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Research Article

Stabilizers Effects Comprehensive Assessment on the Physical and Chemical Properties of Soft Clays

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Deep soil mixing (DSM) is one of the practical methods of soil improvement in the world, which produces cement columns and modification by injecting stabilizing materials such as cement or lime using a mechanically hollow shaft drill in the soil. In this method, the soil characteristics are improved by mixing the soil with cementitious materials by deep mixers and creating cement soil columns. In addition, by overlapping the columns before full setting, continuous walls can be constructed below the ground. The aim of this study was to investigate the effect of the additive type on the strength of the samples. For soil samples stabilized with lime, the maximum value of uniaxial resistance was 247 kPa and for the mixture of 10% lime and 4% sodium silicate was obtained.

1. Introduction

The use of nontoxic additives to the soil and reducing the volume of effluent (spoil) compared to the jet grouting method or the traditional method of in situ piles has strongly introduced the DSM method as an environmentally friendly option [1, 2]. Implementation and quality control of this method is performed using valid regulations such as FHWA or European standard EN14679. Major applications of the deep mixing method include embankment on soft soils, as a support under strip and radius foundations, foundations of bridges and wind turbines, excavation walls using reinforced cement-cement columns, and slope stability, tackle lubrication seal walls, such as cutoff walls, and ultimately prevents the spread of contaminants [2, 3]. In offshore and offshore structures, deep mixing is used to build coastal walls and breakwaters and anchorages. This method is used for the foundation of various structures such as tanks, towers, bridge piers, embankments, basement equipment, retaining structures, and skyscrapers [1].

The purpose of using this method is to control the excavations and to control the pressures in order to prevent the swelling of the foundation and the slipping of the walls [2, 4, 5] Deep mixing is also used to stop leakage in the form of sealing walls in dams, seals, and riverbanks. Two distinct applications of deep mixing are liquefaction reduction and environmental applications to improve contaminated soil. Protective coating in soft clay tunneling, cement restraints in soil stitching, and vibration reduction with wave delay blocks are modern applications of deep mixing technology. In a four-part paper presented in the scientific journal Ground Improvement, the technique of deep mixing has been commented on as a soil remediation technique in which the soil is in situ with cohesive (e.g., cement, lime, fly ash, and the like); chemical or biological substances are mixed in the form of slurry or powder in order to improve the engineering and environmental properties of soft or contaminated soils [1]. Specially designed machines equipped with several mixing shafts and blades and a stabilizing material that stabilizes the soil columns in place through a duct with patterns and specifications will be mentioned later.

The reactions that take place between the soil and the stabilizer increase the resistance and decrease the permeability and decrease the leaching potential of the soil [2]. In situ stabilization, soil and groundwater reclamation is performed in situ without drilling, piling, or dewatering. Recent advances in soil mixing technology include stabilization of contaminated and unused soils, removal of light organic matter with hot air injection, and steam extraction technology [6]. Contaminants are first chemically stabilized and become solid masses. This prevents contamination of contaminated material and at the same time improves the engineering properties of the soil. This technique can be used for organic and inorganic contaminated soils. Since the initial application of this technique, various names have been used for deep mixing technology [4]. So far, with the development of such research, researchers have succeeded in increasing the strength of marine clay soils up to 10 times their initial strength [7]. The first field tests of the deep mixing method were performed by the Mark II machine in Japan, which was only 2 meters high. Also, the first project in which this method was used in practice was Haneda Airport in Japan, where engineers were able to stabilize the seabed to a depth of 10 meters above the water level. It is worth mentioning that in the past, the deep mixing method was known as deep lime mixing due to its common use of lime. In less than 5 years after the deep lime mixing method was introduced, it was used in more than 21 construction sites. Mortar was then substituted with lime to help improve the soil uniformity of the fixed mortar and cement slurry [8]. Peichen in 2021 verified the performance of the self-designed FBG-ESC for direct measurement of effective stress in soft soil, demonstrated the consolidation behavior and creep settlements of singular and double-layer HKMD improved by PVDs and DCM columns, and revealed the load transfer mechanism of soft soil improved by DCM columns [9].

Another study conducted by Bunawan et al. [10] states that limited efforts have been made to investigate and identify the failure behavior of a concrete column group [11]. A proper design of roads and airfield pavements requires an in-depth soil properties evaluation to determine suitability of soil [12]. The main aim of this research is to recommend the optimum specification of the reinforced soil-footing system. A series of geotechnical tests were adopted to measure the properties of the soil profile [13]. Therefore, in their research, an attempt has been made to investigate the bearing capacity of cement floating columns and their failure behavior by a series of experiments of the physical model. In this study, prefabricated cement columns with a diameter of 24 mm with different lengths (50 and 100 mm) under rigid foundation with a width of 80 mm and in a soft clay bed (using the replacement method) were installed. This study also compares the effect of different stability level ratios (17, 26, and 35%) on bearing capacity. Overall, the laboratory results show that the recycling ratio for when the soil bearing capacity is improved compared to conventional soil is in the range of 29 to 79%. In addition, using laboratory results as well as a data set including other related work (55 data in total), this paper presents a bearing capacity prediction model using an adaptive grid-based fuzzy inference system (ANFIS) for cohesive soft soils, which are reinforced with cement columns. The performance of the proposed model (ANFIS) with coefficients of determination of 0.989 and 0.960, respectively, for training and test data shows the appropriate accuracy of the adaptive neural inference fuzzy inference system model.

2. Methodology

In order to investigate the effect of stabilizers on soft clay properties, the soil of the study area was first investigated. The study area is Dolatabad in the city of Yasuj, which is shown in Figure 1.

2.1. Soil Granulation Test. The sieve test can be applied to all organic and inorganic granular materials, including sand, crushed stone, and even clay. The results of the soil granulation test in this study, which was performed according to ASTM-D422 standard, are shown in Figure 2.

2.2. Atterberg Limits Test. The Atterberg boundaries were first proposed by the Swedish chemist Albert Atterberg and then standardized by Arthur Casagrande in a 1932 paper on soil mechanics. Soils intended to support structures, pavements, or other loads must be evaluated by geotechnical engineers to predict their behavior under applied forces and variable moisture conditions. Soil mechanics tests in geotechnical laboratories measure particle size distribution, shear strength, moisture content, and the potential for expansion or shrinkage of cohesive soils. Atterberg limits tests establish moisture contents at which fine-grained clay and silt soils transition between solid, semisolid, plastic, and liquid states. The results of the liquid limit and the plastic limit of the soil tested in this research are shown in Figure 3.

2.3. Direct Shear Test. A direct soil shear test is used to determine the reinforced shear strength of drained soil materials in direct shear. This test is performed by deforming a specimen under strain control conditions or near a single shear plate determined by the configuration and arrangement of the device. Three or more specimens, each under a different normal load, are tested to determine the effects of this load on shear strength and displacement and resistance properties, such as mohair resistance cap. Shear stresses and displacements are unevenly distributed in the sample. To calculate shear strains, it is not possible to define a fixed and appropriate height rate of the sample thickness. Therefore, stress-strain relationships, or any related value, such as modulus, cannot be determined using this experiment. This test can be performed on intact specimens or on specimens with specific gravity and moisture content. The result of the direct shear test of soil tested in this research is shown in Figure 4.

2.4. Consolidation Test. A consolidation test is used to determine the rate and magnitude of soil consolidation when the soil is restrained laterally and loaded axially. The consolidation test is also referred to as the standard oedometer test or the one-dimensional compression test. The results of

Figure 1: The study area near the city of Yasuj.

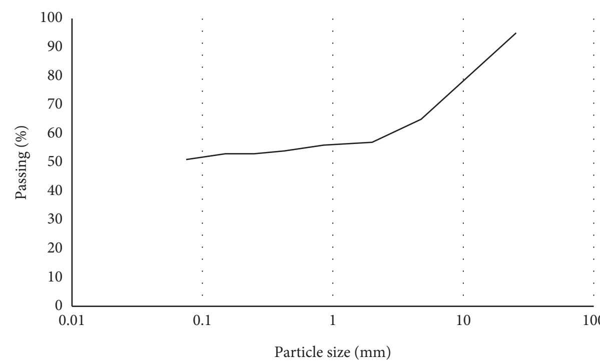


Figure 2: Soil granulation test.

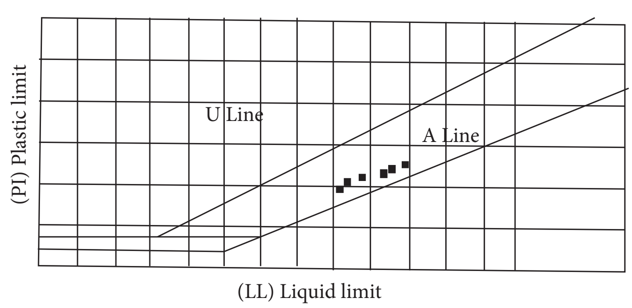


Figure 3: Atterberg result of soil.

the soil consolidation test in this study, which was performed according to the ASTM-D2435 standard, are shown in Figure 5.

2.5. Large-Scale Laboratory Tests of Soil Stabilization. In order to study the materials for the construction of cement columns, large-scale laboratory tests of the soil stabilization scale and the uniaxial pressure test were used. The method of preparation of soil-stabilized samples in the laboratory is based on the standard method presented in many research articles such as [14, 14]. Most of these methods are derived from the method of the Japan Geotechnical Association. This standard applies to the process of fabrication and processing of a cylindrical specimen of compacted soil without compaction. In order to better understand the mixing program required in cement columns, in this research, a special research program for laboratory tests was used. In this first laboratory program, clay samples were evaluated under the influence of stabilizing materials (in this research, cement, sodium silicate powder, and kaolin clay). Table 1 shows the laboratory program used in the second part of the present study.

For the mixing test in the laboratory, city water should be used as mixing water according to construction conditions.

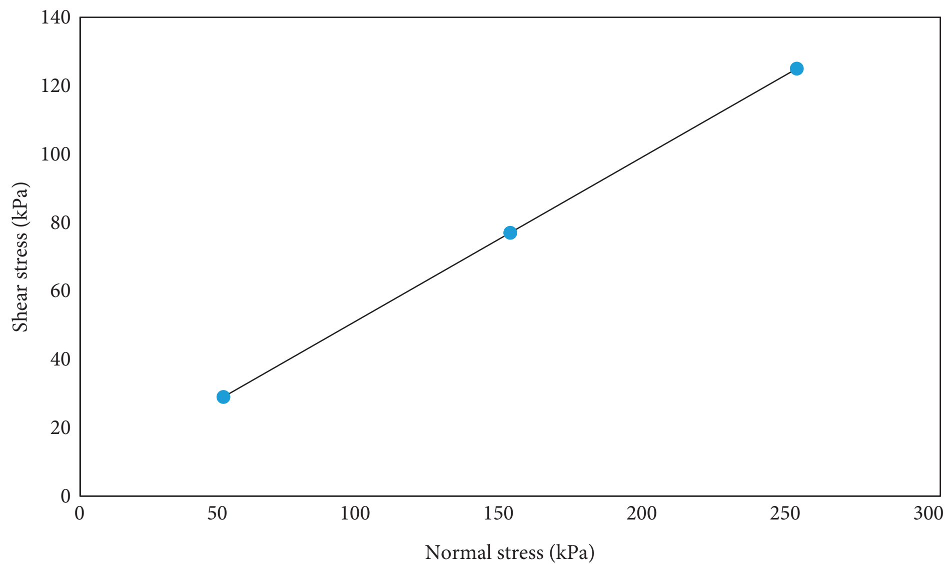


Figure 4: The result of the direct shear test of soil.

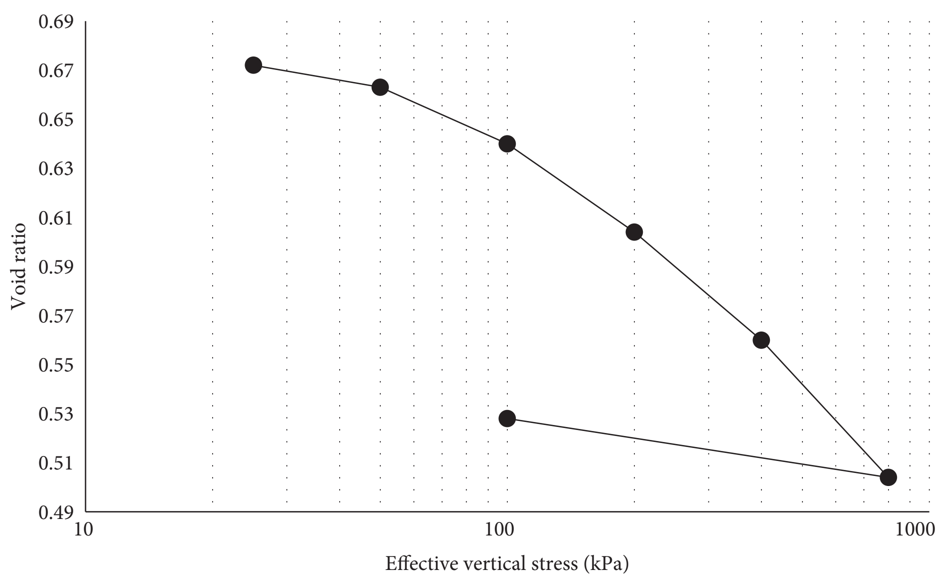


Figure 5: The result of the soil consolidation test in this study.

Table 1: Laboratory program of initial soil stabilization.

Primary materials before stabilization	Stabilizer	Unit of stabilizer	Stabilizer weight percentage				
Clay	Cement	Percentage of soil dry weight	5	10	15	20	25
Clay	Lime		10	8	6	4	2
Clay+ 5 percent of selected cement	Sodium silicate		10	8	6	4	2
Clay+ 5 percent of selected lime	Sodium silicate		10	8	6	4	2

In the mixing process, the initial soil is first mixed with water to determine the moisture content. It should be noted that a certain amount of water is used to make all samples. This has been recommended by various researchers such as [15]. The important point that has been mentioned in scientific references is that in the ratios of water mixture to stabilizing material, such as cement, equivalent to a significant amount of air bubbles are produced that remain even after mixing in the soil sample and this in itself causes the sample to weaken. On the other hand, in low water-to-cement ratios such as 0.8 and 1, the problem of mentally low injection material will be a problem. Therefore, in this study, a similar study was conducted and the ratio of water-to-cement mixture equal to 1.3 was used [14]. In the next step, the stabilizer is added to

Figure 6: Mixing of stabilizing materials in research.

the soil and mixed for ten minutes according to the standard recommendation of the Japan Geotechnical Association (2002). A mixing time of ten minutes is recommended based on good homogeneity considerations and the onset time of hardening [16]. The soil mixture is placed inside the sample mold with a diameter of 5 cm and a height of 10 cm. Of course, larger molds can also be used and there must be a 1 : 2 ratio between the diameter and height of the sample. This issue is based on the recommendation of the ASTM D2166 standard as well as published scientific articles. Before placing the soil sample, the mold is lubricated with grease so that the sample can be easily removed after drying and hardening. It is worth noting that the samples lose some water during the stabilization process and during the hydration reactions, and so-called shrinkage, and this in itself helps the sample to come out of its mold easily [17].

This can even damage the sample if the sample wall is rough or not lubricated. The soil mixture is divided into three layers until it fills the inside of the mold. After placing the mixture for each layer, the mold is shaken to remove air bubbles that may be trapped inside the mixture. After covering the top surface of the sample with a thin plastic plate, the sample is processed at a temperature of 20.3°C and relative humidity of 95%. After a few days of curing, the sample can be removed from the mold and recured under the same conditions as previously described. Three different times of 7, 21, and 30 days were used for processing. The sample processing time mentioned has been used in major soil stabilization studies. Finally, the sample is evaluated using the uniaxial compressive strength test and the final result is equal to non-drained cohesion. In such conditions, it is assumed that the internal friction angle is zero and there are no confinement stresses. Therefore, the mentioned cohesion is a symbol of the shear strength of the stabilized soil sample and can be used to compare the strength of the samples. The steps of preparing and mixing the base soil with stabilizing materials and placing the mixed soil in cylindrical molds in the laboratory are shown in Figure 6. An electric mixer was used to make the mixture of soil and stabilizing materials.

In order to process the samples, the method presented in Kitazume and Terashi [8] research was used [8]. It should be noted that this method has been used by various researchers such as Güllü, [14, 14], Warren, [18, 18], Lin and Wang [19], and Jamsawang et al. [20, 20]. According to this method, the samples were taken out of molds after the first day and placed in small closed containers. The purpose of this work is to maintain the initial moisture of the stabilized soil for use in the soil stabilization process. It should be noted that in all the above methods, while removing the stabilized samples from the original mold (especially in first days after making the sample, which do not yet have appropriate initial strength), the samples are damaged at the edges or cracked or even the compression results from trying to get out of the original mold. In this research, in order to minimize these problems, special plastic molds were used that create a minimum of friction with the samples made in their walls, and after the processing time and in the middle of the time (if necessary), the sample is easily used. It comes out of it. At the same time, it is easily possible to destroy the original mold with scissors or a sharp tool. In this way, the sample itself does not gain or lose any resistance under the influence of manufacturing and processing conditions (Figure 7). Samples were stored under such conditions for 7, 28, and 90 days at laboratory temperature (without overhead). After the processing time, the samples were taken out of plastic containers and tested in the uniaxial compressive strength test under the ASTM D2166 standard.

3. Results and Discussion

The results of the uniaxial soil compaction test and different percentages of cement and lime are presented in Figures 8 and 9, with a curing time of 7 days and 28 days, respectively. Similarly, Figures 10 and 11 show the results of the uniaxial soil compaction test and the optimal percentage of cement and lime after mixing with different percentages of sodium silicate.

A view of the ruptured specimens in the laboratory is shown in Figure 12. In mixing the soil with cement, the soil had shrunk to a lesser extent after 7 and 28 days until the tests were performed. On the other hand, in mixing the tested soil with lime, as soon as mixing and preparing the samples, a lot of shrinkage was observed so that after 7 days of mixing, some samples suffered cracks, and therefore, the author was initially able to observe the results of 7-day samples for mixing with lime that were not presented. Rebuilt cracked specimens were tested. In some 28-day samples, the same thing happened that caused the samples to rebuilt and then the new indicator samples were tested. In the mixture of sodium silicate, lime, and soil, after opening the samples after 48 hours, very small white crystals were formed on the outer surface of the samples, which increased by 2 to 10% with increasing the amount of sodium silicate. In addition, this phenomenon was observed in very low

Figure 7: Steps of preparation, mixing, sample making, and processing.

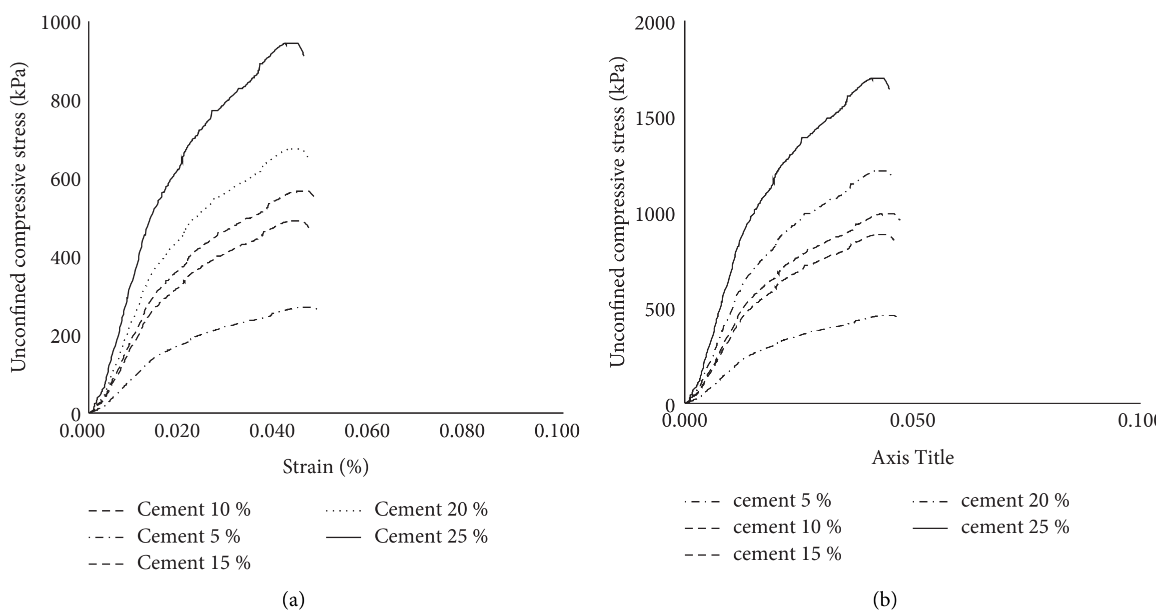


Figure 8: Results of the uniaxial pressure test in different percentages of cement. (a) 7-day curing and (b) 28-day curing.

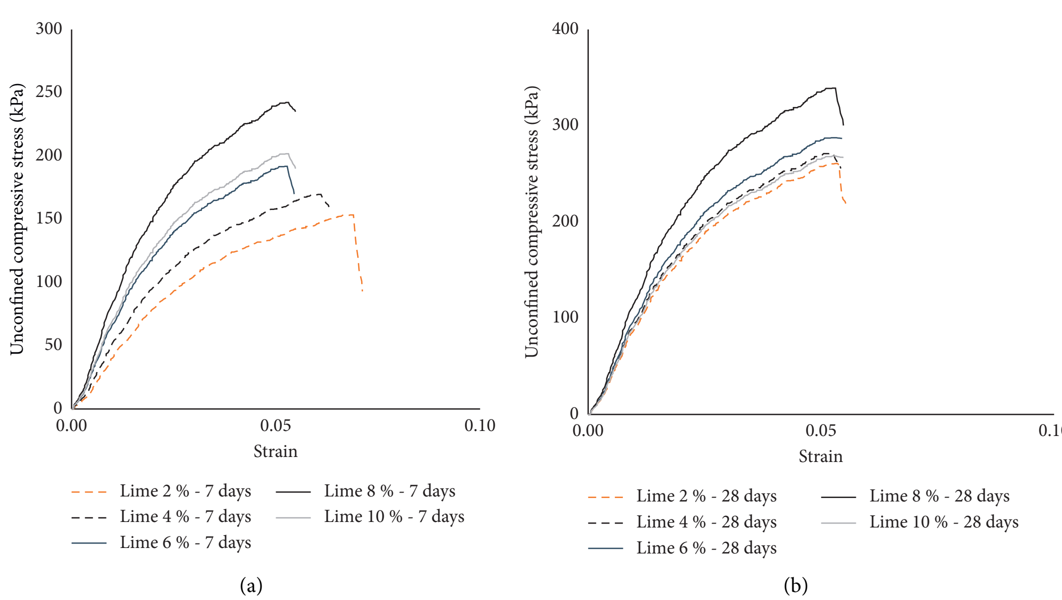


Figure 9: Results of the uniaxial soil compaction test for 28 days and different percentages of lime. (a) 7-day curing and (b) 28-day curing.

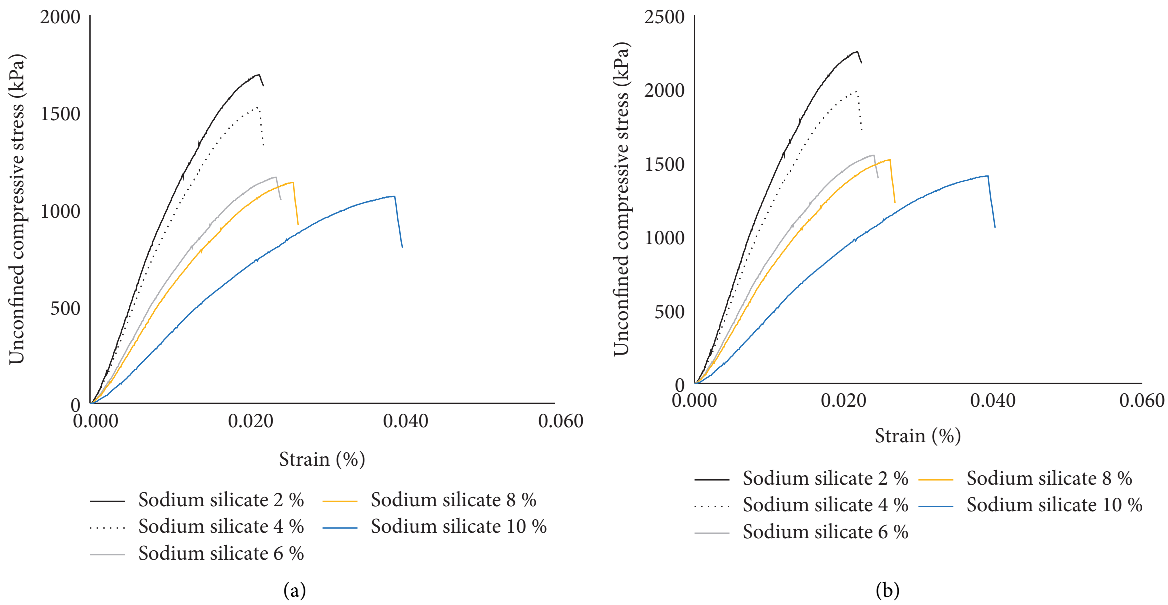


Figure 10: Results of the uniaxial soil compaction test, 25% cement and different percentages of sodium silicate. (a) 7-day curing and (b) 28-day curing.

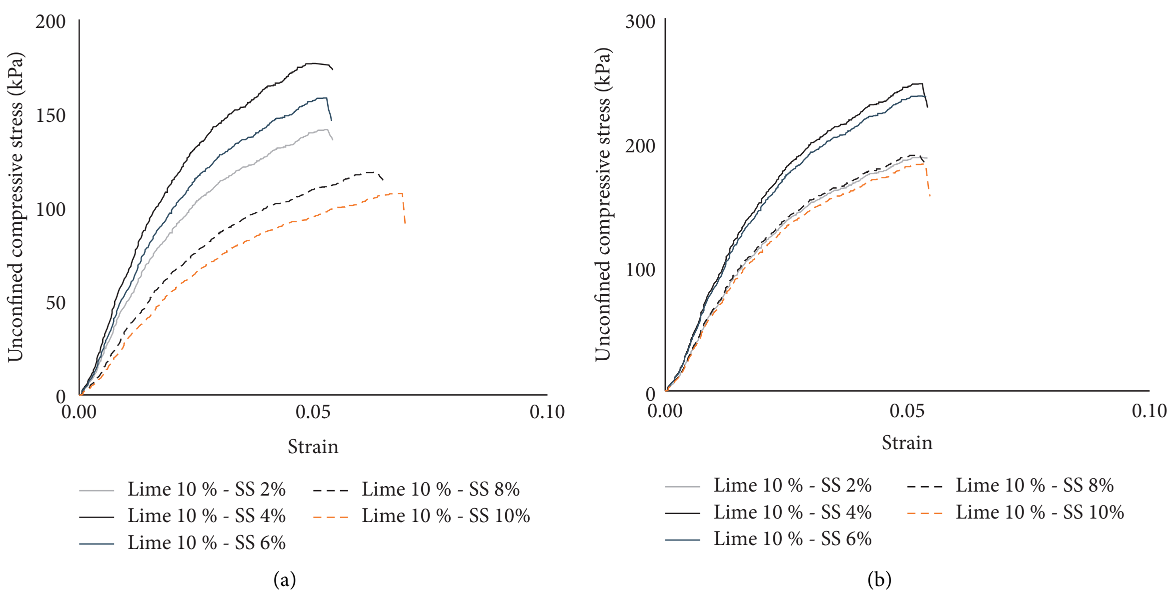


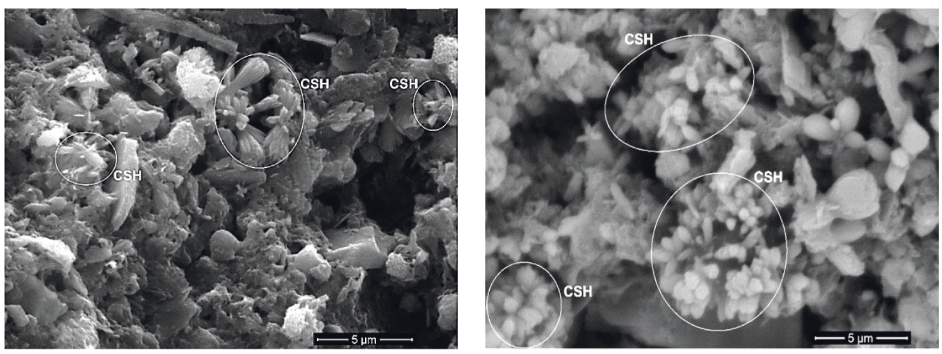
Figure 11: Results of the uniaxial pressure test of soil, 10% lime and different percentages of sodium silicate. (a) 7-day curing and (b) 28-day curing.

percentages of sodium silicate, such as 2%. Comparing the samples with other samples, this phenomenon seems to be due to the reaction of sodium silicate with lime. It is noteworthy that most of the samples made with cement, during the experiment, suffered more crushing (cracks different from the rupture time) than similar calcareous samples.

The following is a microscopic photograph of specimens with the highest uniaxial compressive strength. A very important point in presenting these photos is to change the arrangement of particles that make up the base soil. Also, a new bond between these particles is created by the stabilizing material added to the soil. Also, with the stabilizing material added to the soil, a new bond is created between these particles. These joints, which are due to hydration reactions, have been reported in similar studies to stabilize the strength properties of soil with cement and lime. For example, Tang et al. [17, 17] and Jamsawang et al. [20, 20] referred to this type of interparticle bond that was formed after the addition of stabilizing agents. Figures 13 and 14 show the results of SEM photographs of uniaxial soil pressure tests, 25% cement and lime with 4% sodium silicate.

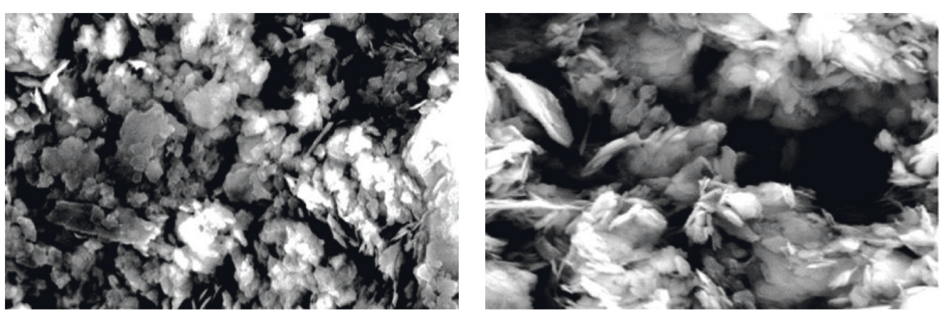
(a) (b)

Figure 12: Examples used in laboratory studies.



(a) (b)

Figure 13: SEM photographs of uniaxial soil pressure tests, 25% cement and 2% sodium silicate.



(a) (b)

Figure 14: SEM photographs of uniaxial soil pressure tests, 10% lime and 4% sodium silicate.

4. Conclusion

In this research, an attempt was made to extract preliminary information from the regional soil near the city of Yasuj, which has a soft clay bed. The technology of the DSM method is based on the improvement of the existing soil of the site or embankment in order to meet the design needs, so the problems of drilling or replacing the soil and using more expensive methods such as deep foundations (piles) in this method are eliminated. A wide range of applications and different patterns of implementation of soil-cement columns lead to reliable and very economical engineering solutions. Then, after initial tests, the soil sample taken from the study area was transferred to the soil mechanics laboratory. Soil samples were dried in an electric hothouse and mixed with different percentages of cement, lime, and sodium silicate and after curing time of 7 and 28 days were subjected to the uniaxial compression test. As expected, in the samples combined with cement, with increasing the amount of cement, uniaxial resistances also increased significantly. For example, soil stabilized with 5, 10, 15, 20, and 25% cement (weight percentage to dry soil) after 28 days of uniaxial resistance were obtained equal to 458, 878, 991, 1213, and 1698 kPa, respectively. It should be noted that in almost all stabilized soil samples, their resistance increased with increasing curing time, which of course is more evident in the case of cement-stabilized soils. The maximum uniaxial strength of stabilized samples with lime content of 8% was obtained, which was equal to 242 and 339 kPa for processing times of 7 and 28 days, respectively. The effect of sodium silicate on lime and cement was positive, so that the maximum uniaxial strength for cement-stabilized soil (with a 28-day curing) increased from 1698 to 2228 kPa. Of course, it is worth mentioning that increasing the amount of sodium silicate from 2% to more reduces uniaxial compressive strength.

Data Availability

Data are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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