Experimental evaluation of the behavior of Sandy Soil–Cement Mixture

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Abstract.- There are various methods for correcting the technical specifications of problematic soils. One of the techniques for improving sandy soils is cement stabilization. Cement stabilization leads to reactions that improve the primary properties of sandy soil. In this study, sandy soil is consolidated with different percentages of cement (0, 3, 6, 9) %, simulated under experimental conditions, and imposed under compression tests such as CBR, direct shear and uniaxial compressions after treatment. Finally, sandy soil behavior is compared with that of the non-cement samples. The test results indicate that cement stabilization significantly increases the CBR strength. Adding 3% of cement to soil greatly increases the soil shear strength parameters.The addition of 9% cement to soil during curing has the greatest effect on the correction of sandy soil properties. In addition to improving the compressive and shear strength of the samples, it also increases the plasticity of the samples, making them more resistant to moisture.

Keywords: mixture of soil-cement; shear strength parameters; CBR tests; uniaxial compression test.

Evaluación experimental del comportamiento de mezclas suelo arenoso–cemento

Resumen.- Existen varios métodos para corregir las especificaciones técnicas de los suelos problemáticos. Una de las técnicas para mejorar los suelos arenosos es la estabilización del cemento. La estabilización del cemento conduce a reacciones que mejoran las propiedades primarias del suelo arenoso. En este estudio, el suelo arenoso se consolida con diferentes porcentajes de cemento (0, 3, 6, 9) %, simulados en condiciones experimentales e impuestos bajo pruebas de compresión como CBR, cizallamiento directo y compresiones uniaxiales después del tratamiento. Finalmente, el comportamiento del suelo arenoso se compara con el de las muestras sin cemento. Los resultados de la prueba indican que la estabilización del cemento aumenta significativamente la resistencia de la CBR. Agregar 3 % de cemento al suelo aumenta en gran medida los parámetros de resistencia al corte del suelo. La adición de 9 % de cemento al suelo durante el curado tiene el mayor efecto en la corrección de las propiedades del suelo arenoso. Además de mejorar la compresión y la resistencia al corte de las muestras, también aumenta la plasticidad de las mismas, haciéndolas más resistentes a la humedad.

Palabras clave: mezcla suelo–cemento; parámetros de resistencia al corte; pruebas CBR; prueba de compresión uniaxial.

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1. Introduction

Soils strengthened with grains by natural or artificial processes are referred to as cement soil. Sandy soils are found in many parts of the world. One of the characteristics of these soils is their sustainability in natural steep slopes. Considering that many buildings across the world are built on 60 degree-angled steep slopes that measure 100 meters in height, it is essential to investigate the stability of these slopes. While gravity or other forces, such as earthquakes lead to slope failure, long-term stability of slopes is mainly due to the adhesion components of cementation. The persistence of steep slopes and the stability of large chips in the construction site of urban and road projects in these types of soils can not be altered by a sole reliance on the basic principles of geotechnical engineering; rather, attention to the effects of cementation is also very necessary. Cementation or the bond among grains in granular soils is produced by a small amount of cement-base materials such as silicates, iron hydroxide

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and carbonates. The spread of artificial and calculated cementation applications for correcting and improving the geotechnical characteristics of granular soils in the recent years is mainly due to recent developments in understanding the properties of natural cementitious soils and the creation of poor bonds among soil grains by the cementation phenomenon. Cementitious soils are seen in vast parts of the world. Environmental conditions, soil texture and particle genre are the most important factors in soil cementation. Typically, cementitious soils are produced by processes such as:

- deposition of carbonate, hydroxides, and organic materials,
- deposition of silica at the contact point of particles due to resolution and redeposition,
- cold welding at the contact point of particles due to high pressures,
- particle growth due to the chemical alteration of some minerals.

The effect of cementation on the behavior of granular soils: Most previous studies have suggested that the addition of cement to granular soil increases the soil's strength and, at the same time, makes its behavior more brittle. According to the Mohr–Coulomb Theory, the shear strength of a soil is a function of its adhesion and friction angle, as seen in following relation:

$$\tau = C + \sigma \tan(\phi)$$

where, C is the amount of adhesion, σ is the effective stress, and ϕ is the friction angle. While soil cementation is reported to increase soil adhesion, most studies have not reported a significant change in the friction angle of soil. Cloufh [1] studied the failure envelope of cementitious and non-cementitious soil and found the results to be parallel. Lade [2] found the failure envelope of cementitious soil to be curvaceous. By emphasizing the behavior friability of cementitious soil, Cloufh [1] showed that the peak strength of these soils occurs at low strains. Evidently, cementitious soil has more elastic hardness than non-cementitious soil. Leroueil [3] declared the occurrence of the yield point as a hallmark of cementitious soils. Failure of cementitious soils is visible in different loading states, such as isotropic pressure, shear and loading. It is very rare for cement bands among the grains to be reduced and destroyed after the yield point. It should also be noted that increasing the pressure of all-round diversion reduces the effect of cementation and, instead shifts the behavior from friability to a more soft and transformable one. Huang [4] showed that the failure level for cementitious soil is increased by increasing the content and cement percentage. Therefore, it is possible to achieve higher levels of stress in cementitious soil. This paper aims to further investigate the experimental study of cement-soil mixture behavior.

2. Literature review

Hamidi [5] used gypseous, calcareous and Portland cements to study the effects they have on the behavior of coarse grained soil. The results of the experiments showed that cementation increases the brittleness of the samples; for example, samples with gypseous cement were found to be more brittle than others, samples containing gypseous cement had the highest degree of strain to failure, and samples containing calcareous cement showed the lowest degree of strain to failure.

The results showed that samples containing gypseous cement had the highest volumetric dispersion rate in the drainage triple axis test. Also, the results of the Brazilian test showed that increasing the cement also increased the tensile strength. The highest tensile strength was first observed in samples containing Portland cement, then in samples containing gypseous cement and finally in samples containing calcareous cement. In the other hand, results of the uniaxial showed that increasing the cement percentage increased the soil compressive strength. Similarly, the highest compressive strength was found in the Portland cement samples and then the gypseous and calcareous samples, respectively.

To evaluate the effect of cement on the mechanical behavior of soil, Hamidi [5] used consolidated drained triple-axis tests that are also used for drainage. Strength variations for saturated gypseous samples showed that water not only strongly weakened the cement bond, but also weakened the cement soil containing gypsum to less than that of the cement soil containing lime.

Hamidi and Hasanzadeh [6] studied the features of compressibility and volume changes of sandy-cementitious soils in terms of one-dimensional triple-axial consolidation conditions. Their experiments showed that the soil relative density, percentage and type of cementation factor strongly affect the properties of cementitious soil volume changes. The results showed that increasing the relative density and cement percentage increases the hardness of the cementitious soil; in other words, the volume modulus and the pressure required to break the bands are increased. Also, increasing the density and cement percentages decreases the soil compressibility. Furthermore, the stress of the bonds in gypsum-cementitious samples was more than cement-cementitious samples. Pantazopoulos [7] implemented the Binder element to examine the dynamic properties of fine-grained material used to form cement in grout-cemented sand and cement-cementitious sand. Their results showed that increasing the circling pressure of the samples increased the initial yang modulus and shear of grout-cementitious sands. The W/C ratio of grout has the strongest effect on the dynamic properties of cementitious sands in terms of cement grain size and cement content. In Japan, Tariq and Maki [8] evaluated the mechanical behavior of samples of cement-consolidated sand by considering the following aspects: compressiveness, compressibility and tensile behavior, elasticity and compression behavior, length of the sample failure area, and relationship between pressure and elasticity of samples made of cementitious sand. The results of the single axial compressive test, Tariq [8] showed that the maximum compressive stress of cementitious sand was independent of the sample size. It was also shown that the amount of compressive failure energy is a constant parameter and is independent of the height to diameter ratio of the samples. Furthermore, the amount of tensile failure energy is negligible due to the absence of coarse grained components. Pakbaz [9] studied the behavior of cementitious soils in mixtures of dry and wet soil and the genus of Portland cement and lime. The results of the experiments showed that the samples with the cement and wet mixture are stronger than the samples with the dry mixture. These results are in contradiction with the results obtained for the soil and lime mixture samples. Pakbaz [9] clarified that the strength of the samples depends on the type and amount of the mixture and processing time.

They obtained the following experimental results:

1. Cementitious samples strengthened with Portland cement using the wet method showed more compressive strength in the unconfined 28-day trial than those strengthened through the dry method. The maximum difference between these methods was about 10 %.
2. The unconfined 28-day compressive strength of the cementitious samples strengthened with lime using the dry method showed slightly to be more than that of the same model through the wet method.
3. The unconfined 28-day compressive strength of the cementitious samples mixed with cement and lime through the dry method was slightly more than that mixed using the wet method.
4. The increase rate of strengthening the cementitious samples through the wet method is 2 to 3 minutes more than the dry method.
5. The increase rate of strengthening the cementitious samples with lime and lime + cement was much lower than samples strengthened with Portland cement.
6. The amount of the compression index is decreased with increasing the additives for cementation.

Consoli [10] evaluated the influence parameters, such as the amount of cement, porosity and ratio of porosity to cement in order to investigate the failure level of the Mohr–Coulomb theory of artificially cementitious sands focused on tensile strength and unconfined compressive strength. Based on the concepts already proven by [10], the relationship between the ratio of tensile strength to the unpressurized compressive strength for each cementitious sandy soil remains at a constant value; therefore, the effective angle of the shear strength of a sandy soil is independent of porosity, and the amount of cement and effective adhesion is directly dependent on the unconfined compressive strength of refined grained material. This concept has been successfully tested for fine-grained sand containing Portland cement with low, medium and high amounts. Obermayr [11] developed a distinct elemental method for the numerical solution of cementitious sands. The results of triaxial compressive tests on artificially cementitious sandy soils have been previously investigated, confirming that the model can obtain the macroscopic behaviors of such materials. As previously mentioned, strength and stiffness of the Thierry element are the parameters of the defined model, and a reverse calibration method is necessary to find model parameters in cementitious sandy soils. A three-axis compressive test can be, therefore, used for this purpose, and local parameters are determined differently by trial and error tests. The application of a three axial compressive test in cementitious sands shows that:

1. Cement bands add extra shear strength to the materials.
2. Expansion is satisfactory if some bonds remain unchanged and constant during the shear period.
3. The compressive strength factor will control the impact of the circling pressure (confining) on the strength envelope.
4. The model will be able to reproduce the strain-tension curve of laboratory tests with varying degrees of cement content.
5. Both the properties of the connection element and the number of primary bonds strongly impact the results.

Maghous and Consoli [12] evaluated the mechanical behavior of sandy soils (Osorio) that were artificially cementitious by laboratory features and micromechanical basic models. Their results indicated that researchers studied artificially cementitious soils from two important aspects: a) predictions of effective elastic hardness of artificially cementitious sand in the micromechanical plan framework and b) the linear homogenization of samples. Zhang [13] conducted a series of experiments to show that the maximum normal forces in tension and pressure tests are the same in size as the cement particles, while the maximum shear or torsional forces in a complex loading test, such as shear compressive tests, torsional compressive tests, and torsional-shear-compressive tests are related to the normal force and cement particle size.

Li [14] conducted laboratory studies on artificially cementitious sands with different percentages of Portland cement (1, 3, 5 and 8) %. They concluded that the percentage of the cementation factor (Cv) has a significant effect on the mechanical and physical behavior of sands. When the cement percentage (Cv) is at the upper limit (3, 5 and 8) %, the strain-tension curve shows a flexible strain behavior, and when the percentage of the cementation factor is low (1 %), the strain-tension curve shows a hardening strain behavior. Nusit [15] examined the failure behavior and damage to cementitious sandy materials on roads.

Using an unconfined compressive test, was showed that the failure evaluation of samples made from cementitious sands depends on uniform compressive loading tests. Motamed and Latifi [16] found that similar to the behavior of non-cementitious sand, cementitious sandy soils are completely dependent on the initial state of the samples in terms of indices, such as internal friction angle, contraction and expansion behavior. The results also showed the cementitious sands to have contraction behavior with the positive state parameter and expansion behavior with the negative state parameter.

Mackevicius [17] investigated the effect of calcite particles on the mechanical properties of cementitious sandy soils with grout and showed that the addition of calcite particles to cementitious sand reduces the compressive strength (dense strength) of cementitious sandy soil samples with grout three months after cementation. Ho [18] studied the effects carbonates, water percentages and reaction of pozzolans under dry mixture conditions have on improving the strength of consolidated soils with cement and showed that cement hydration, pozzolan reactions in the mixture soil, carbonation and water percentage all significantly improve the strength of cementitious soil.

While the compressive behavior of soil materials has always been an important topic for geotechnical engineers, many aspects regarding the effect of cement percentage and density on the contact between particles during isotropic pressure have not been properly examined. A comparison of non-cementitious and cementitious sandy soils in terms of the effects of cement percentage, dry density and porosity ratio can provide a reasonable framework for better understanding cementitious materials with special rates of cement percentage and circling pressure. Dehnavi [19] investigated the monotonic behaviour of marine calcareous sand obtained from northern coastal of Hormuz Strait at Persian Gulf.

The results of isotropic compression tests showed that, at imposed stress, the crushing of soil particles due to confining pressure is considerable.The unique behaviour of carbonate sediments under shear loading has stimulated in investigating of their geological and engineering properties. Their shapes are very different varying from needle shaped to platy shaped. Hence, it is important to examine their fabric effect on soil response under shearing condition. To this aim a series of small scale laboratory element testing were carried out on North Cornwall Rock" beach sand. Non-cemented and cemented Carbonate sand response under compression and extension loading and different initial density and confining pressure with samples allowed to be drained were investigated and compared. The results show that the sand shear strength under Extension loading is lower than compression regarding to anisotropic fabric due to platy and needle shape of grains. The anisotropy is reduced with increasing the confining pressure and initial relative density with non-cemented sand. Furthermore, present of cement bounds reduces the anisotropy especially in low confining pressures, Salehzadeh [20]. Shahnazari [21] showed a series of undrained monotonic and cyclic simple shear tests was performed on saturated Hormuz calcareous sand specimens using hollow cylinder torsional apparatus.The tests were carried out on specimens with various relative densities under different effective consolidation stresses. Based on the results, pore pressure generation, shear strain development, stress–strain characteristics of the specimens are presented and compared with the technical literature. In addition, dissipation of strain-based energy during the cyclic loading and its relation to excess pore water pressure is described. The cyclic resistance curves of specimens with different initial conditions are plotted. Also the results of monotonic and cyclic tests are compared together for better interpretation of Hormuz calcareous sand under undrained torsional loading. Baziar [22] investigated on the effect of silt content on excess pore water pressure generation in silty sands.they showed that The increase in the silt content percent passing the No.200 sieve) caused an increase in the liquefaction resistance of silty sands and also, increasing the percentage of silt content, volumetric strain rate increases at constant relative density. This rate increased with increasing percentage of silt content. On the other hand, such increase in the rate for clean sand is less than that of silty sand.

3. Material description, sample preparation and procedures

To perform the laboratory research, it was necessary to use tools that could allow the model created in the lab to match well with the actual model.

3.1. Materials

Specifications of the sand and cement used in this research are listed below.

3.1.1. Soil used

The soil used in this study has a uniform grain size. The geotechnical specifications and parameters of the soil used in the laboratory are in accordance with the ASTM standards, and the results are summarized in Table 1.

Table 1: Geotechnical parameters of the used soil.

Gs	CBR	Opt ω	γd(max) [g/cm^3]	C [kg/cm^2]	ϕ
2,63	24,29	5%	1,81	0,016	44°

It should be noted that the soil used in this test is obtained from the city of Noshahr, Iran.

3.1.2. *Cement*

Type 2 cement was used in this study.

3.2. *Preparation and processing of samples*

Samples were prepared in the following three stages.

a) Soil preparation.
   The soil used for the tests was carefully observed and had almost uniform grains.
b) Sample preparation.
   In the CBR test, a mixture of soil and cement was poured in three layers in the mold, and each layer was crushed 56 times by a hammer weighing 5,4 kg and from a height of 30 cm. In direct shear tests, once the mixture was poured in three layers in the mold, the cementitious soil mixture was condensed with a special tool.
c) Time process.
   The test molds were kept and processed in a heater at 65 °C for 48 hours. This was mainly done for two reasons: The cement used gains strength only by losing moisture, and losing moisture accelerates this process. The temperature and humidity conditions of the environment vary on different days, while the conditions provided for all samples in the oven are the same.

3.3. *Experimental program*

The testing process of this study is described in detail in this section.

3.3.1. *Grading test*

The grading test is established based on the particle size and percentage of different grains in the soil mass and is the simplest experiment on the soil.

3.3.2. *Density test*

The purpose of density is to reduce the soil porosity (empty space) and, thereby, improve the engineering properties of the soil.

3.3.3. *The CBR test*

The CBR test was introduced by Porter in 1926 and was later expanded in 1929 by the Road Administration of California State, USA. The CBR test is the most common method for determining the relative strength of soil for road construction. The results of this experiment can help obtain the freight capacity of the bed soil and all pavement layers, such as the sub-base and base, as well as the thickness of these layers.

The CBR of a soil is the ratio of the force required to dip a piston with a definite figure, velocity, and depth in a tested soil to the force required to dip the same piston with the same speed and depth in the standard material, as seen in the following relationship. The standard materials include a broken stone with a standard load that is in accordance with Table 2, for penetrating the standard piston in it.

Table 2: Standard load values.

Pressure [MPa]	Pressure [kg/cm^2]	Load [kg]	Penetration [mm]
6/9	70	1366	2/5
10/3	105	2039	5
13	133	2572	7/5
16	163	3162	10
18	184	3562	12/7

The CBR is calculated as follows: CBR = (Standard load / load used in the test) × 100

3.3.4. *Direct shear test*

Understanding soil strength is crucial to achieving proper soil sustainability in areas such as foundation designs, barrier walls and dykes.

Measuring and determining the soil strength, of especially sticky soils, is important in soil stability and is among the complex topics of soil mechanics.

3.3.5. Uniaxial compression test

This test is most commonly used to determine the compressive strength and shear strength of soil and is the fastest and easiest test method for determining the shear strength.

4. Results and analysis

4.1. Grading the test results

Sand grading was carried out through the dry method. Figure 1 shows the grading curve.

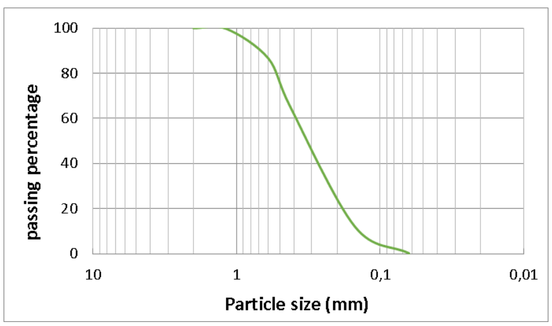

Figure 1: Sand grading curve

4.2. Density experimental results

After conducting the density test for four times, the wet specific gravity and moisture content of each experiment is calculated. The dry specific gravity is then determined using the relationship $\gamma d = \frac{\gamma}{1+\omega}$. The diagram of the dry specific gravity against moisture is drawn for this test. Finally, the maximum dry specific gravity and optimal moisture content are determined from the diagram.

4.2.1. Density test without additives

The Table 3 shows the results of the density test without additives and the Figure 2 shows the soil density curve that is used to determine the maximum dry specific gravity and soil optimum moisture content.

According to the Figure 2, the maximum dry specific gravity is equal to 1,81 g/cm^3, and the optimum moisture content is 5,75 %.

Table 3: Results of the density test without additives.

	Sample			
	1	2	3	4
Mold and soil weights [g]	6125	6185	6200	6255
Soil weight [g]	1750	1810	1825	1880
Wet specific gravity [g/cm^3)]	1,848	1,912	1,927	1,985
Moisture [%]	3,06	5,75	8,83	12,58
Dry specific gravity [g/cm^3]	1,793	1,808	1,770	1,760

Mold weight = 4375 g; Mold bulk = 7,946 kg/cm^2

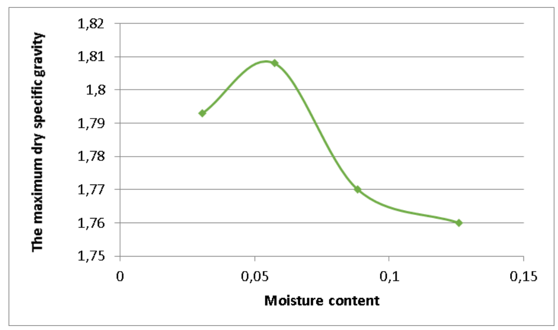

Figure 2: Soil density curve without additives

4.2.2. Density test with 3 % cement

Table 4 shows the results of the density test with 3 % cement. According to Figure 3, the maximum dry specific gravity is equal to 1,85 g/cm^3, and its optimum moisture content is 4,8 %.

Table 4: Results of the density test with 3 % cement.

	Sample			
	1	2	3	4
Mold and soil weights [g]	6145	6210	6270	6315
Soil weight [g]	1770	1835	1895	1940
Wet specific gravity [g/cm^3]	1,87	1,938	1,990	2,049
Moisture [%]	2,7	4,8	8,5	12,1
Dry specific gravity [g/cm^3]	1,82	1,849	1,834	1,827

Mold weight = 4375 g; Mold bulk = 7,946 kg/cm^2

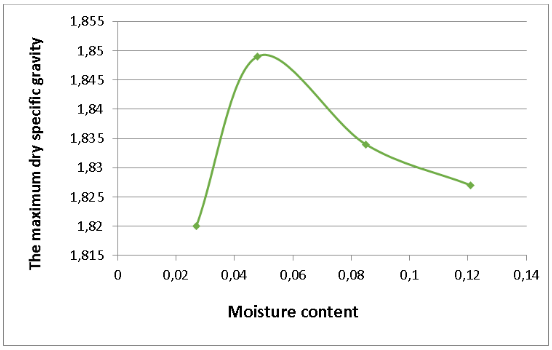

Figure 3: The curve related to the density test with 3 % cement.

4.2.3. *Density test with 6 % cement*

Table 5 shows the information related to the density test with 6 % cement. According to the Figure 4, the maximum dry specific gravity is 1,855 g/cm^3, and its optimal moisture content is 5,4 %.

Table 5: Results of the density test with 6 % cement.

	Sample 1	2	3	4
Mold and soil weights [g]	6138	6215	6265	6320
Soil weight [g]	1763	1840	1890	1945
Wet specific gravity [g/cm^3]	1,863	1,943	1,990	2,050
Moisture [%]	2,1	4,8	7,9	11,1
Dry specific gravity [g/cm^3]	1,825	1,854	1,844	1,833

Mold weight = 4375 g; Mold bulk = 7,946 kg/cm^2

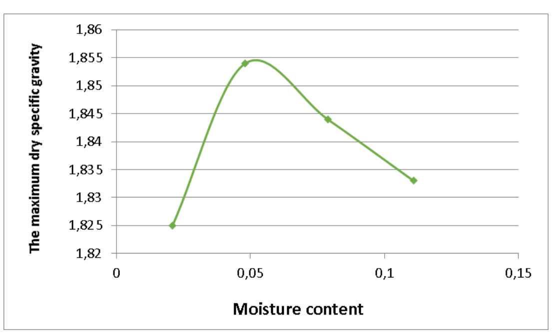

Figure 4: The curve related to the density test with 6 % cement.

4.2.4. *Density test with 9 % cement*

Table 6 shows the information related to the density test with 9 % cement. According to the Figure 5, the maximum dry specific gravity is 1,855 g/cm^3, and the optimum moisture content is 5,8 %.

Table 6: Results of the density test with 9 % cement.

	Sample 1	2	3	4
Mold and soil weights [g]	6165	6212	6265	6300
Soil weight [g]	1,890	1,940	1,990	1,925
Wet specific gravity [g/cm^3]	1,890	1,940	1,990	2,030
Moisture [%]	2,5	4,84	8,1	10,5
Dry specific gravity [g/cm^3]	1,844	1,851	1,849	1,840

Mold weight = 4375 g; Mold bulk = 7,946 kg/cm^2

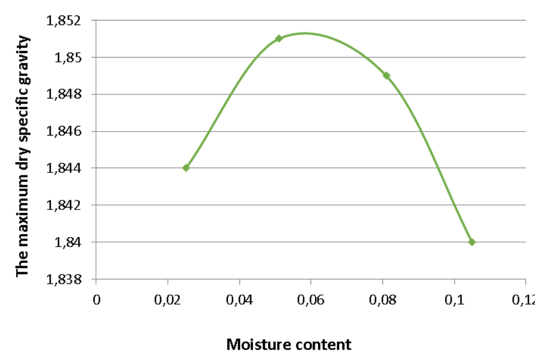

Figure 5: The curve of the density test with 9 % cement.

4.2.5. *Interpreting the results of density tests*

Figure 6 shows the maximum dry specific gravity in terms of cement percentage, and Figure 7 illustrates the optimum moisture content in terms of cement percentage.

The diagram indicates that the addition of cement increases the maximum dry specific gravity, and by increasing the cement, the maximum dry specific gravity is gradually decreased. It should be noted that the addition of cement does not virtually change the optimum moisture.

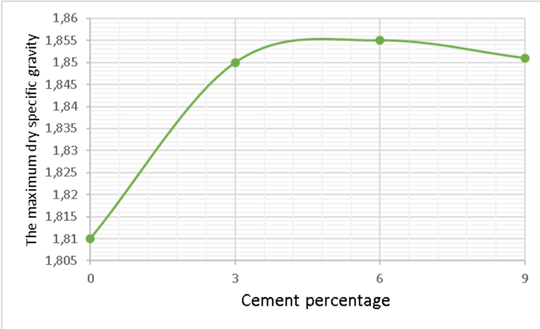

Figure 6: The curve of maximum dry specific gravity variations with different cement values.

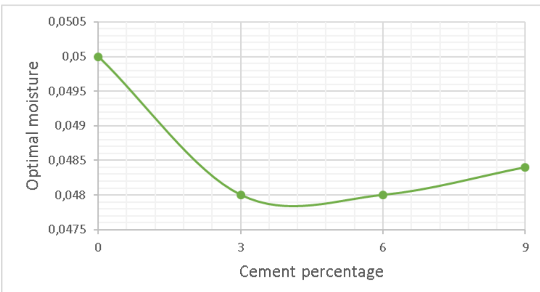

Figure 7: Diagram of the optimal humidity variations with different cement values.

4.3. *Results of the CBR test*

4.3.1. *The CBR test without additives*

The test results for the sand without additives are described in Table 7.

Table 7: Results of the CBR test without additives.

Pressure [kgf/cm^2]	Force [kgf]	Load [Gage]	Penetration [mm]
0	0	0	0
3,4471	66,667	25	0,5
6,8942	133,33	50	1
10,893	210,67	79	1,5
13,788	266,67	100	2
16,546	320	120	2,5
19,028	368	138	3
22,889	422,67	166	4
25,508	493,33	185	5

According to the pressure-penetration diagram, because the curve has no turning point, it is not necessary to reform the diagram.

Calculations

$P_{2,5_{reform}} = ((P_{2,5}=16,546)/70) \cdot 100 = 23,63$

$P_{5_{reform}} = ((P_5=25,508) / 105) \cdot 100 = 29,24$

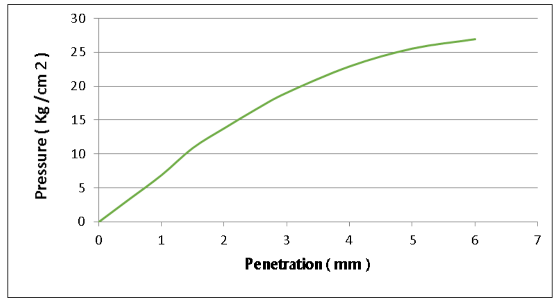

Figure 8: Pressure - penetration diagram for the soil without additives.

Because the second value is greater than the first one, the test should be repeated. Repeating the test and obtaining the same results makes the second number the CBR number. Therefore:
CBR = 29,24

4.3.2. *The CBR test with 3 % cement*

The results of the test for sand with 3 % cement are described in Table 8.

Table 8: Test information related to the CBR test with 3 % cement.

Pressure [kgf/cm^2]	Force [kgf]	Load [Gage]	Penetration [mm]
0	0	0	0
9	173,3	65	0,5
16,7	322,7	121	1
24,1	466,7	175	1,5
40	733,3	290	2
55,2	1066,7	400	2,5
68,9	1333,3	500	3
93,8	1813,3	680	4
106,2	2053,3	770	5
114,4	2213,3	830	6
126,2	2440	915	5,7

According to the pressure - penetration diagram in Fugue 9, the curve should be modified from the turning point. The diagram is modified as Figure 10, and the beginning of the diagram is transferred from 0 to 1. According to the modified diagram, $P_{2,5} = 80$ and $P_5 = 112$, is obtained:

$P_{2,5_{reform}} = ((P_{2,5} = 80)/70) \cdot 100 = 114,28$

$P_{5_{reform}} = ((P_5 = 112)/105) \cdot 100 = 106,67$

According to the calculations:
CBR = 114,28

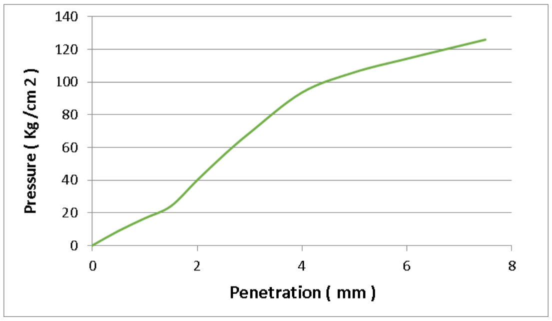

Figure 9: Pressure - penetration diagram for soil with 3 % cement.

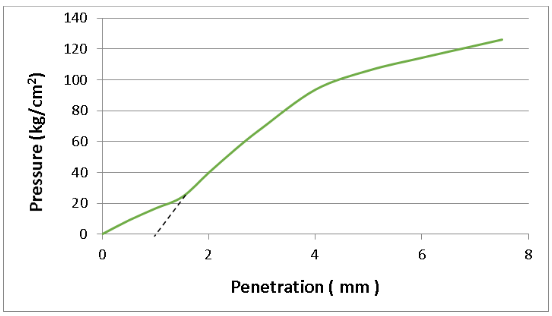

Figure 10: Modified pressure - penetration diagram for soil with 3 % cement.

4.3.3. *The CBR test with 6 % cement*

The test results for sand with 6 % cement are described in Table 9.

Table 9: Results of the CBR test with 6 % cement.

Pressure [kgf/cm^2]	Force [Kgf]	Load [Gage]	Penetration [mm]
0	0	0	0
12,4	240	90	0,5
23,4	453,3	170	1
45,5	880	330	1,5
63,4	1226,7	460	2
81,4	1573,3	590	2,5
94,5	1826,7	685	3
110,3	2133,3	800	4
128,2	2480	930	5
142	2746,7	1030	6
158,6	3066,7	1150	7,5

According to the pressure - penetration diagram in Fugure 11, the curve should be modified from the turning point.

The diagram is modified as Figure 12, and the beginning of the diagram is transferred from 0 to 0,5.

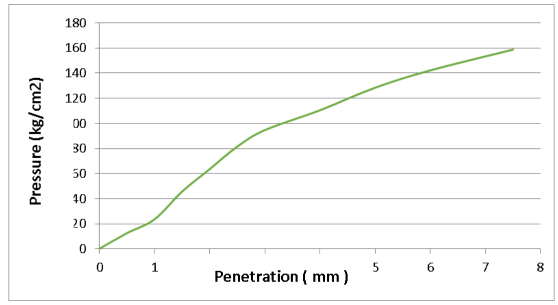

Figure 11: Pressure - penetration diagram for soil with 6 % cement.

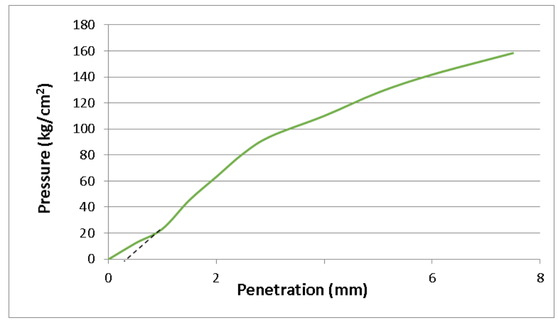

Figure 12: The modified pressure – penetration diagram for soil with 6 % cement.

According to the modified diagram, $P_{2,5} = 94{,}5$ and $P_5 = 135$, is obtained:

$P_{2,5_{reform}} = (P_{2,5} = 94,5 / 70) \cdot 100 = 135$

$P_{5_{reform}} = (P_5 = 135 / 105) \cdot 100 = 128,57$

According to the calculations:

CBR = 135

4.3.4. *The CBR test with 9 % cement*

The test results for sand with 9 % cement are described in Table 10.

Table 10: Results of CBR test with 9 % cement.

Pressure [kgf/cm^2]	Force [kgf]	Load [Gage]	Penetration [mm]
0	0	0	0
15,9	306,7	115	0,5
37,2	720	270	1
57,9	1120	420	1,5
81,4	1573,3	590	2
103,4	2000	750	2,5
120	2320	870	3
139,3	2693,3	1010	4
151,7	2933,3	1100	5
166,1	3213,3	1205	6
179,2	3466,7	1300	7,5

Based on the pressure - penetration diagram in Figure 13, since the curve has no turning point, it is not necessary to correct the diagram, is obtained:

$P_{2,5_{reform}} = ((P_{2,5}=103,4)/70)\cdot 100 = 147,7$

$P_{5_{reform}} = ((P_5=151,7)/105)\cdot 100 = 144,47$

According to the calculations:

CBR = 147,7

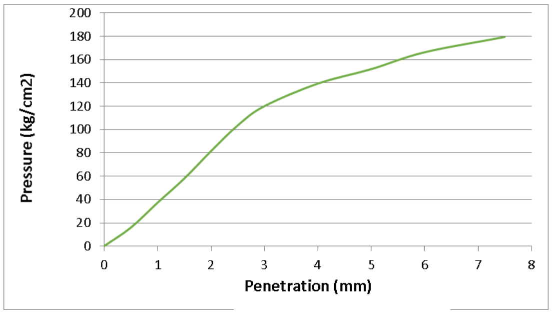

Figure 13: Pressure - penetration diagram for soil with 9 % cement.

4.3.5. *Interpreting the results of the CBR test*

Figure 14 shows the relationship between different percentages of cement and the CBR number.

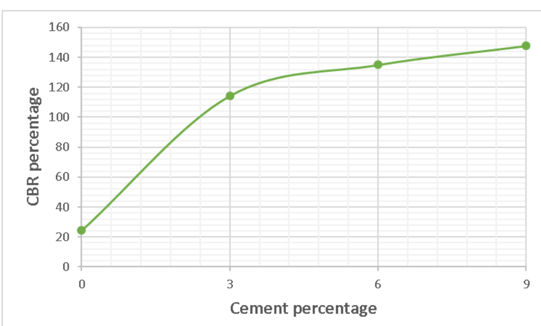

Figure 14: Changes of CBR with different amounts of cement.

Based on the slope of the diagrams and CBR values, it is found that the addition of a minimal amount of cement to the samples (3 %) creates a mutation in the strength of the cementitious samples, but not in that of non-cementitious samples.

4.4. *Results of the direct shear tests*

A direct shear test is performed for each sample under three vertical loads of 20, 40 and 80 kg. The shear stress-vertical stress, internal friction coefficient and soil adhesion are then obtained. As a result, the vertical stress is calculated from the mentioned loads, and the shear stress is calculated using the maximum shear force that is obtained from the test. Figure 15 shows the diagram of the shear stress-vertical stress for the sand without additives.

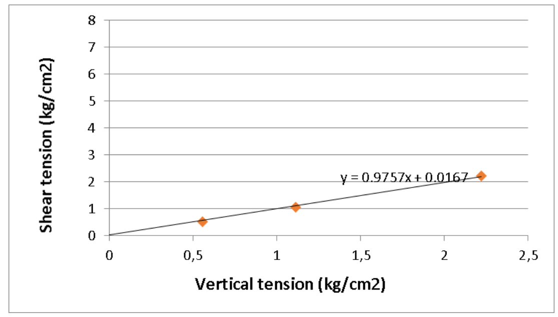

Figure 15: Shear stress- vertical stress diagram for soil without additives.

Figure 16 shows the diagram of the shear stress - vertical stress for the sand with 3 percent cement.

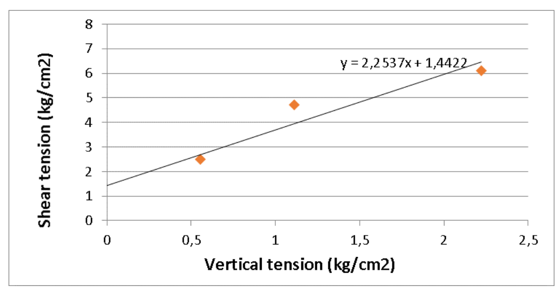

Figure 16: Shear Stress-vertical stress diagram for soil with 3 % cement.

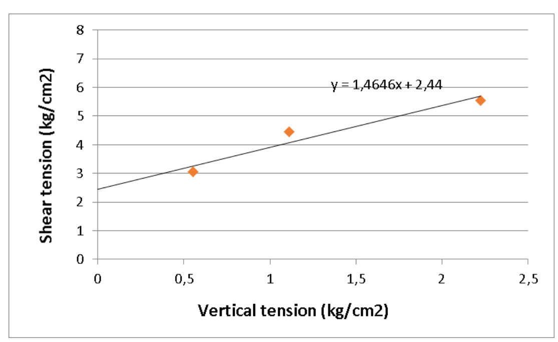

Figure 17: Shear Stress-vertical stress diagram for soil with 6 % cement.

The use of cement alone significantly improves the mechanical properties of the sand. The results of the direct shear test with 6 % cement are as Figure 17.

With 9 % cement, Figure 18 shows the shear stress-vertical stress diagram of this test.

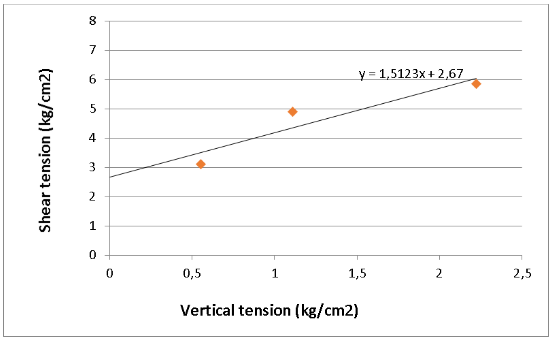

Figure 18: Shear stress - vertical stress diagram for the soil with 9 % cement.

4.4.1. *Interpreting the results of the direct shear test*

Figure 19 shows the changes in the internal friction angle of the soil, and Figure 20 shows the changes of soil adhesion in different proportions of cement mixed with soil.

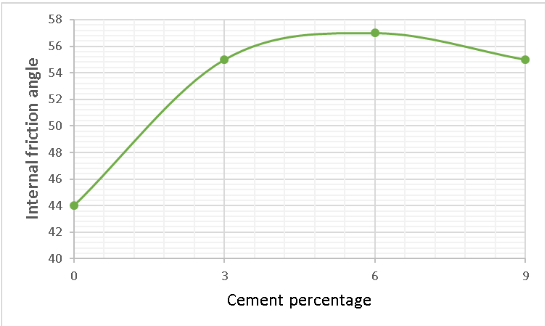

Figure 19: Changes in the internal friction angle of the soil with different cement values.

It can be seen that using a mixture of cement significantly improves the mechanical properties of the sand and increases both the internal friction angle and adhesion of the soil. Using cement both prevents the sudden failure of the soil and considerably increases its adhesion. However, the internal friction angle of the soil is slightly decreased relative to the use of cement alone.

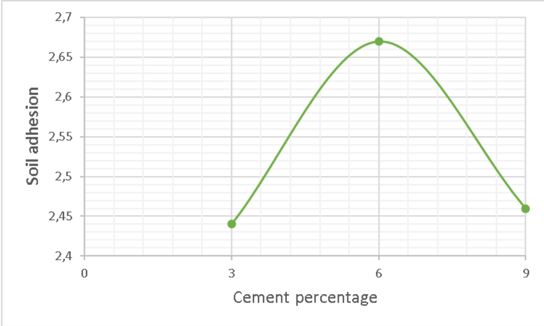

Figure 20: Adhesion changes of the soil with different cement values.

4.5. *Results of the uniaxial test*

The Uniaxial is used for the adhesive soil, because the grainy soil seed can not be in the form of a cylinder without confinement. Because the cement used in the test after mixing it with the sand used in this study makes the soil somewhat sticky, this test can be applied to the mentioned soil. Since, it was not feasible to conduct the test on sand without additives, the test results of cementitious and non-cementitious sand was obtained using the single-axis test, which evaluated the sand with various percentages of cement.

Figure 21 illustrates the axial tension-stress diagram for sand without additives, the maximum compressive strength is 0,29 kg/cm^2, and the maximum shear strength is half of this value and equal to 0,145 kg/cm^2.

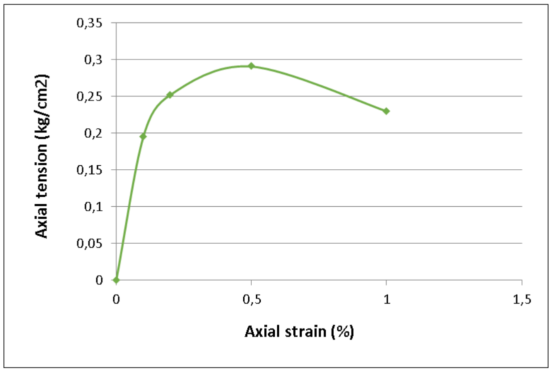

Figure 21: Stress - strain diagram for non-additive sand.

Figure 22 illustrates the axial tension-stress diagram for sand with 3 % cement, the maximum compressive strength is 3,68 kg/cm^2, and the maximum shear strength is half of this value and equal to 1,84 kg/cm^2.

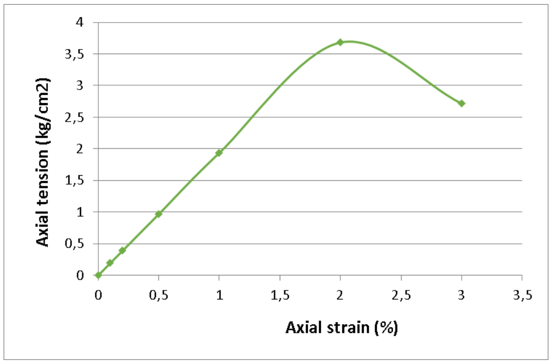

Figure 22: Strain- tension diagram for sand with 3 % cement.

Figure 23 illustrates the axial tension-stress diagram for sand with 6 % cement, the maximum compressive strength to be 10,18 kg/cm^2, and the maximum shear strength to be half of this value and equal to 5,09 kg/cm^2.

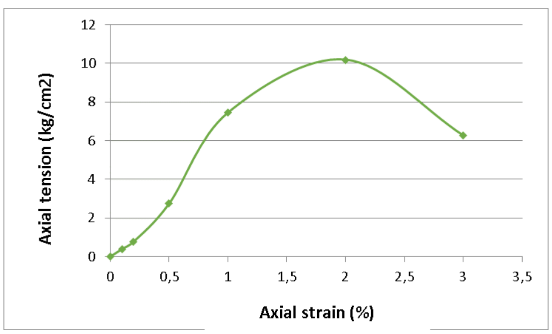

Figure 23: Tension - stress diagram for sand with 6 % cement.

Figure 24 illustrates the axial tension-strain diagram for sand with 9 % cement, the maximum compressive strength is 10 kg/cm^2, and the maximum shear strength is half of this amount and equal to 5 kg/cm^2.

4.5.1. *Interpreting the results of the Uniaxial tests*

Adding cement to sand significantly increases the compressive and shear strength of the soil. Figure 25 shows the diagram of the compressive strength, and Figure 26 shows the diagram of the maximum shear strength of the soil at different

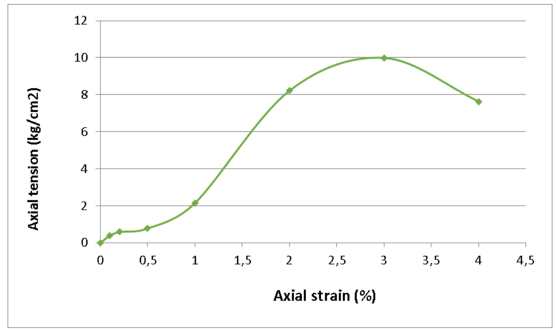

Figure 24: Tension - strain diagram for sand with 9 % cement.

percentages of cement, adding cement to the soil significantly increases the compressive and shear strengths of the soil. This increase has an ascending trend by adding higher levels of cement.

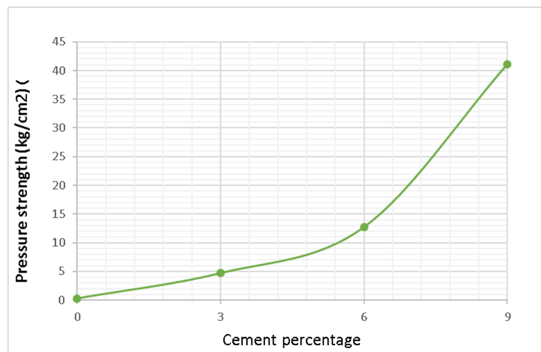

Figure 25: Diagram of soil compressive strength variations in cement percentages.

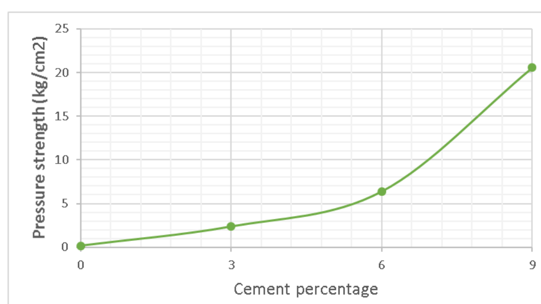

Figure 26: Diagram of the soil shear strength variation in different cement percentages.

According to Figure 27, it can be concluded that adding 3 % cement to the mixture increases the compressive and shear strength. Furthermore, the addition of cement not only increases the strength, but also changes the sample failure state from a sharp failure to a soft one.

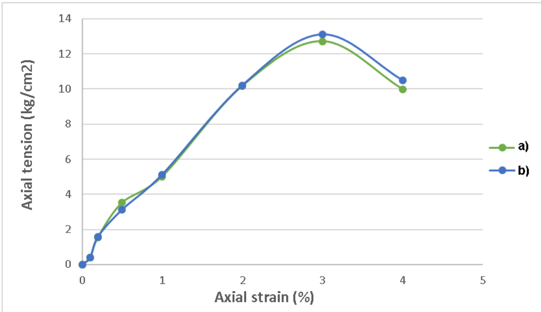

Figure 27: Tension-strain diagram - strain for sand, a) without cement, b) with 3 % cement

In the end, a mixture of 6 and 9 % cement was added to the sand to increase the sample's resistance to moisture and increase its flexibility. The Uniaxial results from this case are presented in the Figures 28 and 29.

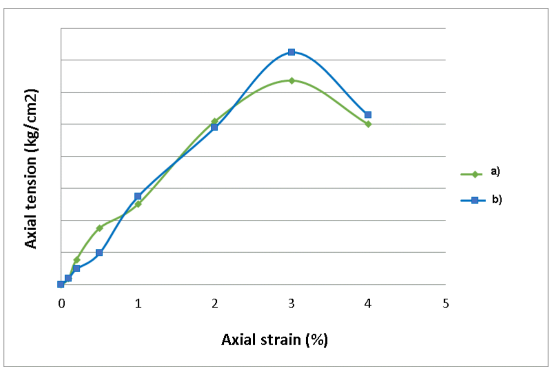

Figure 28: Tension- strain diagram for sand a) without cement, b) with 6 % cement.

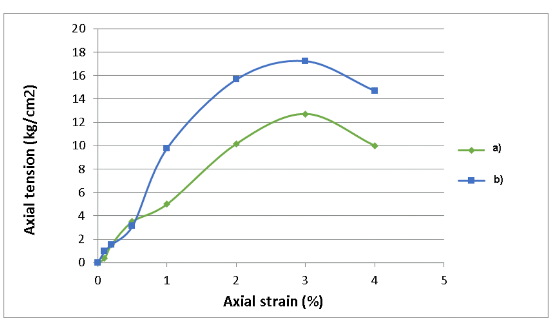

Figure 29: Tension - strain diagram for sand a) without cement, b) with 9 % cement.

According to Figures 28 and 29, it can be concluded that adding a mixture of 9 % cement to the soil has the most contribution on modifying the properties of the sand. As a result, the compressive and shear strengths of the sample are increased, sample plasticity is increased and the simple failure is soft and resistant to moisture.

5. Conclusion

The present study is based on a laboratory analysis to evaluate the effect of cement on improving the mechanical and geotechnical properties of sand. Experiments were conducted to find the optimal amount of cement for improving the CBR, compressive and shear strengths. According to the density results, adding 3 % cement to the soil increases the maximum dry specific gravity and decreases the optimum moisture content. Increasing the cement gradually decreases the maximum dry specific gravity and increases the optimum moisture content. The CBR tests showed that adding cement to the sand significantly increases the CBR strength. The direct shear test results showed that adding 3 % cement increases the shear strength parameters of the soil to a great extent. The single-axis compressive tests showed that the addition of cement improves the shear and compressive strengths of the soil. It was also found that the mixture of 9 % cement with soil has the most effect on the correction of sand characteristics. This is because both the compressive and shear strength of the sample are increased, the sample's flexibility is higher and the sample failure is soft and resistant to moisture.

6. Bibliography

[1] G.W. Clough, N. Sitar, R.C. Bachus, and N.S. Rad. Cemented sands under static loading. *ASCE Journal of Geotechnical Engineering*, 107(6):799–817, 1981.

[2] P.V. Lade and D.D. Overton. Cementation Effects in Frictional Materials. *ASCE Journal of Geotechnical Engineering*, 115(10):1373–1387, 1989.

[3] S. Leroueil and P.R. Vaughan. The general and congruent effects of structure in natural soils and weak rocks. *Geotechnique*, 40(3):467–488, 1990.

[4] J.T. Huang and D.W. Airey. Properties of artificially cemented carbonate sand. *ASCE Journal of geotechnical and geoenviromental engineering*, 124(6):492–499, 1998.

[5] A. Hamidi and S.M. Haeri. Critical state concepts for a cemented gravely sand. *Electronic Journal of Geotechnical Engineering*, 10(E):1–12, 2005.

[6] A. Hamidi and A. Hasanzadeh. Investigating the compressibility and volume change behavior of cemented sands. *Journal of Civil Engineering, Modarres University*, 11(3):15–26, 2010.

[7] I.A. Pantazopoulos and D.K. Atmatzidis. Dynamic properties of microfine cement grouted sands. *Soil Dynamics and Earthquake Engineering*, 42:17–31, 11 2012.

[8] K.A. Tariq and T. Maki. Mechanical behaviour of cement-treated sand. *Construction and Building Materials*, 58:54–63, 2014.

[9] M.S. Pakbaz and M. Farzi. Comparison of the effect of mixing methods (dry vs. wet) on mechanical and hydraulic properties of treated soil with cement or lime. *Applied Clay Science*, 105, 2015.

[10] N.C. Consoli. A method proposed for the assessment of failure envelopes of cemented sandy soils. *Engineering Geology*, 169:61–68, 2014.

[11] M. Obermayr, K. Dressler, C. Vrettos, and P. Eberhard. A bonded-particle model for cemented sand. *Computers and Geotechnics*, 49:299 – 313, 04 2013.

[12] S. Maghous, N. Consoli, A. Fonini, and V. Pasa Dutra. A theoretical–experimental approach to elastic and strength properties of artificially cemented sand. *Computers and Geotechnics*, 62:40–50, 10 2014.

[13] N. Zhang, L. Cui, and S. Jin. A size-dependent bond failure criterion for cemented granules based on experimental studies. *Computers and Geotechnics*, 69, 09 2015.

[14] D. Li and X. Liu. Experimental study on artificial cemented sand prepared with ordinary portland cement with different contents. *Materials*, 8:3960–3974, 07 2015.

[15] K. Nusit and P. Jitsangiam. Damage behavior of cement-treated base material. *Procedia Engineering*, 143:161–169, 12 2016.

[16] M. Motamed and M. Latifi. Experimental study of cement effect on mechanical behavior of treated sands. In *10 th Congress in Civil Engineering*, University of Tabriz. Iran-Tabriz, 2015.

[17] R. Mackevičiusa, D. Sližytėa, and T. Zhilkinab. Influence of calcite particles on mechanical properties of grouted sandy soil. *Procedia Engineering*, 172:681–684, 2017.

[18] L. Ho, K. Nakarai, Y. Ogawa, T. Sasaki, and M. Morioka. Strength development of cement-treated soils: Effects of water content, carbonation, and pozzolanic reaction under drying curing condition. *Construction and Building Materials*, 134:703–712, 03 2017.

[19] Y. Dehnavi, H. Shahnazari, H. Salehzadeh, and R. Rezvani. Compressibility and undrained behavior of hormuz calcareous sand. *Electronic Journal of Geotechnical Engineering*, 15(1):1684–1702, 01 2010.

[20] H. Salehzadeh, M. Hassanlourad, D. Procter, and C. Merrifield. Compression and extension monotonic loading of a carbonate sand. *International Journal of Civil Engineering*, 6(4):266–274, 12 2008.

[21] H. Shahnazari, Y. Jafarian, M. Tutunchian, and R. Rezvani. Undrained cyclic and monotonic behavior of hormuz calcareous sand using hollow cylinder simple shear tests. *International Journal of Civil Engineering*, 14, 06 2016.

[22] M. Baziar, H. Shahnazari, and H. Sharafi. A laboratory study on the pore pressure generation model for firouzkooh silty sands using hollow torsional test. *International Journal of Civil Engineering*, 9:126–134, 06 2011.