Kerman collapsible clay amendment by lime, bentonite, and nano silica

A. Firoozfar[*], M. Dousti
University of Zanjan, Iran
* E-mail: firoozfar@znu.ac.ir

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Abstract. This paper presents an experimental study to understand the effects of selected additives on Kerman collapsible soil behavior which is dominated with such clay and is semi-arid province in the south-east of Iran. Collapsible soils, known as problematic soils, are materials with a relatively high porosity and demonstrate a potential for sudden and large decrease in their volume under water content changes with or without change in the applied stress level. In this study, soil samples are obtained from a project site in Kerman city and the collapse potential tests were performed on the prepared samples in accordance with ASTM as double oedometer consolidation test. Initially, the undisturbed level of collapsibility. Next, samples are treated with three kinds of additives namely: lime and bentonite in the 3, 5 and 8 percent and nano silica in 0.4, 0.7 and 1 percent of dry soil weight. For each percentage of additive, one sample was created and the results demonstrated that 5 % of Lime, 3 % of Bentonite and 1 % of nano silica are the optimum percentage of additives for decreasing the collapsibility. The collapsibility of Kerman clay is reduced significantly after treating with lime and nano silica in comparison to bentonite.

1. Introduction

There are various types of problematic soils such as dispersive soils, collapsible soils, expansive soils, etc. Collapsible soils are unsaturated soils, which show volume decrease in confronting increased moisture content under constant stress. Collapsible soils are scattered all around the world in a great volumes and they can be found in the United States, Europe, China and South Africa. It has been estimated that about 10 % of the surface area of the Earth is covered by these soils [1, 2]. Collapse phenomena have been reported in an extensive rate in many arid areas around the world, and all of them are happened due to wetting [3]. Several methods currently exist for improving the characteristics of collapsible soils such as dynamic compaction, chemical stabilization, inundation, and piling [4, 5]. Chemical stabilization is one of the most common methods for stabilization of the soil. This method is a process for enhancing the characteristics of soil by using additives such as lime, bentonite, Portland cement, fly ash and recently Nano-particles [6, 7, 8, 9]. Lime's reaction with soil is categorized in two different processes of short and long term reactions. Cation exchange and flocculation occur immediately within the soil, rapidly increase soil's pH level. This is regarded as a result of the dissolution of $Ca(OH)_2$. Pozzolanic and carbonation reactions are categorized as the long-term reactions. The Pozzolanic reaction is actually a slow reaction which is mainly controlled by time, temperature and moisture. This reaction produces calcium silicate and calcium aluminate, which gradually enhances strength and durability in days or weeks after adding lime to the soil. Carbonation reaction is a damaging reaction which decreases the number of free ions in the mixture for cation exchange and pozzolanic reactions [6, 10]. The influence of lime on the collapsibility of tropical residual soils was investigated and the results showed a significant reduction in comparison with untreated soil samples [10]. A comprehensive study was conducted on the soil stabilizing effect of lime and made an estimation of the initial lime consumption (ICL) showing that, 5 % lime is sufficient for ICL [6]. The impact of lime on the strength of soil mixture was investigated in road construction and the result indicated that all

tested samples reach a significant strength level when enough amount of lime is provided [11]. Another material which is commonly used for soil stabilization is bentonite. One of the most important features of bentonite is its usability in both granular and cohesive soils by determining the required amount of bentonite. It has been found that in cohesive and well-graded soils, less than 6 % and in the uniformly sized sands, 10 to 15 % of bentonite is sufficient, where compressibility and shear strength of the soil was investigated [12, 13, 14]. Besides, bentonite can improve the hydraulic conductivity of soils to meet the technical requirements of compacted clay liner (CCL). This was investigated using different percentages of bentonite and the result showed a considerable reduction in permeability caused mostly by swelling characteristics of bentonite, meeting most of the worldwide standards [9,15]. Over the last two decades, nanotechnology has been significantly used in many fields of science and using materials with the sizes smaller than 100 nm is defined as nanotechnology. In geotechnical engineering, nanotechnology is used in two different approaches: first, to have a better understanding of soil structure by studying the soil in nanoscale and secondly, soil stabilization using nano-size additives [16]. Despite previously conducted studies on the utilization of nanotechnology in soil mechanics, there are still numerous untouched analytical and experimental subjects. Experimental works were done to show the effect of nanomaterial on soil stabilization and soil permeability. It was found that the addition of nanomaterials decreases the permeability of soils [17]. The addition of nanomaterial to the sand affects the cyclic behavior of the soil. The inter-particle siloxane bonds due to collisions between nanoparticles forms the silica solution gel. This gel contains the individual sand particles together and maintains the soil structure under the dynamic loading [16,18, 19]. Kerman is a province located in the south-east of Iran. It has a number of notable sites such as the Bam Citadel and the ruined city of Arg-e-Bam made entirely of mud bricks, clay, straw and the trunks of palm trees (224–637 AD) (Figure 1). This province covers an area of 175,069 square kilometers including 11 % of the total area of Iran. The geographical diversity of this province causes a varying climate. Geologically, alluvial and aeolian sediments form most of the top layer of the Kerman plain [20]. The land of the City of Kerman, geographically located in the north west of the Kerman province, is mostly made up of the collapsible soils. This availability has resulted in the prevalence of these soils utilization in various projects due to the economic reasons. As an under-structure basement, these collapsible soil covers cause serious problems to the building structures and urban infrastructures such as water and gas pipelines, and embankment dams. Therefore, soil treatment can be a beneficial preconstruction operation in almost all projects in Kerman.

Figure 1. Kerman Province and city of Kerman.

This study considers the Kerman collapsible soil and suggests different approaches to amend this problematic soil which would address a major need in this province. This paper aims to explore the effect of different types of additives on the collapsibility of Kerman clay.

2. Materials

In this section, we discuss and elaborate on the materials used in this study.

Soil: soil samples are taken from a 5-meter depth of a construction site. In order to determine the physical and chemical properties of the soil, such as particle size, Atterberg limits, dry unit weight, and optimum moisture content, different tests are conducted according to ASTM. More than 90 % of the soil passed the sieve, which indicates no. 200 grain size distribution curve of the soil according to ASTM D422 Standard [21], see Figure 2. With reference to unified soil classification system (USCS), this soil is categorized as CL. Physical and chemical properties of the disturbed soil are shown in Tables 1 and 2:
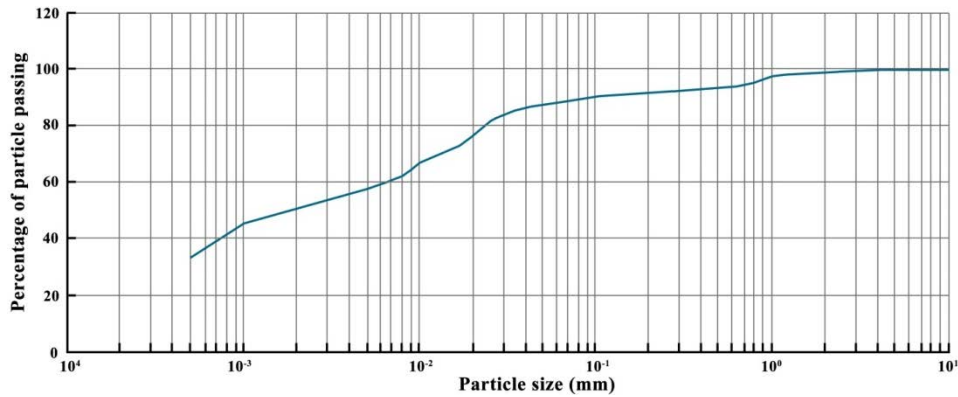
Figure 2. Particle size distribution of the Kerman collapsible soil.

Table 1. Physical characteristics of the soil used in the tests.

Characteristics	Value and Description
Density(gr/cm^3)	1.74
Liquid Limit (%)	33
Plastic Limit (%)	21
Clay content (%)	32
Passing no. 200 sieve (%)	90
Specific gravity (G_s)	2.77
Unified classification system	CL

Table 2. Chemical compositions of the soil and bentonite used in the tests.

Characteristics	Soil	Bentonite
SiO_2	45.01	55.35
CaO	13.62	1.09
Al_2O_3	11.95	14.07
Fe_2O_3	4.91	2.79
MgO	3.93	3.86
K_2O	2.49	0.21
Other	18.09	15.2

Additives: three additives namely lime, bentonite and Nano-silica are investigated in this study. These additives are readily available and their interaction with clay is clearly known.

Lime: The hydrated lime used for this project is a product of the Lorestan Lime Company and is a high-quality lime passes through an $80\,\mu m$ sieve opening, with 56.7 % of Ca(OH)$_2$.

Bentonite: Sodium bentonite from Arak Poodr Factory is the other additive in this study. The chemical property of the bentonite and its physical analysis is shown in Tables 2 and 3.

Table 3. Physical characteristic of bentonite used in the tests.

Characteristics	Value and Description
Water absorption (%)	100–110
Absorption of montmorillonite (%)	>75
Liquid limit (%)	230
Plastic limit (%)	110
PH	9
Percent finer than No. 200	99.08

Nano-Silica: Silica nanoparticle is a white color powder. We use the Nano-silica from Pasargad Novin Company. A further discussion on the main properties of the Nano-silica is provided in the subsequent sections in this paper.

Permeants: For all tests, tap water was used.

3. Experimental Methods

Sample preparation: To achieve a homogeneous soil sample, dry soil and additives have to be mixed, and then water should be added to the mixture. Accordingly, the soil is air dried at the normal laboratory

temperature. All the specimens in this experiments are prepared with optimum moisture content and compacted at the maximum dry density. Next, lime and bentonite are added to the soil in the proportions of 3, 5, and 8 percent, respectively, and hand mixed together to obtain a homogeneous soil-additive mixture. Next, tap water is gradually spray-added to the mixture. Lime-soil reactions begin when the PH of the mixture reaches 12.4. By adding additional 2 percent or more of lime to the soil, PH reaches to 12.4. This also facilitates the long-term pozzolanic reactions [11, 22]. Nano-silica is added to the soil in 0.4, 0.7 and 1 % ratios with respect to the soil dry weight. Specific surface area (SSA) is an important parameter in nanomaterial's reaction with soil. At nanoscale, a higher ratio of surface to volume causes intense interaction. Therefore, even small amounts of nanoparticles yield considerable effects on mechanical properties of the soil [8, 23]. For each percentage of additive, one sample is created.

Testing Procedure: As double odometer consolidation test (ASTM D 5333-03) is commonly performed on samples to determine their collapse potential. The significance of one dimensional collapse that occurs when unsaturated soils are flooded with water is covered by this test. Initially, undisturbed soil samples at natural water content are tested. Double odometer test examines collapsibility of soil samples regarding the void ratio variation resulted by the inundation of the sample. The collapse potential can be calculated as follows [24]:

$$I_c = \frac{\Delta e}{1+e_0} \times 100,$$

(2)

where I_c stands for the collapse potential;

Δe is the change in void ratio upon flooding;

e_0 represents the void ratio before flooding.

Figure 3 shows the result of a double odometer test on an undisturbed sample. According to [11] and considering the results of the laboratory experiments, the base soil is classified as moderate collapsible clay exhibiting a collapse potential value of 5.9. Table 4 categorizes I_c from none to severe in degree of collapse potential.
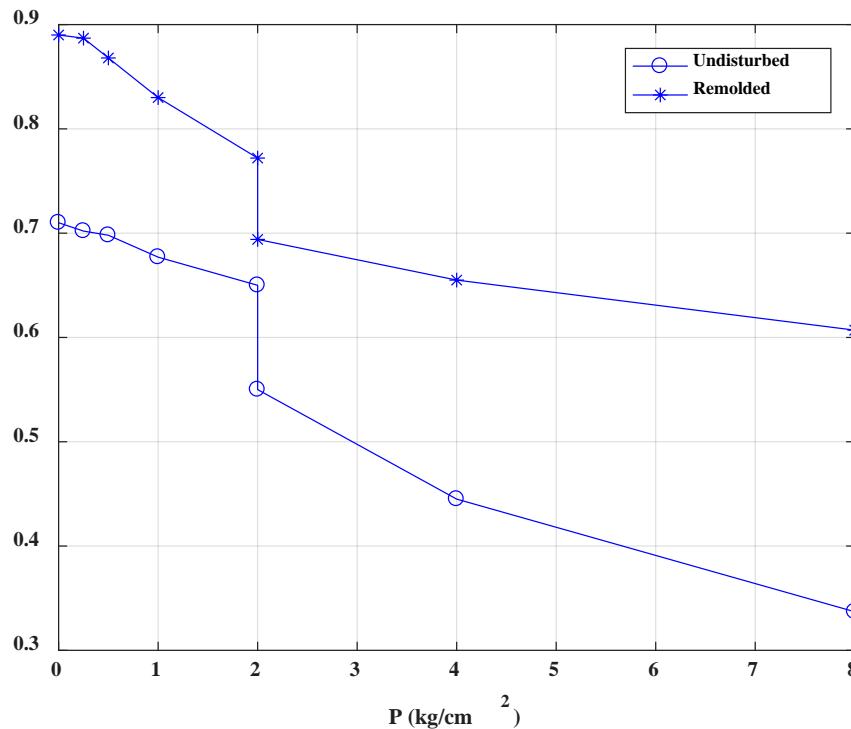
Figure 3. Result from double oedometer test on undisturbed and remolded specimen.

Table 4. Classification of Collapse potential [24]***.***

Degree of collapse	Collapse potential (%)
None	0
Slight	0.1 to 2.0
Moderate	2.1 to 6.0
Moderately severe	6.1 to 10.0
Severe	>10

The double odometer test is re-applied on remolded samples under natural moisture without any additives. This test also is conducted on soil samples combined with additives to understand the effects of the additives on collapse potential. Double odometer tests are conducted on all the additive-amended samples with the optimum moisture content and at 100 % of maximum standard proctor dry unit weight.

4. Result and Discussion

In order to determine the collapsibility of an undistrubed soil sample, the specimen is tested according to ASTM regulation [25]. The result is shown in Figure 3. Considering Figure 3, the collapse potential of the undisturbed soil, i.e., I_c, is 5.9 which indicates a relatively high collapse potential. Up to a loading of 2 (Kg/cm^2), the sample shows a slight rate of settlement. At the vertical stress of 2 (Kg/cm^2) and after 24 hours, a significant change in strain observed, as a result of inundation. This severe change is due to the loss of the resistance factor binding the soil particles. This can cause serious problems the projects that use this type of soil. To prevent these phenomena, soil stabilization is one of the most effective and economic approaches. In the process of stabilization, soil inevitably remolded. Therefore, additionally the collapse potential test is also carried out on a remolded specimen to have a better understanding of the effect of different additives on soil behavior. The results from the experiment on the remolded sample without any additives are presented in Figure 3. The remolded specimen demonstrated a collapse potential equal to 4.17 and is categorized as moderate in the degree of collapse according to Table 4. As it can be seen, an anticipated reduction occurs in the collapse potential. This reduction is attributed to the impact of mechanical compaction of the soil under which the open structure of the collapsible soil breaks in comparison with the undisturbed sample. A comparison between the undisturbed and the remolded specimens reveals that the collapse potential decreases by 28 % under standard compaction. The Scanning Electron Microscopic (SEM) observation of the remolded sample, as presented in Figures 5 and 6, shows pores which can yield in a collapsible soil fabric. Thus, collapse under wetting should clearly occur by the densification of the areas where grains are clean with large pores around them
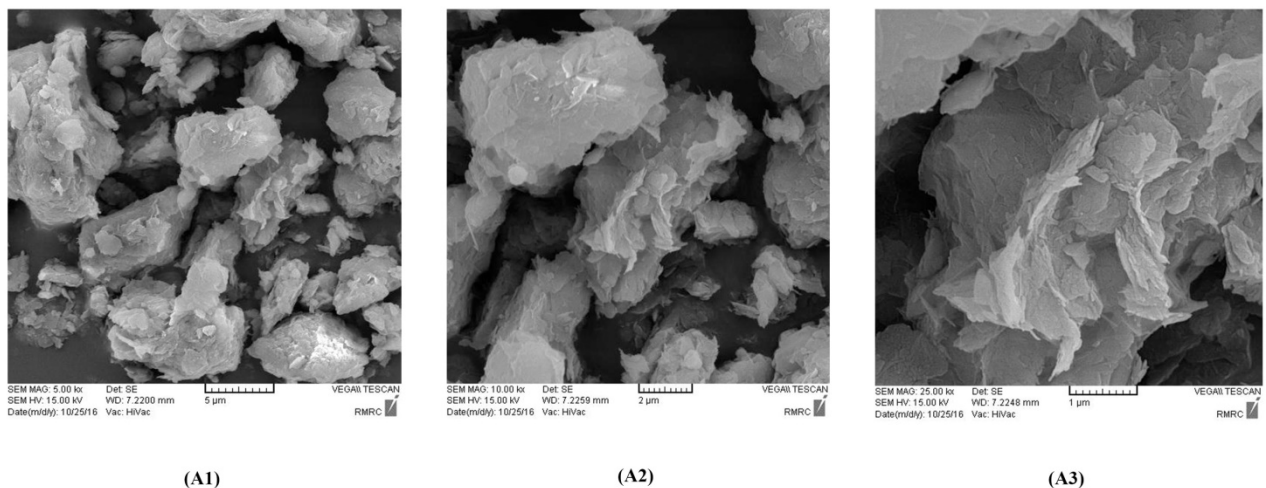

(A1) (A2) (A3)

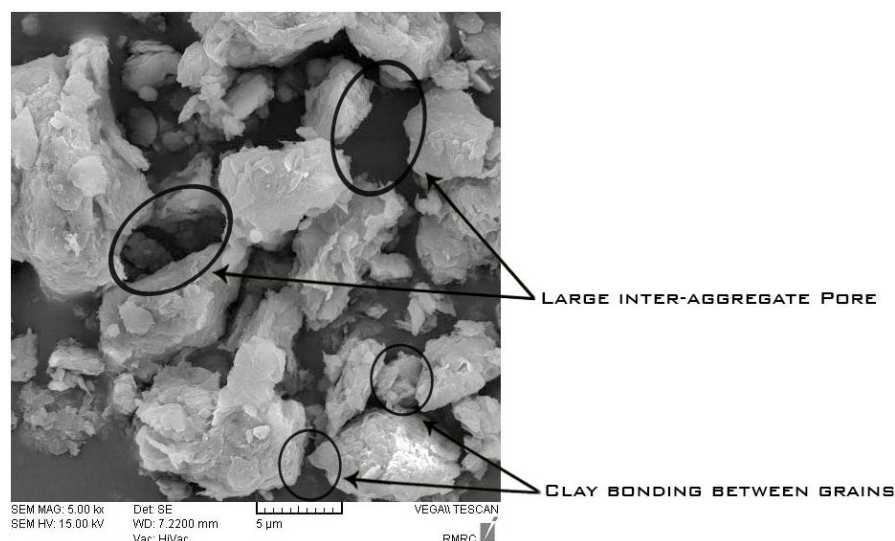**Figure 4. Microstructure observation of remolded collapsible soil sample at different magnification (A1-A2-A3).**

Figure 5. Large inter-aggregate pores and unstable clay bonding between grains in remolded collapsible soil.
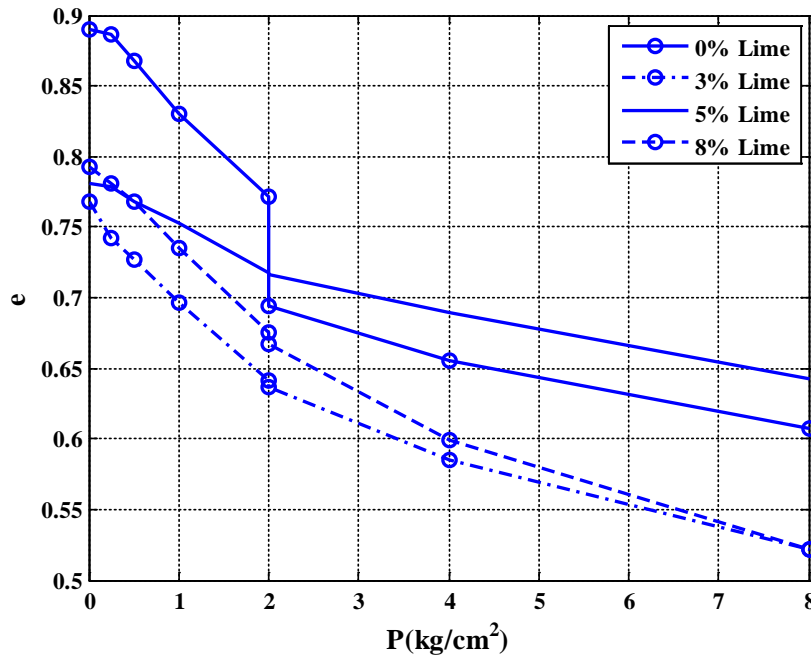
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Figure 6. Comparison between results from double oedometer tests on three different lime-soil mixtures and remolded soil specimen.

4.1. Effects of lime on soil collapsibility

Lime-soil mixtures is treated for 18 days at a constant temperature and then the collapse potential test is conducted on the samples. In Figure 7 and Table 5, the results of the tests conducted on the lime-soil mixtures are presented. In all three different samples prepared by different percentages of additives, collapse potential decreases (from 4.17 to 0.12) drastically which shows lime can act as a proper additive for stabilization of Kerman collapsible clay. In all three lime-soil samples the degree of collapse decreases and mixtures with less than 5 % lime show a decreasing trend in the amount of strain and after that, the trend shows a gently sloping increase: therefore, it can be concluded that the most significant decrease in collapse potential occurs with 5 % of lime. Collapse potential decrease 97 percent in the 5 % lime treated samples compared with remolded pure soil samples. This result is in line with those of the previous studies [10, 26].
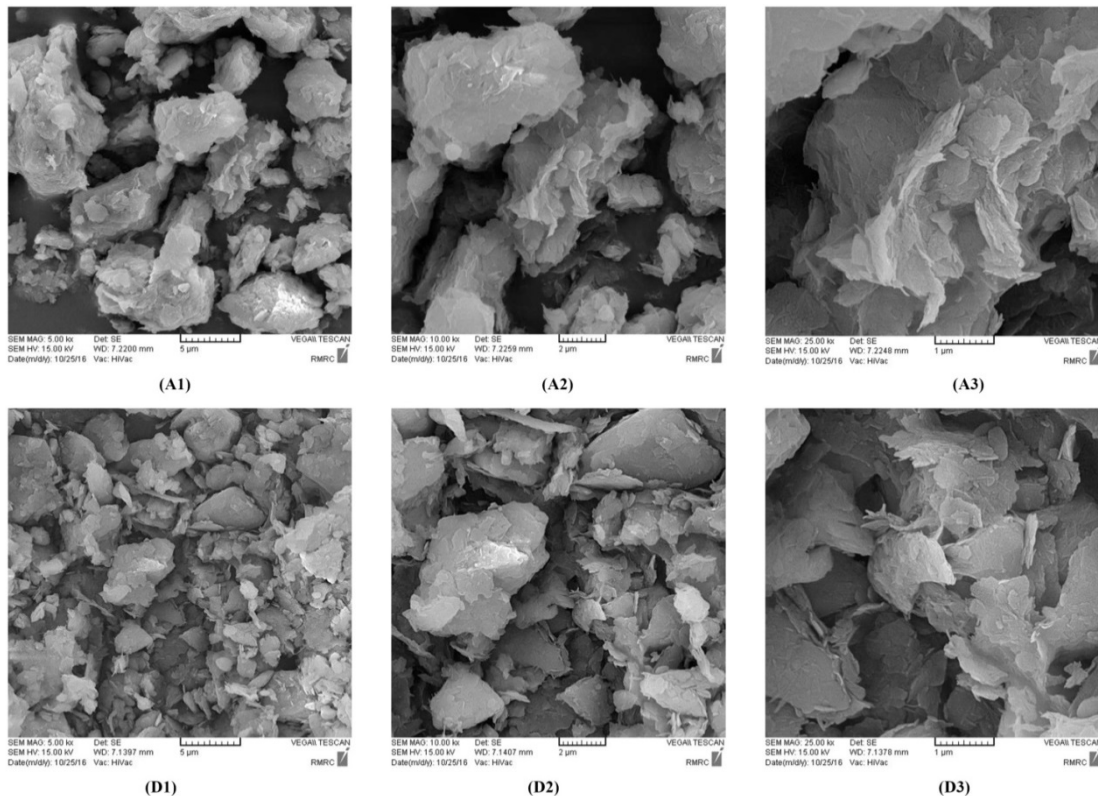

Figure 7. Microstructure observation of the effect of 5 % lime on collapsible soil (D1-D2-D3) in comparison to remolded raw specimen (A1-A2-A3) at different magnification.
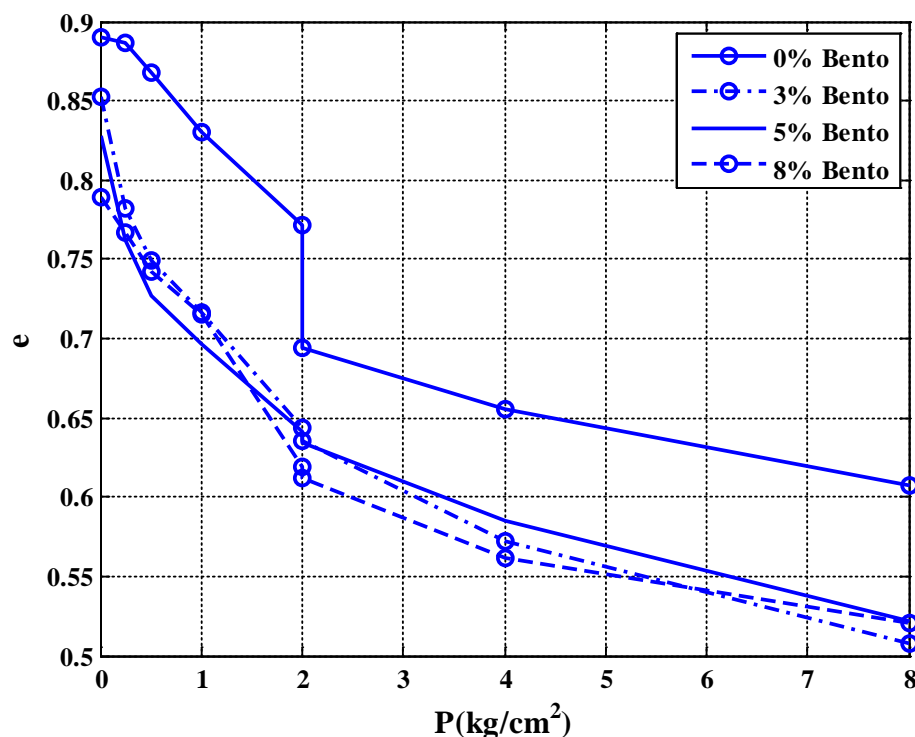
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Table 5. Comparison between results from double odometer tests on three different lime-soil mixtures and remolded soil specimen.

Parameter	Soil	3 % Lime	5 % Lime	8 % Lime
Δe at vertical stress 2 (Kg/cm^2)	0.0788	0.004	0.002	0.008
Initial void ratio (e_o)	0.89	0.768	0.781	0.793
Collapse potential (%)	4.17	0.23	0.12	0.45
Degree of collapse	Moderate	Slight	Slight	Slight

The reactions between lime and soil are highly dependent on the time of curing hence, curing time significantly affects the results of the collapse potential test. The decrease in collapse potential in lime amended soil samples is attributed to three different procedures:

- Addition of moisture during the mixing process

- Compaction of the mixture which breaks the open structure of the collapsible soil

- Pozzolanic reaction between soil and lime which causes inter-particle bonding and flocculation of the soil particle leading to stabilize soil structure

The Scanning Electron Microscopy (SEM) images of 5 % lime-soil mixture as presented in different magnifications in Figure 8, indicate that the porous collapsible structure of soil, shown in Figure 8-A1, are filled in through the flocculation and, cation exchange reactions between lime and soil, which obviously decrease the volume of the inter-aggregate pores. Furthermore, the pozzolanic reactions happen between soil and lime strengthening the weak bonding between the particles in the soil. These reactions create a homogenous microstructure in the soil which is quite evident in Figures 8 D1, D2 and D3.

Figure 8. Comparison between results from double oedometer tests on three different bentonite-soil mixtures and remolded soil specimen.

4.2. Effects of bentonite on soil collapsibility

Bentonite-soil mixtures are left to rest for two days, and then the collapse potential tests are conducted on the samples. In Figure 9 and Table 6, the results of the tests on bentonite-soil mixtures are depicted. According to Table 4, in all three different samples, the degree of collapsibility decreases from the moderate level in the remolded soil sample to the slight level in treated samples. Although in all bentonite-soil mixture samples the collapse potential decreases, the maximum decline is observed by adding 3 % bentonite and with further addition, a minor increase is observed. Below 3 % bentonite addition, the amount of strain and consequently, the settlement showed a decreasing trend and after that, the trend is reversed showing a slight increase. Previous researches showed that the addition of bentonite up to 6 %, decreases the settlement of the mixture [27]. This differs from the findings of the present study. This inconsistency may be due to three different reasons: type of the used soil and bentonite, and the differences in the test procedure.
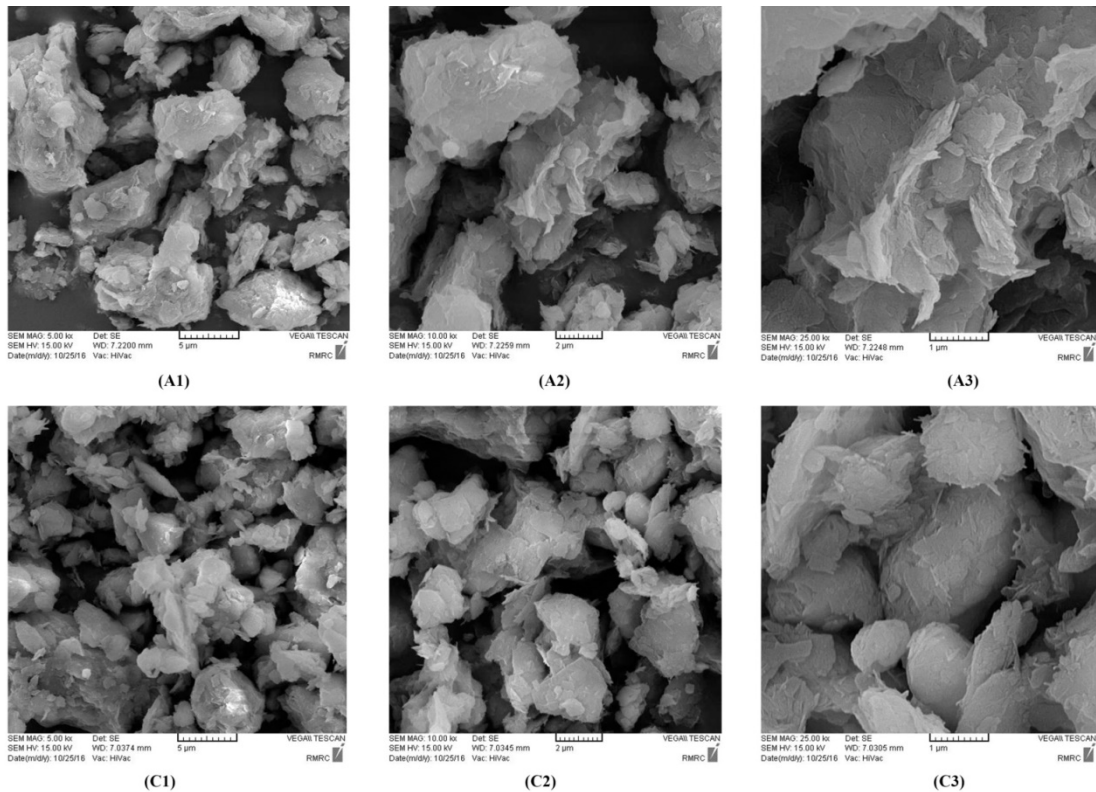
Figure 9. Microstructure observation of the effect of 3% bentonite on collapsible soil (C1-C2-C3) in comparison to remolded soil specimen (A1-A2-A3) at different magnification.

Table 6. Comparison between results from double oedometer tests on three different bentonite-soil mixtures and remolded soil specimen.

Parameter	Soil	3 % Bentonite	5 % Bentonite	8 % Bentonite
Δe at vertical stress 2 (Kg/cm^2)	0.0788	0.0047	0.0073	0.0092
Initial void ratio (e_0)	0.89	0.853	0.827	0.789
Collapse potential (%)	4.17	0.27	0.39	0.51
Degree of collapse	Moderate	Slight	Slight	Slight

The Scanning electron microscopy (SEM) observation of 3 % bentonite-soil mixture as presented in different magnifications in Figure 10 shows that, the inter-particle pores demonstrated (Figures 10 A1, A2 and A3) are supplied with the additive through the swelling characteristic of bentonite. In addition, high water absorption capability of bentonite forms a kind of gel which fills the pores (Figures 10 C1, C2 and C3). Moreover, expanded particles of bentonite act as filling materials of the pores and reduce the collapse potential of the soil. A comparison between lime and bentonite induced change shows that, although both of them decrease the collapsibility, it seems that the, lime creates a more homogenous microstructure which is more useful in collapsibility reduction of Kerman clay.

4.3. Effects of Nano-silica on soil collapsibility

Nano silica amended soil samples are packed and isolated for 48 hours and then the collapse potential tests are conducted on the samples. In Figure 11 and Table 7, the results of the collapse potential tests on Nano-silica soil mixtures are presented. In all the three different samples, collapse potential decreased reviling that Nano-silica can be an effective additive for stabilization of the Kerman collapsible soil. Regarding the obtained results, the collapsibility of the used clay is treated with adding 1 % Nano silica by dry weight of the soil. Nano silica is known as a pozzolanic material and is frequently used to improve soil properties. It is believed that the enhancement mechanism of colloidal silica is bonding between the gel and the clay particles. Gel encapsulates the individual clay particles and it is widely held view that this bonding and encapsulation improve soil structure [19].

The SEM images of the soil samples mixed with 1 % Nano-silica is depicted in different magnification in Figure 12 and shows changes in the basic structure where the inter-particles pores (Figures 12 A1, A2 and A3) are filled with CSH gel which is created by reaction between CaO and Al_2O_3. Furthermore, this gel strengthens the bonding between soil particles and results in a homogenous microstructure (Figures 12 B1, B2 and B3) and consequently, decreases the collapse potential of the soil. These results match those observed in previous studies [8, 28].
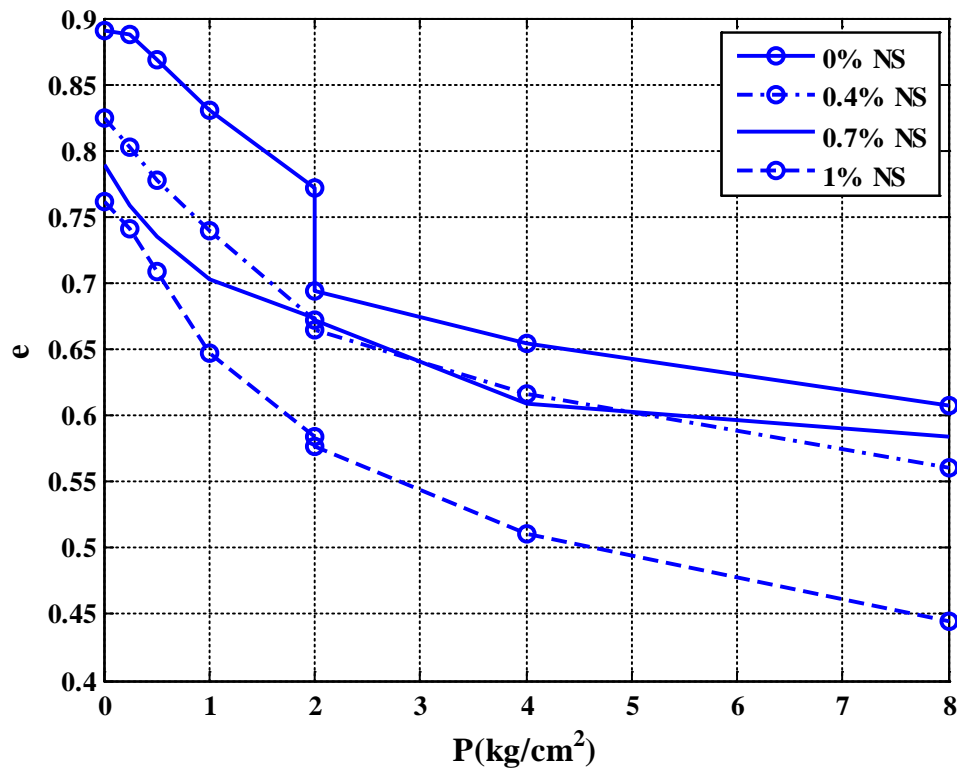
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**Figure 10. Comparison between results from double oedometer tests
on three different Nano-silica-soil mixtures and remolded soil specimen.**
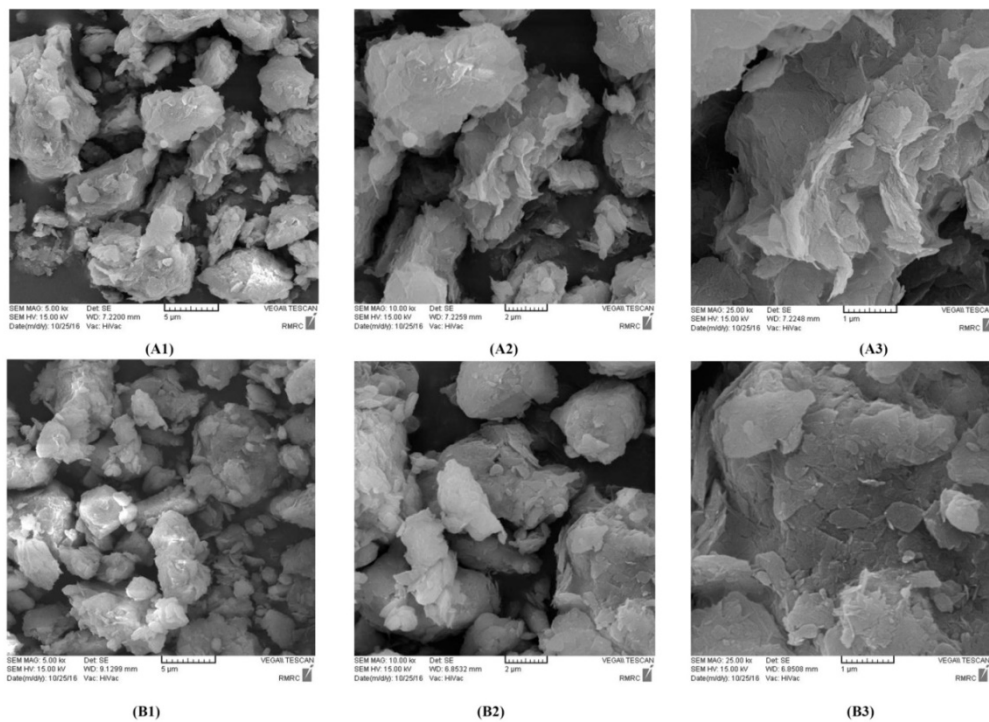

**Figure 11. Microstructure observation of the effect of 1 % Nano-silica on collapsible soil
(B1-B2-B3) in comparison to remolded soil specimen (A1-A2-A3) at different magnification.**

Table 7. Comparison between results from double oedometer tests on three different Nano-silica-soil mixtures and remolded soil specimen.

Parameter	Soil	0.4 % Nano-silica	0.7 % Nano-silica	1 % Nano-silica
$\varDelta e$ at vertical stress 2 (Kg/cm^2)	0.0788	0.007	0.007	0.002
Initial void ratio (e_0)	0.89	0.82	0.79	0.76
Collapse potential (%)	4.17	0.39	0.38	0.12
Degree of collapse	Moderate	Slight	Slight	Slight
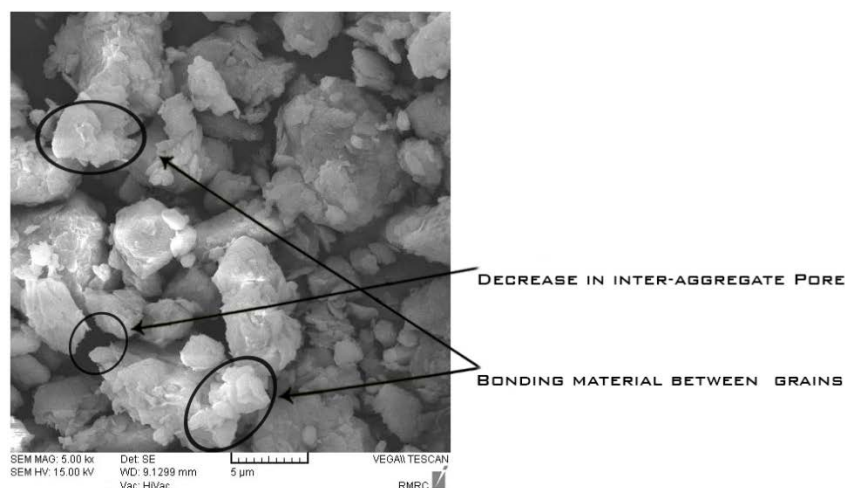
**Figure 12. Effect of Nano-silica in filling the inter-aggregate pore
and strengthening the unstable bonding between grains.**

The SEM images of the soil samples mixed with 1 % Nano-silica is depicted in different magnification in Figure 12 and shows changes in the basic structure where the inter-particles pores (Figures 12 A1, A2 and A3) are filled with CSH gel which is created by reaction between *CaO* and *Al₂O₃*. Furthermore, this gel strengthens the bonding between soil particles and results in a homogenous microstructure (Figures 12 B1, B2 and B3) and consequently, decreases the collapse potential of the soil. These results match those observed in previous studies [8, 28].

Figures 10 C1 and 12 B1 prove the lesser impact of the bentonite swelling property on filling the collapsibility of the specimens. At last, the differences in Figures 8 D1 and 12 B1, exhibit the sufficiency of both additives in decreasing the collapsibility of the Kerman clay.

The results demonstrated that 5 % of Lime, 3 % of Bentonite and 1 % of Nano silica are the optimum percentage of additives for decreasing the collapsibility.Both lime and Nano-silica demonstrate positive effects on reducing the Kerman clay collapsibility as the collapse potential diminished considerably in both specimens treated by these additives which is shown in Figures 7 and 11. In comparison of bentonite and Nano silica treated soil specimens in Figures 9 and 11, the reduction of the inter-particles in Nano silica treated specimens are evident. Also, the structure of the soil seems to be more homogenous.

5. Conclusions

The structure of a particular soil has a significant influence on it behavior in engineering particles. An open structure and weak inter-particle bonding may result in a higher collapsibility which requires a careful attention to factors affecting the collapse potential of the soils. A safe and applicable method to treat collapsible soils is using additives. The mixture of the soil and the additives is very sensitive to the quantity and the quality of it components. Thereby, finding the optimum additive ratio is important. In this research, three additives, namely lime, bentonite, and Nano-silica are selected and their effects on the collapse potential of the Kerman clay are investigated. Additive-soil mixture samples are tested and the results show that all of them decrease the collapsibility potential. The optimum additive percentage for lime, bentonite, and Nano-silica are determined as: 5 %, 3 and 1 % by the dry weight of soil, respectively. The collapsibility of Kerman clay is reduced significantly after treating with Lime and Nano silica in comparison to Bentonite. Although, both lime and Nano-silica had similar impacts on the collapse potential of the Kerman soil, Nano-silica is more recommended due to the sorted curing time of the specimens which is attributed to the great specific surface of the Nano-silica, leading to a lesser required material. Thus, it is recommended to consider Nano-particles as soil stabilizers. They do not need a long time of curing and small volume of minute volume of Nano-particle can effectively improve soil properties.

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Contacts:

Alireza Firoozfar, 09121414177; firoozfar@znu.ac.ir

Majid Dousti, +989122426030; dousti.mj@gmail.com