The Effect of Wetting-Drying Cycles and Plasticity Index on California Bearing Ratio of Lime Stabilized Clays

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Received: 6 Oct 2013 Revised: 8 March 2014

Abstract

This paper aims to present an experimental and numerical study on the effect of wetting-drying cycles and plasticity index on the California Bearing Ratio (CBR) of lime stabilized clayey soils. The numerical analysis was carried out based on finite element method for comparison between results of experimental and numerical studies. Three clays with different plasticity indices were mixed with various amounts of hydrated lime and compacted at optimum water content. The CBR tests were conducted to the soils and admixtures after specified curing time and various numbers of wetting-drying cycles. The experimental results indicate that addition of lime content up to 4% causes significant increase in the CBR values. Based on the obtained results the CBR decreases during the wetting phase and increases during the drying phase of each cycle. After 3 cycles the CBR values of lime stabilized clayey soils are increased. Also, for stabilized clays by increasing the plasticity index, the CBR values resulted by increase of lime content are decreased. The comparison between numerical and experimental analyses indicates a good agreement between results.

Keywords: Lime stabilized clay, Plasticity Index, Wet-Dry cycle, CBR tests, Numerical analysis.

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[DOR: 20.1001.1.22286837.1394.9.2.7.2]

[DOI: 10.18869/acadpub.jeg.9.2.2817]

Introduction

The reduction in strength of soft clays that causes bearing capacity failure and excessive settlement leads to severe damage to buildings and foundations. The stabilization, especially with lime, is a common applied method among others because of its effectiveness and economic benefits. Almost all fine-grained soils can be modified by lime, but the most dramatic improvement occurs in clayey soils of moderate to high plasticity.

Lime-clay reactions occur via two distinct processes (Clare and Cruchley [1], Eades and Grim [2], Wang et al. [3], Greaves [4], Holt and Fleer-Hewish [5], Rogers and Glendinning [6], Boardman et al. [7]): (i) rapid ion exchange reactions known as soil improvement or modification and (ii) slower soil-lime pozzolanic reactions known as stabilization/solidification. Based on the studies conducted by Thomson [8], Thompson [9], as a result of lime stabilization, clay particles stick to each other and form larger particles. They have found that the plasticity indices are reduced and CBR values are increased.

Akinlabi [10] investigated the stabilization of Lateratic soils in Zarya, Nigeria with hydrated lime, by performing wet CBR tests. His results indicate that by addition of lime, maximum dry density and plasticity index are reduced, but optimum water content and liquid limit are increased. Rahman [11] indicated that for Lateratic soils stabilization, addition of 5% of lime can improve strength properties of Lateratic soils to use in subgrade layers, while Bell [12] found that

[DOR: 20.1001.1.22286837.1394.9.2.7.2]
[DOI: 10.18869/acadpub.jeg.9.2.2817]

the optimum addition of lime needed for the stabilization of clays is between 1% to 3% and Kassim and Chern [13] presented 3% to 6% of lime as an optimum additional lime content. Researchers have illustrated that the impact of lime addition on strength of clayey soils depends on soil type, curing time, test method, moisture content, soil unit weight and time elapsed between mixing and compaction (Mitchell and Hooper [14], Ingles and Metcalf [15], Al-Rawi [16], Lees et al. [17], Bell [12], Locat et al. [18], Greaves [4], Rao and Venkataswamy [19]). Kamon and Katsumit [20] investigated engineering properties of soil stabilized with Ferrum lime, and they found that, lime and ferioxid admixture is effective in improvement of durability of stabilized road bases. Guettala et al. [21] evaluated durability of lime stabilized earth blocks by carrying out wetting-drying and freezing-thawing tests on soil samples of Biskra (south east of Algeria), they concluded that, in both wetting-drying and freezing-thawing tests to 12 cycles, increasing of compacting stress and lime content improves the compressive strength and reduces weight loss and water absorption. Kavak et al. [22] explained that the use of lime stabilization for road construction reduces the thickness of the upper layers due to high CBR values and makes the overall constructions more economical. They concluded that, permanent deformation in green and brown lime stabilized clays is reduced from 18 mm to 1 mm and 24 mm to 4 mm, respectively. Khattab et al. [23] evaluated the effect of lime and industrial waste lime admixture on strength, durability and hydraulic properties of clays, and found that by increasing in setting time and stabilizer content, confined compressive strength is increased. The studies of Abdel Majid and Muzahim [24] on effect of hydrated lime on engineering behavior of expansive soils indicate that, addition of hydrated lime to this type of soils is so effective on swelling pressure and swelling potential reduction. Manasseh and Olufemi [25] studied the effect of lime on geotechnical properties of Igumale shale, and concluded that, by addition of 14% lime to Igumale shale, liquid limit and plasticity index of soil is reduced and plastic limit is increased. Also, they found that maximum CBR value of 37% is achieved in this amount of lime. Soni and Jain [26] evaluated the effect of wetting-drying and freezing-thawing cycles on tensile strength of Black Cotton soil stabilized with lime and fly ash. It was found that maximum tensile strength arise, when lime/fly ash ratio is between 1:4 and 1:3. Tawfiq and Nalbantoglu [27] investigated swell-shrink behavior of expansive clays. The results indicate that wetting-drying cycles caused an increase in the swell potential of the soils which were subjected to full swell-full shrinkage cycles. Sahoo and Pradhan [28] investigated the effect of lime stabilized soil cushion on strength behavior of expansive soil, by conducting Unconfined Compression and CBR tests. The test results reveal that maximum increase in strength was achieved after 14 days of curing for 8% lime content. Harichane et al. [29] investigated the effect of lime and natural pozzolana admixture on durability of clayey soils by performing a study on two types of clays, red and grey. The results indicate that stabilized samples have more workability and can endure 12 wetting-drying cycles. Akcanca and Aytekin [30] investigated the influence of wetting–drying cycles on swelling pressures of sand–bentonite mixtures before and after lime treatment of the mixtures. Their results indicated that the swelling pressure is decreased when lime is added to the mixtures. In addition, decrements were observed on swelling pressures by wetting–drying cycles.

The lime stabilized clayey soils used for highway construction, airports and building foundations are usually exposed to different environmental conditions. One of most common condition is wet-dry process. Due to the importance of this issue and a few experimental works about the effect of wetting-drying conditions on clayey soil's strength and no performance of CBR tests in this issue, and also using a finite element method has not been extensively analyzed and developed about this thus, the purpose of this study is to present an experimental and numerical analysis of the effect of plasticity index and wet-dry cycles on the CBR value of clayey soils stabilized with hydrated lime.

Experimental Study

1. Materials used

Three clayey soils used in the present experimental test were obtained from the clay deposits of Abyek, Iran. They are defined as soil (I) and soil (II) with low plasticity soils (CL) and soil (III) defined as high plasticity soils (CH) according to the unified soil classification system ASTM D422-63 [31]. Due to results of XRD test, these clayey soils consist of montmerillonite, nontronite, halloysite, palygorskite and hydrobiotite. The ASTM D4318-00 [32] test was used for the determination of liquid and plastic limits of the soils. The grain size distribution of the selected reference soils are shown in Figure 1. Also, physical and mechanical properties of the selected reference soils and mixture of them with optimum lime content are presented in Tables 1 and 2, respectively.

The material used for stabilization of the considered clays in this study, is hydrated lime supplied by the Hamadan Lime Company. This type of lime has been selected because its usage is safer and more common in industry. It is very fine and passes through an 80 μm sieve opening and contain 85-90 percent Ca $(OH)_2$. The standard chemical and physical properties of the lime used are given in Table 3

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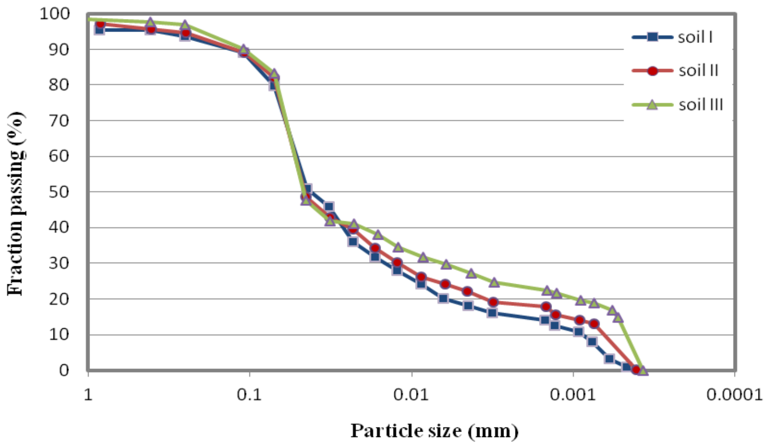

Figure1. Grain size distribution curve of selected soils

[DOR: 20.1001.1.22286837.1394.9.2.7.2]

[DOI: 10.18869/acadpub.jeg.9.2.2817]

Table1. Physical property of tested soils

Soil	Lime content (%)	G_s	LL (%)	PI (%)	ω_{opt} (%)	$\gamma_{d,max}$ (KN/m^3)	soil classification
I	0	2.62	32.5	18.8	11	19.42	CL
	4	2.61	36.7	22.2	12.2	18.94	
II	0	2.69	45.5	22.5	14	18.44	CL
	6	2.71	52.1	28.7	15.9	17.67	
III	0	2.75	55.0	33.8	15	17.65	CH
	4	2.73	59.6	37.7	16.4	17.05	

Table2. Mechanical properties of tested soils

Soil	Lime content (%)	C (kPa)	φ (degree)	E (Mpa)	e_0	C_c	C_s
I	0	24.8	22.1	5.40	0.323	0.045	0.006
	4	16.8	30.1	20.80	0.365	0.051	0.007
II	0	26.5	16.1	7.25	0.431	0.052	0.007
	6	22.3	24.8	14.30	0.511	0.067	0.009
III	0	33.9	13.3	8.61	0.528	0.081	0.012
	4	29.8	18.9	15.40	0.657	0.100	0.014

Table3. Physical and Chemical properties of lime

property	Value
Bulk density (Kg/m^3)	Max: 480
Physical appearance	white powder
Specific gravity	1.25-1.5
Over 80 µm (%)	0
Over 90 µm (%)	2-4
$Ca(OH)_2$ (%)	85-90
Active CaO (%)	59.5-65.2
H_2O (%)	1-2
Fe_20_3 (%)	1.5-2
AL_20_3 (%)	2-3
MnO (%)	2-3
MgO (%)	1-2

2. Preparation and Test procedure

For preparation of samples, lime was added to each reference soil at the room temperature (25±°C) in the order of 4%, 6% and 8% by weight. The lime was thoroughly mixed by hand until homogeneity was reached, and the mixture was quickly stored in a large plastic bag to prevent losing of moisture content. All lime treated soil specimens were tested after curing time of 7 days. The optimum water content of the samples and the maximum dry unit weights were analyzed by the Standard Proctor Tests in accordance with ASTM-698-00 [33]. The Proctor Tests were performed for three clays.

In the CBR experiments performed, the reference clays and clays mixed with 4%, 6% and 8% lime were prepared at their optimum water content and were compacted. The prepared samples were rested for 7 days cure time at room temperatures. The CBR tests were performed in accordance with ASTM D 1883 [34] on wet and dry samples, before and after stabilization. The bearing ratio mould is a rigid metallic cylinder with an inside diameter of 152 mm and a height of 178 mm. A mechanical loading machine equipped with a movable base that moves at a uniform rate of 1.27 mm/min and a calibrated proving ring is attached with a piston, which penetrates into the compacted specimen. The diameter of the piston is 49.6 mm. The loads are carefully recorded as a function of penetration up to 24 mm.

In order to determine the shear strength parameters of unstabilized and lime stabilized samples, a series of direct shear box tests was carried out in accordance with ASTM D 3080-03 [35]. For these tests, samples were placed in the standard shear box of 60 mm× 60 mm in plane and 25 mm in depth. The shear strength parameters such as cohesion and internal friction angle were obtained by performing direct shear tests at the vertical normal stress of 50, 100 and 200 kPa. The strain rate was 0.1 mm/min in all tests.

The wet–dry cycle tests were performed to investigate the effect of wet-dry conditions on CBR values of lime stabilized clays. After preparing the samples at curing time of 7 days, the wet-dry cycle test was undertaken on samples. This process has some steps for each type of clays and admixtures as follow: (i) six samples of three clays with different plasticity index stabilized with lime were submerged in tap water to absorb water over 24 h. (ii) After 24 h, one of the wetted sample was tested by CBR test and five of the samples were then allowed to air-dry at room temperature of 25±°C. The drying of samples required 24 h. (iii) After 24 h, one of the samples that were subjected to 1 wet-dry cycle is tested by CBR test and the others are submerged in water and then, step (ii) was repeated again. This process was continued until CBR test was performed on the last sample that is subjected to 3 wet-dry cycles.

Numerical Study

Finite element analyses

The finite element method has been widely used in analyzing mechanical behavior of soil based materials and structures that deals with soil in recent years. Most of the analyses were used to study stress-strain behavior of soil underlying foundations, earth dams, retaining walls and etc. In this paper, due to experimental study performed in previous sections, in order to investigate the correspondence of results of numerical and experimental analysis, a series of numerical analyses based on Finite Element Method by using ABAQUS 6.9 software were conducted on simulated model of the considered soil. In fact, in this section CBR test is simulated.

Due to geometry of soil sample and dimension of mould in CBR test, axisymmetric stress method was used for static analyses. In this model, mechanical properties of test such as, penetration rate and dimension of penetration piston, applied load from annular metal weights and also the interactions between soil and inside wall of mould were considered. The geometry of soil sample and mould of CBR test in framework of ABAQUS 6.9 software is shown in Figure 2. For modeling the behavior of soil sample, the modified Drucker-Prager/Cap plasticity model was used.

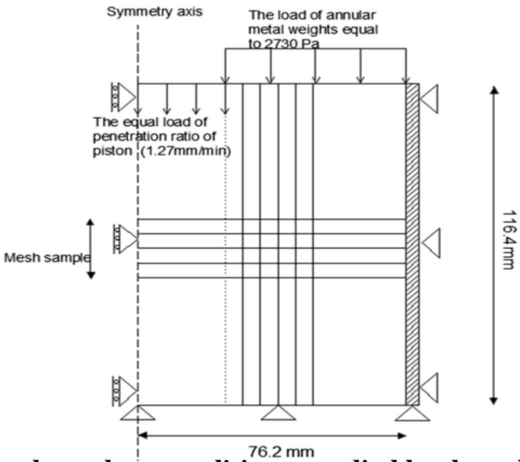

Figure2. Geometry, boundary conditions, applied loads and meshing of soil sample in framework of ABAQUS 6.9

The mechanical properties of considered soils that are recommended to define for using Modified Drucker-Prager/Cap plasticity model are shown in Table 4. As indicated in the table, since cannot model the chemistry effects of lime on behavior of soils, we consider the effect of lime on definable properties of soil in Modified Drucker-Prager/Cap plasticity model, due to experimental investigations mentioned at previous sections.

Table4. Mechanical properties of selected soils defined in Modified Drucker-Prager/Cap plasticity model

Soil	Lime content (%)	γ (KN/m^3)	E (MPa)	β (degree)	D (kPa)	ε_{vol}^{pl}	α	R	K	μ
I		21.55	5.40	40.71	158.91	0.029	0.05	1	0.8	0.3
	4	21.35	20.80	50.30	104.71	0.032	0.05	1	0.8	0.3
II		21.02	7.25	29.71	167.23	0.031	0.05	1	0.8	0.3
	6	20.13	14.30	44.28	121.20	0.038	0.05	1	0.8	0.3
III		20.30	8.61	26.48	214.38	0.045	0.05	1	0.8	0.3
	4	19.04	15.40	35.99	179.64	0.051	0.05	1	0.8	0.3

Results and discussions

1. Experimental

Compaction test

The results of compaction test indicate that by increasing of plasticity index in clayey soils, optimum water content is increased and maximum dry density is diminished (Table 1). The evidence of this behavior is the tendency of soils with high plasticity index in absorbing more water that cause reduction in dry density. The results are in line with Broderick and Daniel [36] and Manasseh and Olufemi [25].

Effect of Lime Content

Figure 3 shows the results of CBR test for three types of clays with various amount of lime. As shown, addition of lime to clays led to increasing of strength in comparison with reference clays, entirely. But in each clay by increasing of lime content to a specified percent age, the strength is increased and addition of lime upper than this content causes reduction in soil's strength. For example, in clay I the addition of 4% lime cause a considerable increase in strength. The cause of this behavior is the existence of pozzolanic reactions that make the soil particles to attach together. At lime contents upper than 4%, the value of strength increment is reduced.

The curves of normalized CBR values versus lime content for three clays are presented in Figure 4. The normalized CBR value is equal to the ratio of CBR value for lime-clay admixture to CBR value of reference clay, for each lime contents. It is noted that the addition of lime content has an optimum percentage. This percentage for clays I, II and III is 4%, 6% and 4%, respectively. The optimum lime content provided in this study corresponds to the results presented by Kassim and Chern [13] and Rahman [11].

Effect of plasticity index

[DOR: 20.1001.1.22286837.1394.9.2.7.2]

[DOI: 10.18869/acadpub.jeg.9.2.2817]

The curve of CBR values versus plasticity index for clays I, II and III at each lime contents is plotted in Figure 5. As shown, for reference clays by increasing of plasticity index the CBR value is increased. This is because of high cohesion in soils with high plasticity index. The results also show that at each percent of lime by increasing of plasticity index the CBR values are reduced. Because, for soils with higher plasticity index the cohesion between particles has more effect

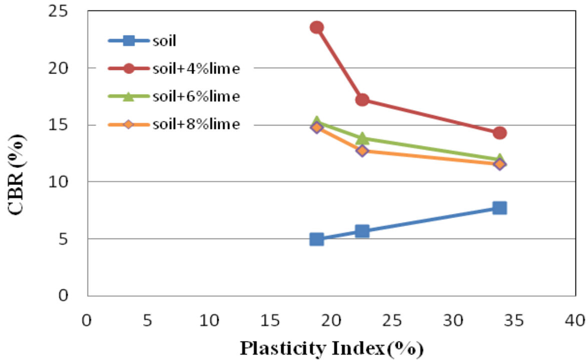

Figure3. Stress-penetration curves for referenced and treated soils

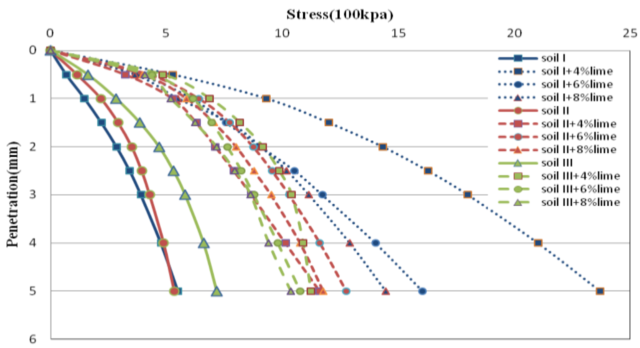

Figure4. Normalized CBR -lime content for selected soils

on soil strength, but, by increasing of lime content in treated soils this cohesion decreased and leads to reduction in CBR values for soils with higher plasticity. As shown in Figure 5 and Table 5, it can be found that by addition of various amounts of lime to clays, the CBR values are increased considerably compared to reference clay, but by increasing of plasticity index, this increment of CBR is diminished. For example, the increment ratio of CBR values for soils I and III by adding 4% lime are 377% and 86%, respectively.

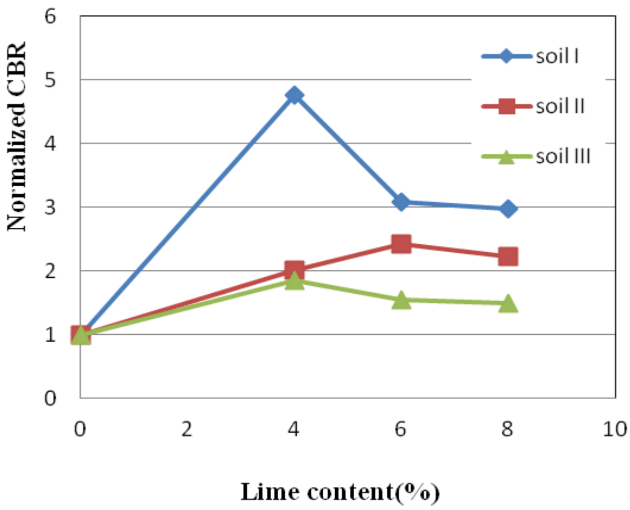

Figure5. CBR value-Plasticity Index curve in each lime contents

Effect of wetting-drying cycles

As described in the previous sections, wetting-drying cycle tests were conducted on clay samples with optimum lime content. Figure 6 presents the results of these tests for clay I. Figure and Table 6 reveal

Table5. Stress values for clays I, II and III at each lime contents

Soil	Stress at 2.5mm penetration (100 kPa)
I	3.418
I+4%lime	16.281
II	3.936
II+6%lime	9.547
III	5.300
III+4%lime	9.859

that the wet-dry conditions have an undesirable effect on strength of lime treated clays. It is obvious that, by performing wet-dry cycles on clays treated with optimum lime content the strength is totally diminished. Also, it can be concluded that for clays with low plasticity index by increasing of number of cycles from 1 to 3 cycles the strength values are increased, but for clays with high plasticity index the process is the reverse. For both of them, the strength at the end of 3 cycles is less than strength of treated clay at normal conditions. For example, the strength of clay I at 2.5mm penetration with PI=18.8 treated with 4% lime at normal conditions is 1628 kPa and this value at the wet phase of the first cycle is reduced considerably to 803 kPa and at the dry phase of this cycle is increased to 1257 kPa and at the end of 3rd cycle the strength value is equal 941 kPa. But, for clay III with PI=33.8 treated with 4% lime, by increasing the number of cycles the strength value at the end of 3rd cycles increased from 197 kPa for cycle0 to 678 kPa at the end of cycle 3. Therefore, the increment of soil's moisture which caused by curing time of 7 days and also short time of wet-dry cycles, results in activation of free ions and increasing of soil strength.

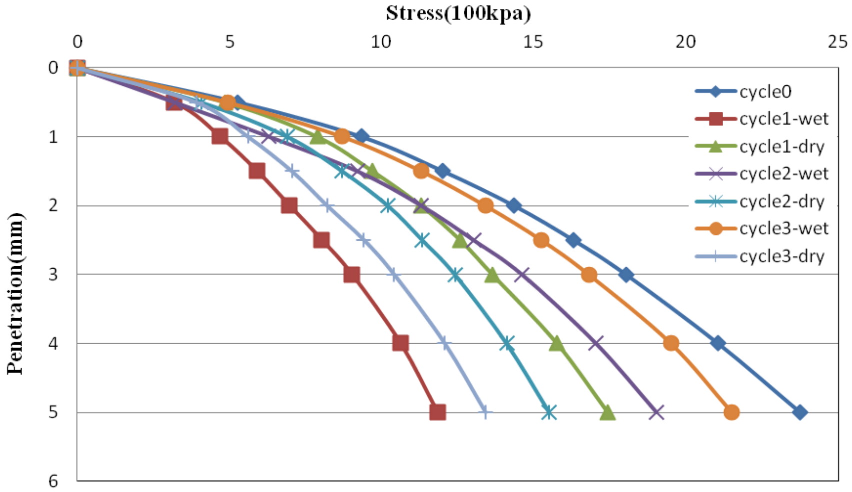

Figure. 6 Stress- penetration curves at each wet-dry cycles for soil I treated with 4% lime

Table 6 Results of wet-Dry cycles test for three clays treated with lime

Cycles	**Stress at 2.5mm penetration(100 kPa)**		
	Soil I+4%lime	**Soil II+6%lime**	**Soil III+4%lime**
cycle0	16.28	9.55	9.86
cycle1-wet	8.03	2.18	1.33
cycle1-dry	12.58	5.25	1.97
cycle2-wet	13.01	2.09	3.71
cycle2-dry	11.33	2.55	2.75
cycle3-wet	15.24	2.48	4.97
cycle3-dry	9.41	7.06	6.78

2. Numerical Analyses

The numerical analysis based on finite element method by using ABAQUS 6.9 was performed on simulated samples of soil I, II and III, and the results are shown in Figures 7, 8 and 9 in comparison with experimental results presented in the previous section.

Figure 7 shows the stress-penetration curves for both numerical and experimental analyses for reference soils and soils treated by optimum lime content. As indicated in the figure, the curves of numerical analysis have a good coincidence with experimental curves, especially in reference soils. By addition of lime to soil, due to chemical reactions that numerical analyses are not capable of modeling them, a negligible difference appears in high stresses. The cause of negligibility of this difference is that in numerical analysis we defined β and d as parameters of Modified Drucker-Prager/Cap plasticity model that are dependent on φ and C of soil, respectively.

The effect of wet-dry cycles on behavior of soil I with 4% lime is shown in Figure 8 for both numerical and experimental analyses. As shown, the results of numerical analysis have correspondence with experimental results. Similar to the previous figure, because of chemical effects of wet-dry cycles on soils and by attention to this fact that we can only presume the mechanical parameters of soils as inputs of numerical analyses, a trifle disparity appears between numerical and experimental results. For example, in soil I as shown in Figure 8, the difference of strength values between experimental and numerical analyses at penetration value of 2.5 mm, in normal conditions (cycle 0) is 8 kPa, but by increasing of cycle number this value is increased to 19 kPa at the end of 3^{rd} cycle. On the other hand, the difference ratio of strength at normal conditions and at the end of 3^{rd} cycle is trifle amount of 0.5% and 2%, respectively.

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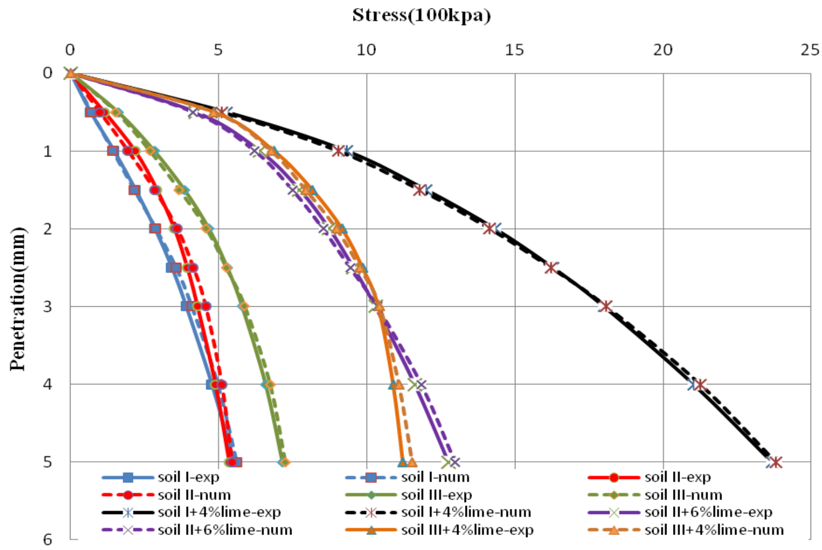

Figure7. Stress- penetration curves for clays in both experimental and numerical analyses

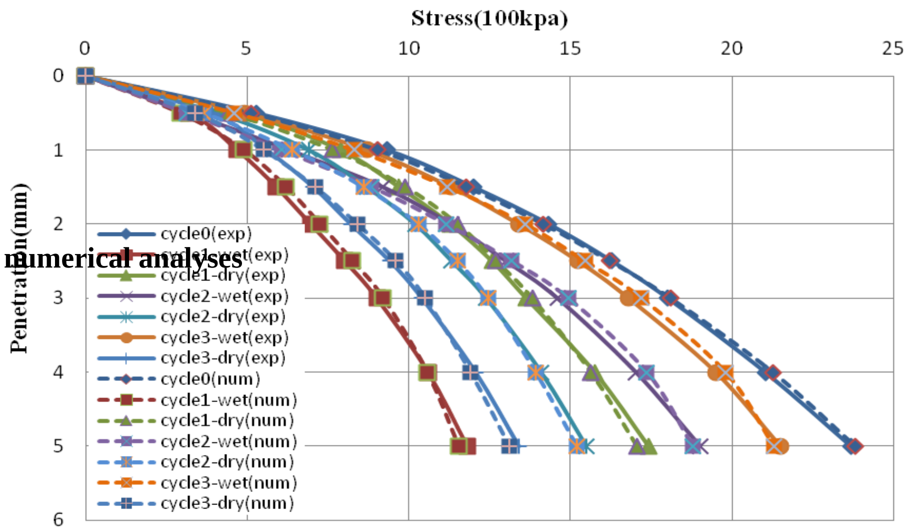

Figure8. Stress-penetration curves for wet-dry cycles of soil I treated with 4% lime in both experimental and numerical analyses

Figure 9 indicates the curve of normalized CBR versus number of cycles for treated clays. As shown in the figure, for clay with low plasticity index (soil I) the normalized CBR values decrease by an increase of wet-dry cycles and for soils II and III with moderate and high plasticity, respectively, at first and second wet-dry cycles the normalized CBR values reduce and then at third cycle increase. It means that, by increase of soil plasticity, the increment of wet-dry cycles results in an increase of bearing capacity of soil. Also, as can be seen in the figure, the maximum disparity between normalized CBR values of numerical and experimental results occurs in soil III treated with 4% lime at the end of 3rd cycle, is very negligible and equal to 0.024. So, it can be concluded that the behavior of soils resulted by numerical analyses based on finite element method have a good correspondence with these experimental analyses.

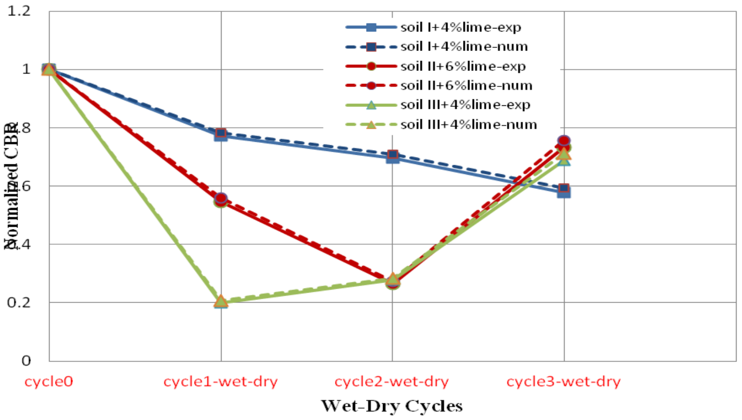

Figure9. Normalized CBR-number of cycles curve for each treated soil in both numerical and experimental analyses

Conclusions

This study was undertaken to present an experimental and numerical investigation of the effect of wetting-drying cycles and plasticity index on the CBR values of lime stabilized clayey soils. The results bring forth the following conclusions:

1) By increasing of plasticity index in clayey soils, optimum water content is increased and maximum dry density is diminished.
2) By addition of lime to soil and increasing of plasticity index, optimum water content is increased and maximum dry density of hydrated lime stabilized soil is diminished.
3) The plasticity index affects the bearing ratio of soil. The bearing ratio of clays is increased by increasing of plasticity index. By addition of various amounts of lime to clays, the CBR values are increased considerably. But this increment of CBR is diminished by increasing of plasticity index.
4) Wet-dry conditions have a distractive effect on clayey soils treated with lime. The CBR decreases during the wetting phase and increases during the drying phase of each cycle, and applying wet-dry cycles is caused to reduction in strength compared with reference clays.
5) The comparison of experimental and numerical analyses indicates a good correspondence of results. The existent trifle disparity is because of incapability of numerical analysis in modeling of chemical reactions.

Acknowledgements

This work was supported by Soil Mechanic Laboratory of Imam Khomeini International University, Qazvin, Iran. The financial support is gratefully acknowledged.

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