001 mm (colloidal particle) for samples determined through grain size distribution analysis using a sieve and a hydrometer. This information was obtained from the samples. It has come to our attention that an increase in the percentage of sodium silicate substitution results in a decrease in the rate of colloidal particles; the same thing changed with (15) while making swelling soils better with Me-takaolin. One of the markers that may be used to estimate the capacity of soil to expand is the proportion of colloidal particles in the soil. The ability of soil samples to swell is negatively impacted due to an increase in the percentage of sodium silicate substitution.

Table 9 Colloidal particle content for soil samples.

Soil Sample No.	colloidal content, %
1	70
2	67
3	60
4	53
5	47
6	41
7	35
8	22
9	20

2-Tests using the Atterberg limits: Table 10 presents the results of the Atterberg tests using the samples. Calculating the soil swelling potential (using a sample compacted to the optimal moisture to obtain maximum dry density and then soaked under an additional one-psi load) is possible with Equation 1 for soils with a clay content ranging from 8 to 65%. This calculation also takes into account the plasticity index. The decrease in soil swelling potential coincides with an increased sodium silicate replacement ratio. The plasticity index decreased when (13) Cement Dust was used.

$$S = 60K(PI)^{2.44} \dots\dots\dots [1] \quad (5)$$

Where:

S= Swelling Potential, %

K=constant= 3.6×10⁻⁵

PI= Plasticity Index, %

The extent to which the soil has expanded can also be determined by looking at the values of the liquid limit and the plasticity index, which are presented in Table 10. (25).

Table 10 Atterberg limits Test

Soil Sample No.	Atterberg Limits*			Swelling Potential From eq. 1, %	Degree of Expansion
	LL (%)	PL (%)	PI (%)		
1	112	42	70	-	High
2	110	50	60	-	High
3	102	45	57	42	High
4	98	54	44	22	High
5	85	49	36	14	High
6	78	45	33	11	High-Marginal
7	74	46	28	7	High-Marginal
8	65	41	24	5	High-Marginal
9	62	39	23	5	High-Marginal

* According to(26), the soil's moisture content was evaluated.

3- The Dry Density and the Water Content: The tests conducted are for the Compaction Characteristics, namely the Dry Density (γ_{dry}) and Optimum Moisture Content (O.M.C). The results of these experiments are presented in Table 11. When the effect of soil moisture is considered, a decrease in dry density value typically results in a reduction in the number of materials capable of experiencing an increase in volume per unit volume (27). In general, the effect of the various proportions is seen in the fluctuation in the value of the (γ_{dry}) and the optimal

moisture content for bentonite. Both of these metrics are affected by the varied proportions. Different numbers for the (O.M.C) and (γ_{dry}) were found when (10) and (11) used materials to improve the behaviour of swollen soils.

Table 11 Characteristics of Compaction Obtained from a Compaction Test

Soil Sample No.	O.M.C % *	γ_{dry} max. KN/m3
1	36	13.20
2	35	13.50
3	36	13.18
4	39	12.39
5	35	12.50
6	41	12.10
7	31	13.80
8	30	13.63
9	40	12.47

*The moisture content of the soil was tested based on(26)

3.1.2 direct measurement of Evaluating the Swelling Properties in Soils:

According to (5), utilising a traditional one-dimensional consolidometer as a direct technique for analysing a soil's swelling potential and swelling pressure is a good approach. This method incorporates both a free swelling test and a constant volume test (28). The swell-consolidation method is the name of the free swelling test. The results of the tests are presented in Table 12 and Figure 1, respectively. We note that for the identical samples in terms of replacement ratios, the swelling pressure findings reported using the constant volume method were lower than those discovered using the free swelling method, and this is well-known (29).

Table 12 The Free Swell and Constant Volume Test for Soils, in addition to the Factor of Reduction.

Soil Samples	Free Swell Test ¹			Constant Volume Test ²	
	Free Swell, %	Swelling pressure, kPa	Reduction in the Swelling Potential, %	Swelling Pressure, KPa	Reduction in the Swelling Pressure, %
1	83	882	0	588	0
2	34	638	59	425	28
3	32	488	61	325	45
4	20	195	76	130	78
5	18	188	78	125	79
6	9	120	89	80	86
7	8	113	90	75	87
8	7	113	92	75	87
9	5	38	94	25	96
1 (30), 2 (31)					

Based on the findings of the swelling pressure test, which are displayed in Figure 2, it can be deduced that the sodium silicate material with dunes helped to lower the swelling pressure. Even while there was a general trend towards less dune substitution in the samples, the sodium silicate proportion rose. At the same time, the percentage of dune replacement fell. (10) also came to the same conclusion: expansive soil that was stabilized with different amounts of lime, cement, and silica fume had 65% less accessible swelling and 76% less swelling pressure than soil that wasn't treated.

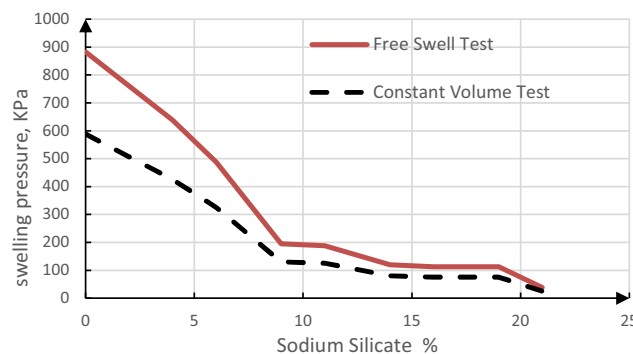


Figure 2: The effect of varying percentages of replacement material on the swelling pressure

3.2 Mechanical tests

These tests (consolidation tests and shear tests), whose goal is to determine if the replacement process has any adverse effect on the models in terms of engineering properties, are crucial because the enhancement of a given soil is linked to the absence of any detrimental impact on its engineering properties.

3.2.1 Consolidation tests

The maximum dry density values and the optimal moisture content in preparing the Consolidation test samples were used to determine the consolidation characteristics of the prepared soil samples. Table 13 compiles the findings of various consolidation experiments. The values of the swelling indicators cannot be related to the information gained from the Consolidation coefficients test. The addition rates did not significantly impact C_c and C_s levels. Therefore, the soil's properties can be improved this way, making the replacement process more likely to succeed. (15) found that when Metakaolin is used with expanding soil, the values of the compression index go up, and the void ratio goes down in a straight line.

Table 13 Summary of Consolidation Tests (32)

Soil Samples	Specific Gravity (Gs)	e_0	C_c	C_s	mv m ² /MN	C_v m ² /year	$K \times 10^{-8}$ m/sec
1	2.78	1.106	0.29	0.032	0.203	1.616	0.004
2	2.78	1.059	0.27	0.026	0.225	1.239	0.009
3	2.78	1.110	0.26	0.028	0.219	1.622	0.014
4	2.77	1.239	0.29	0.028	0.160	1.315	0.017
5	2.76	1.226	0.21	0.025	0.360	2.075	0.036
6	2.66	1.198	0.26	0.024	0.185	3.669	0.036
7	2.72	1.014	0.24	0.026	0.235	3.941	0.029
8	2.56	1.046	0.27	0.027	0.346	1.675	0.032
9	2.63	1.158	0.27	0.028	0.273	2.910	0.025

Changes in the C_c and C_s values as a function of the substitution ratio for sodium silicate are depicted in Figure 3. The highest C_c number we observed was 11%, whereas the C_s value dropped due to substitution.

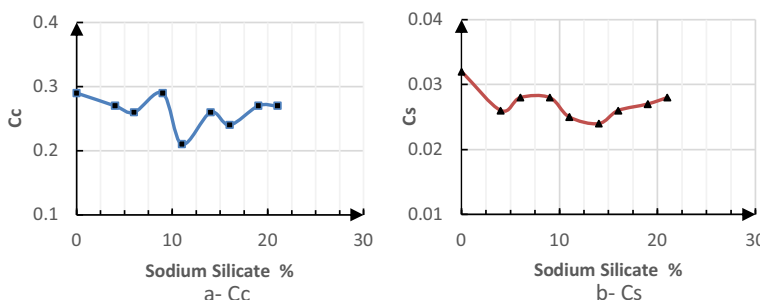


Figure 3: Effect of Different Replacement Material Percentages on the C_c , and C_s

3.2.2 Unconfined Compression Test, and Triaxial Compression Test UU (Unconsolidated-undrained test)

Unconfined compression and UU triaxial compression experiments were conducted using the soil samples' optimal moisture content and maximum dry density values. Table 14 displays the test results. It should be observed that the values (C and Φ) were changed by the replacement rates, although not in a detrimental way. It should be noted that the soil shear parameters could not be correlated with the soil's ability to swell. The results show that using replacement materials has significantly enhanced the soil quality. Unconfined compressive strength was substantially boosted by using high silica soil stabilisers (33).

Figure 4 depicts the variation in C_u (Undrained Shear Strength) values between the Unconfined Compression (UC) and Triaxial Compression (UU) tests. The sodium silicate replacement ratio and C_u value could be better correlated. Still, when we trace a new course for each curve, they meet with a suitable substitution ratio of nearly 9%. This observation can be linked with what was obtained from the study of the effect of replacement ratio on the swelling pressure values referred to in paragraph 3.1.2.

Figure 5 also displays the data for the sodium silicate replacement ratio and the angle of internal friction (Φ). The more significant value of the 11% replacement ratio is consistent with this relationship.

This study examined the enhancement of (C_u) and (Φ), as opposed to the studies conducted by (12) and, (13) which focused on the strength behaviour of the treated samples.

Table 14 Summary of Unconfined Compression, and Triaxial Compression (UU) test

Soil Sample No.	Unconfined Compression Test ¹		Triaxial compression (UU) test ²			
	Undrained Shear Strength, Cu kN/m ²	Increase in Cu, %	Cohesion Cu, kN/m ²	Increase in Cu, %	the angle of internal friction Φ_u , degree	Increase in Φ_u , %
1	95	0	110	0	10	0
2	-	-	261	137	28	180
3	147	55	-	-	-	-
4	247	160	-	-	-	-
5	-	-	181	65	41	310
6	216	127	-	-	-	-
7	-	-	250	127	18	80
8	-	-	195	77	26	160
9	-	-	147	34	31	210

¹ (34), ² (35)

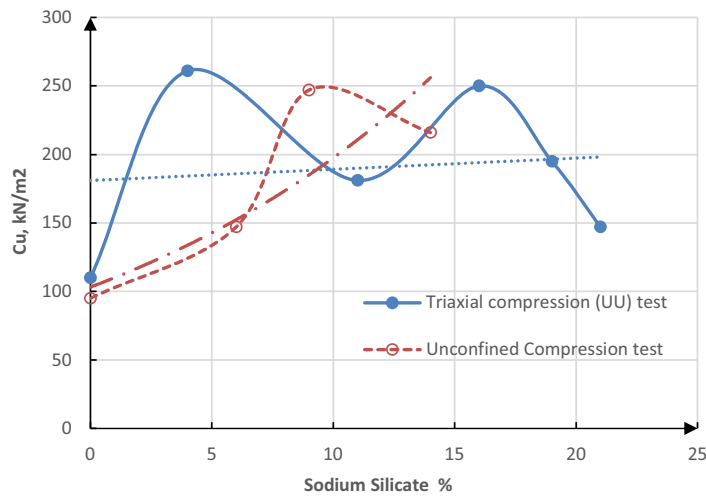


Figure 4: Comparison of Unconfined Compression (UC) and Triaxial Compression (UU) Test Results on Soil Cohesion at Varying Replacement Ratios

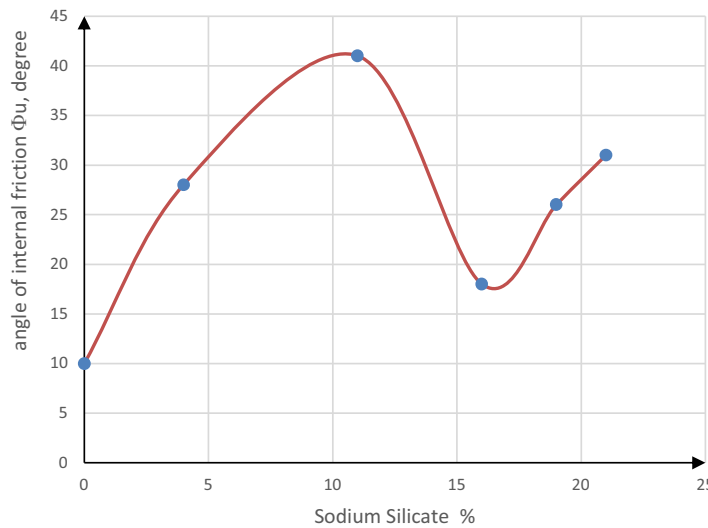


Figure 5: Analysis of the Internal Friction Angle of Soil Subjected to Triaxial Compression (UU) with Varying Replacement Material Contents

4 CONCLUSION

Results from physical and engineering property testing conducted on samples allow for the drawing of crucial conclusions:

- 1- Dune sand and sodium silicate are suggested as soil amendments because dune sand can make it easier for sodium silicate to mix with the soil.
- 2- The sodium silicate substitution approach alters the grain structure, Atterberg limits, maximum dry density unit, and optimum moisture content of soil sample 1.
- 3- The high values of the Atterberg limits that give the soil high swelling qualities were significantly lowered by adding Dune sand and sodium silicate.
- 4- Tests measuring free swelling and constant volume directly proved that soils with higher adding rates had less swelling capacity. With a replacement rate of 10 %, the reduction in soil swellability has become perfect.
- 5- The unconfined and triaxial compression UU tests showed that the C_u values and internal friction (Φ) improved significantly with the sodium silicate replacement process. The optimal sodium silicate addition rate is 10%.
- 6- The consolidation test coefficients (C_c and C_s) also have not changed negatively.

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