The Effect of Rice Husk Ash on Mechanical Properties of Clayey Soils Stabilized with Lime in the Presence of Sulphate

Mohammad Hossin Bazyar[*1], Mostafa Ebrahimi[2],
Mehdi Zamani Lenjani[3], Masoud Makarchian[4]
1, 2 & 3. Department of Civil Engineering, Faculty of Engineering, Yasooj Univeersity
4. Department of Civil Engineering, Faculty of Engineering, Bu-Ali Sina University, Hamedan

Received: 17 Jan 2016 Accepted: 10 June 2016

Abstract

Geotechnical engineers, in many cases face with low strength or high swelling potential of clayey soils. Stabilization methods are used to improve the mechanical properties of this type of soils. Lime and cement are the most popular materials used in chemical stabilization of clayey soils. If sulphate exists in the stabilized clayey soil with lime, or if soil is exposed to sulphates, problems such as strength reduction and swelling will occur. Reuse of industrial residual such as Rice Husk Ash (RHA) can be beneficial from the economy point of view. RHA includes a proper amount of silica with high specific surface area which is very suitable for activating the reaction between the soil and lime. In this paper, chemical stabilization of gypsum clays using lime and RHA is addressed.

[*]Corresponding author mhbazyar@mail.yu.ac.ir

[DOR: 20.1001.1.22286837.1396.11.3.7.8]
[DOI: 10.18869/acadpub.jeg.11.3.23]

Sulphates exist in the constitution of the soil. Unconfined compression strength and swelling potentials of the stabilized soil are evaluated. The results of this study indicate that RHA has positive impacts on improving mechanical properties of the gypsum clays stabilized with lime. From the view point of strength and swelling characteristics, and economy, addition of 6–8% lime and 8-10% RHA as an optimum amount is recommended.

Keywords: Gypsum clay, Unconfined Strength, Swelling potential, Stabilization, Rice Husk Ash.

Introduction

Detrimental role of sulphates in concrete and the Ettringite formation has been recognized since long time ago. However, the adverse role of sulphates in stabilized clayey soils with lime was not known until the works done by Sherwood [1]. Hunter [2] studied the sulphate-induced swelling of the stabilized soils with lime and cement. In clay stabilization with lime when sulphate is present in the soil environment, suspension products including complex compounds of calcium, hydrated alumina and silica are formed on the surface of clay particles. If the materials formed on the surface of clay particles absorb the water, crystalline products named Ettringite with needle-shaped structures are produced. The production rate is controlled by the amount of free lime, gypsum and alumina presented in the environment [3]. Since the Ettringite formation causes the environment water to be absorbed, it initially increases the soil

[DOR: 20.1001.1.22286837.1396.11.3.7.8]
[DOI: 10.18869/acadpub.jeg.11.3.23]

strength. However, soil swelling potential increases significantly, instead [4]. The ability of water absorption only exists during the formation of Ettringite, so when the crystalline structure is completed, this capability is lost [4]. In spite the swelling problems, Ettringite formation results in an increase in the strength of stabilized soils as it can fill the empty spaces and creates a spatial structure [5].

Researchers have proposed several methods for reducing the damaging effects of sulphates on soils. Some of these methods include: adding barium chloride and barium compounds before lime added to soils [6], adding lithium salts with lime [7], using ground cement blast furnace slag or fly ash with cement [8], adding blast furnace slag with cement and lime [4] and using sulphate resistance cement [9].

Annually millions of tons of industrial, mineral and agricultural wastes are produced in the world, which create serious problems in different areas such as environmental pollution leading to dangers to the health of many inhabitants. Due to this fact, research aims at finding solutions to use of waste materials is an inevitable necessity. On the other hand, the sources of coal, sand, clay and other raw materials, especially resources that are located near large urban centers may be finished, or may lead to expensive materials due to transportation costs and environmental restrictions. However, some of these wastes and their by-products may be used as a substitute raw material in construction of building materials. One of the agricultural

[DOR: 20.1001.1.22286837.1396.11.3.7.8]

[DOI: 10.18869/acadpub.jeg.11.3.23]

waste materials is husk separated from rice. Due to its limited applications, it is burned and destroyed. The product remained from the burning phase, which is called rice husk ash (RHA), has unique characteristics such as possessing high amount of silica.

One of the most common and least expensive ways to improve soil mechanical properties is stabilization with lime. Studies show that the reactivity of lime and clay in the presence of moisture and low temperature is performed slowly. Hence, for accelerating the reaction, adding RHA containing abundant silica with high specific surface area is suitable. The positive effect of RHA on the engineering characteristics of soil has been reported in the literature [10,11].

AlHassan [12] investigated the effect of the RHA on the soil-lime mixtures using unconfined compressive strength (UCS) test and coefficient of permeability. The results showed that UCS of the specimens increased with increasing RHA content at specified lime contents to their maximum values at 6% of RHA content. Moreover, Muntohar [13] showed that the addition of 6% lime in combination with RHA, has a significant effect on reducing swelling potential and increasing the durability of soils.

With various tests performed by Choobbasti et al. [14] on the soil stabilized with lime and RHA, remarkable results were obtained. Based on their results, with the increase of amounts of lime and RHA, soil maximum dry density decreased and optimum moisture content increased. Adding RHA and lime to the soil mixture reduces plasticity

[DOR: 20.1001.1.22286837.1396.11.3.7.8]

[DOI: 10.18869/acadpub.jeg.11.3.23]

index (PI), and increases shear strength and CBR of soil samples. Qasim et al. [15] reviewed effectiveness of RHA for different applications including soil stabilization which is very important for environment to be used waste materials. The previous studies on use of RHA in stabilizing soils have shown the favorable potentials of improving the engineering properties of soils. However, the majority of investigations performed till now have focused on clay soils without sulphates or the soils were not exposed to sulphates. This paper aims at investigating the effects of RHA on some geotechnical properties (unconfined compression strength and swelling potential) of gypseous clays. The soil used in this study is gypseous clay having 10.1% gypsum content. It was obtained from a region near Dehdasht, Kohgiluyeh and Boyer-Ahmad Province, Iran. The clayey soils stabilized with different percentages of lime and RHA were cured for periods of 7 and 28 days. As the second objective, this study is carried out to investigate the effectiveness of RHA in reducing lime usage in stabilizing clayey soils.

Materials

In next sub-sections the properties of the clayey soil, lime and RHA are discussed in detail.

Gypseous clay

The presence of gypsum as a widespread soil component in semi-arid and arid regions is due to its solubility. In spite of having a relatively low solubility in aqueous systems, gypsum can be dissolved in the soil. Further precipitation of Ca^{2+} and SO_4^{2-} as gypsum, leads to the formation of convex gypsum in the soil. The low rainfall in these areas prevents the leaching of the gypsum accumulated in the soil. Gypsum in soil can be uniformly distributed, isolated in the soil matrix, or concentrated in special peso-features in some horizons. When uniformly distributed, it will be only possible to detect gypsum by identifying SO_4^{2-} ions through a qualitative chemical test for sulphates [16]. To measure the amount of gypsum in the soil, acetone method is used. To measure the amount of sulphate in the soil, acid soluble sulphate method is also used [17]. To determine the physical specifications of the gypseous soil, laboratory tests such as particle-size analysis, compaction test and Atterberg limits are performed. The soil used in this study is a gypseous clay having 10.1% gypsum content. The soil color is milky and based on the unified soil classification system (USCS), the soil is classified as CL. Soil liquid limit, plastic limit, and plasticity index are 30.5, 16.0 and 14.5, respectively. The specific gravity of the gypseous clay was found to be 2.61. Figure 1 depicts the particle size distribution curve of the gypseous soil and its chemical and physical specifications are shown in Table 1.

Lime

For the gypseous clay stabilization, lime and RHA are used. The type of the lime used in this study is the hydrated lime. The specific gravity of 2.31 is determined for the lime in the lab. The lime was provided from the market of construction materials in Yaosuj, Iran. Its color is white and the amount of calcium and magnesium oxide was obtained to be around 87%.

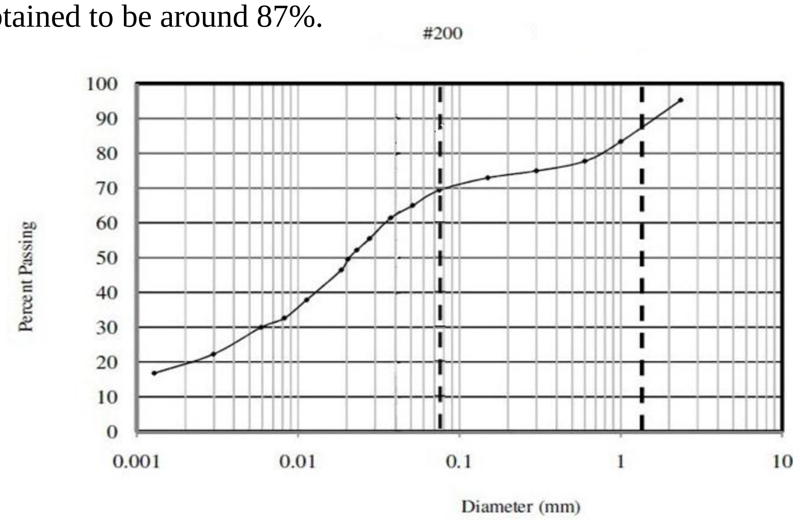

Figure 1. Particle size distribution curve of the gypseous soil

Table 1. Chemical and physical properties of the natural gypseous soil

Chemical and Physical characteristics	Quantity
Natural Water Content (%)	1.7
Liquid Limit (%)	30.5
Plastic Limit (%)	16.0
Plasticity Index (%)	14.5
Sulphate Content (%)	13.9
Gypsum Content (%)	10.1
Specific Gravity (G_S)	2.61
Optimum Moisture Content (%)	16.8
Maximum Dry Density (kN/m^3)	16.9
Color	Milky
USCS	CL

Rice Husk Ash

Two-stage combustion method was used for the preparation of RHA. Firstly, prepared rice husk was cleaned by hand and dried completely at the environmental temperature in the sun. Then, the dried rice husk was burned in a brick kiln. This stage is called rice husk carbonization in which the burning temperature reaches to 300°C. The next stage is called de-carbonization in which the carbonized rice husk is transferred to the electric furnace and is burned in 600°C temperature to completely remove the carbon. To identify and quantify the oxide elements present in the obtained rice husk ash, X-Ray Fluorescence (XRF) analysis was performed. XRF technology provides one of the simplest, most accurate and most economic analytical way to determine the chemical composition of many materials, especially in the investigation of building materials. Chemical oxide composition of RHA is shown in Table 2.

Table 2. Chemical oxide composition properties of the RHA

Chemical characteristics	Quantity (%)
SiO_2	88.26
Al_2O_3	0.35
Fe_2O_3	0.24
CaO	0.88
SO_3	0.34
MgO	0.41
Na_2O	0.04
K_2O	1.65
P_2O_5	0.55
TiO_2	0.02
LOI	6.94

According to Table 2, the produced RHA includes 88.26% silica meaning that the ash is approximately net silica. As a result, it can cause a pozzolanic reaction between the soil and lime. In this investigation, RHA passing through sieve No. 200 (75 micrometers) with specific gravity 1.91 was used in the tests.

Laboratory test procedures

To determine the influence of lime and RHA on mechanical properties of the gypseous clay, unconfined compressive strength and CBR [18] tests were performed. Each specimen used in unconfined compressive strength tests was compacted at optimum moisture content and maximum dry density. Uniaxial tests were conducted under a constant strain rate of 1mm/min. Experiment layouts with their indexes carried out in this study are summarized in Tables 3 and 4.

Table 3. Unconfined compressive strength test mixtures and their indexes

Mix Design	Index
Soil without additive	Soil
Soil+2, 4, 6, 8, 10 % Lime	2, 4, 6, 8, 10 L
Soil+2, 4, 6, 8, 10 % RHA	2, 4, 6, 8, 10 RHA
Soil+2%Lime +2, 4, 6, 8, 10 % RHA	2L+2, 4, 6, 8, 10 RHA
Soil+4%Lime+ 2, 4, 6, 8, 10 % RHA	4L+2, 4, 6, 8, 10 RHA
Soil+6%Lime+ 2, 4, 6, 8, 10 % RHA	6L+2, 4, 6, 8, 10 RHA
Soil+8%Lime+ 2, 4, 6, 8, 10 % RHA	8L+2, 4, 6, 8, 10 RHA

Table 4. CBR test mixtures and their indexes

Mix Design	Index
Soil without additive	Soil
Soil+2, 6, 10 % Lime	2, 6, 10 L
Soil+2%Lime +2, 4, 6, 8, 10 % RHA	2L+2, 4, 6, 8, 10 RHA
Soil+6%Lime+ 2, 4, 6, 8, 10 % RHA	6L+2, 4, 6, 8, 10 RHA
Soil+10%Lime+ 2, 4, 6, 8, 10 % RHA	10L+2, 4, 6, 8, 10 RHA

Two curing period of 7 and 28 days of samples in laboratory temperature were selected for the experiments. To prevent from getting dry and losing the moisture, samples were kept in plastic bags. To make sure about the precision of the results of experiments all tests were repeated three times. The soil mixtures, with and without additives, were thoroughly mixed with various moisture contents and allowed to equilibrate and homogenize for 24h prior to compaction. Figure 2 shows the effect of the addition of Lime, RHA, and Lime–RHA mixtures on the compaction characteristics of the soil. As displayed in this figure, increase of lime and RHA percentages in the soil mixtures increases the optimum moisture content and decreases the maximum dry density of the stabilized clayey soil. The maximum dry density decreases with the increase in lime content and is in agreement with earlier findings by Osinubi [19], AlHassan [12] and Choobbasti et al. [14]. This decrease resulted from the flocculation and agglomeration of clay particles, caused by the cation exchange reaction. The maximum dry density further decreases with the introduction and subsequent increase of RHA at specified lime contents. This decrease is attributed to the relatively lower specific gravity of the ash [12]. The increase in optimum moisture content with increasing lime content confirms with the findings of Ola [20]. The reason is that the increased desire for water is somewhat appropriate to the increasing amount of lime, as more water is required for the dissociation of lime into Ca and OH ions to supply more Ca ions for the cation exchange reaction [12]. The specimens used for uniaxial and CBR tests were prepared with the optimum moisture content and maximum dry density for different soil mixtures obtained from compaction tests.

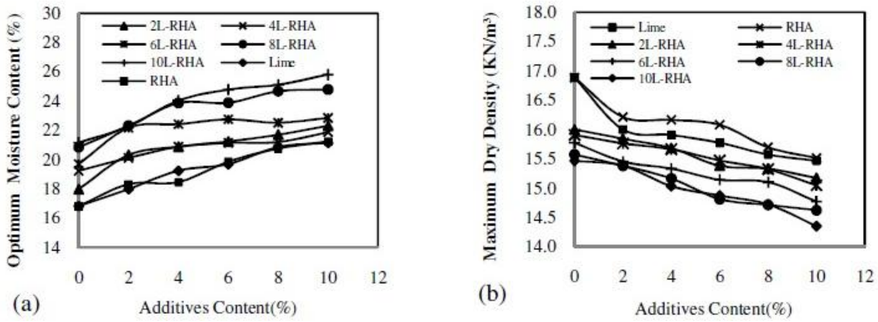

Figure 2. Variation of compaction characteristics with percentage of additives: (a) optimum moisture content; (b) maximum dry density.

Results and Discussions

In this section, the results obtained from the experiments are explained and some discussions are provided. For the first part results and discussions related to unconfined compression strength tests are presented. It is followed by results obtained from the CBR tests.

Effect of lime and RHA on the UCS of the gypseous soil

Unconfined compressive strength (UCS) test is the first and simplest test suggested for the determination of the required amount of additives to be used in stabilization of soils especially in the design of pavements.

Gypseous clay stabilized with only lime or RHA

For quantitative comparison of the unconfined compressive strength in the samples, a Soil Improvement Ratio (SIR) indication equal to the amount of the increase in the unconfined compressive strength in the gypseous clay stabilized with lime (UCS_{Lime}) to that of the gypseous clay (UCS_{Soil}) is defined

$$SIR_L = \frac{UCS_{Lime}}{UCS_{Soil}} \quad (1)$$

The results of unconfined compressive strength tests for different percentages of Lime and RHA after 7 and 28 days of curing are shown in Figure 3 and Tables 5 and 6, respectively. As shown in Figure 3(a) and Table 4, with adding lime to the soil samples, lime reaction with clay could be due to the Ettringite formation according to the literature. The Ettringite absorbs the water in the environment and increases the soil strength. For tests with 7 days of curing time, maximum unconfined compressive strength in specimens was obtained in test with 6L combination. With increasing the curing time to 28 days, the lime reaction with clay increases

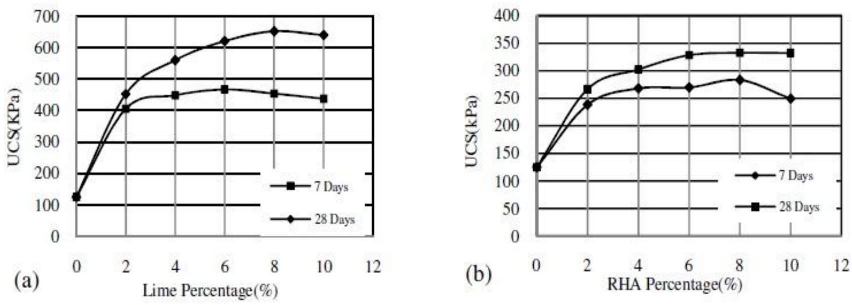

Figure 3. The influence of curing period and additives content on UCS of gypseous clay: (a) lime; (b) RHA

Table 5. The optimum lime contents and UCS and SIR_L values

Mix Design	UCS (kPa)	SIR_L
Gypseous clay	124.9	1
Gypseous clay stabilized with lime		
7 days curing time optimum lime content 6%	466.89	3.74
28 days curing time optimum lime content 8%	652.13	5.22

Table 6. The optimum RHA contents and UCS and SIR_{RHA} values

Mix Design	UCS (kPa)	SIR_{RHA}
Gypseous clay	124.9	1
Gypseous clay stabilized with Lime		
7 days curing time		
Optimum lime content 8%	283.34	2.27
28 days curing time		
Optimum lime content 10%	332.51	2.66

As a result, the unconfined compressive strength of the gypseous clay increased and maximum unconfined compressive strength in samples was obtained for the 8L combination. In other words, with increasing the curing time from 7 to 28 days, both the optimum lime content and the unconfined compressive strength values have been increased. To obtain a beneficial effect of stabilizer on soil, the soil improvement ratio should be greater than 1. The values of SIR_L for 7 and 28 days of curing time for the clayey soil mixed with lime are presented in the last column of Table 5. As it can be seen, for 7 and 28 days of curing the SIR values are equal to 3.74 and 5.22, respectively showing the effect of lime on the increasing the unconfined compressive strength of the clayey soil. For the case of stabilization with RHA, as shown in Figure 3(b) and Table 6, by increasing the percentage of RHA to the samples, unconfined compressive strength of soil slightly increases. This may be due to the fact that clay-RHA combination particles were rougher than clay particles. In other words, clay-RHA combination is rougher than the natural clay. Increasing the curing time from 7 to 28 days also had no significant effect on the increase of soil unconfined compressive strength. A new soil

[DOR: 20.1001.1.22286837.1396.11.3.7.8]
[DOI: 10.18869/acadpub.jeg.11.3.23]

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improvement ratio is introduced to quantify the effect of RHA on the unconfined compressive strength of the stabilized soil with RHA:

$$SIR_{RHA} = \frac{UCS_{RHA}}{UCS_{Soil}} \tag{2}$$

The values of maximum unconfined compressive strength and SIR_{RHA} are demonstrated in Table 6. In comparison with the values of SIR_L, the values of SIR_{RHA} is about 2.27 resulting in a very less increase of unconfined compressive strength compared with that of the soil stabilized with lime. As a result of this part of investigation, it can be suggested that RHA solely and without lime had less cementations properties and is not suggested to be used by itself for the stabilization of soils.

Gypseous clay stabilized with both lime and RHA

The results of unconfined compressive strength tests for different percentage of lime-RHA combination, after 7 and 28 days of curing are shown in Figure 4 and Tables 7 and 8, respectively. In the presence of lime, pozzolanic properties of RHA are activated and the mixture strength is increased a lot. The results of this part of study as depicted in Figure 4(a) show that for 7 days of curing time, maximum unconfined compressive strength is obtained in the 4L-8R samples. It means that for soil mixtures with 4% lime and 8% RHA, the maximum unconfined compressive strength is achieved. In samples with 7 days of curing, the pozzolanic reaction is not completely activated so the unconfined compressive strength increased with increasing the lime content to 4%, but in higher values of the lime, it decreased. This test shows the optimum content of additives combination which is necessary to be determined for each soil stabilization project.

In 28 days of curing time, samples have sufficient curing time for completing pozzolanic reaction so with increasing lime content in samples up to 6 %, unconfined compressive strength of the lime-RHA

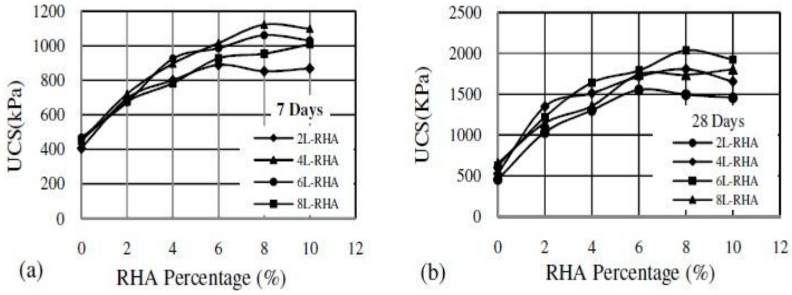

Figure 4. The influence of lime-RHA combination content on unconfined compressive strength of the gypseous clay: (a) 7 days of curing time; (b) 28 days of curing time

Table 7. The optimum lime-RHA combination content and UCS and $SIR_{Lime-RHA}$ values in 7 days of curing time

Lime Content	Combination	UCS (kPa)	$SIR_{Lime-RHA}$
2L	2L-6RHA	888.1	7.11
4L	4L-8RHA	1122.8	8.99
6L	6L-8RHA	1060.9	8.49
8L	8L-10RHA	1008.9	8.08

Table 8. The optimum lime-RHA combination contents and their UCS and $SIR_{Lime-RHA}$ values in 28 days of curing time

Lime Content	Combination	UCS (kPa)	$SIR_{Lime-RHA}$
2L	2L-6RHA	1550.2	12.41
4L	4L-8RHA	1806	14.46
6L	6L-8RHA	2035.2	16.29
8L	8L-10RHA	1804.6	14.45

[DOR: 20.1001.1.22286837.1396.11.3.7.8]

[DOI: 10.18869/acadpub.jeg.11.3.23]

combination increased, but in the lime content of 8%, it decreased slightly. It can be said that combination of 6L-8RHA is the optimum amount of additives for 28 days of curing time. The results show that for samples with 28 days of curing time, maximum unconfined compressive strength is obtained in the combination 6L-8R. As is illustrated in Figure4, in all specimens, the unconfined compressive strength increased with the increase of the curing time. With the increase of curing time from 7 to 28 days, pozzolanic reactions between the gypseous clay, lime and RHA have been more completed and unconfined compressive strength increased.

In both 7 and 28 days of curing time, the specimens with lime content 2%, the unconfined compressive strength increased with the increase of the RHA to 6%, but in higher value of the RHA, UCS decreased slightly which can be caused due to the lack of lime in the samples for pozzolanic reaction with the RHA. With the increase in lime content, further RHA was reacted with lime. Hence, in samples with the lime of 4% and 6%, maximum unconfined compressive strength is obtained in the 4L-8RHA and 6L-8RHA. This process continues so that in the samples with 8% lime, maximum unconfined compressive strength is obtained in the 8L-10RHA. Results of other researchers show that there is optimum combination of lime and RHA for soil stabilization, if more RHA is used, then reaction of the amorphous silica and alumina in RHA will not occurred. Also, more lime results in decrease in UCS which is due to insufficient silica and alumina for reaction with lime [14,16]. As for the soil mixtures with only lime and RHA, for the soil stabilized with both lime and RHA a new soil improvement ratio is defined as:

$$SIR_{Lime-RHA} = \frac{UCS_{Lime-RHA}}{UCS_{Soil}} \tag{3}$$

The values of unconfined compressive strength and $SIR_{Lime-RHA}$ for 7 and 28 days of curing are presented in Tables 7 and 8. As it can be observed from Table 7, for samples with curing time of 7 days, maximum $SIR_{Lime-RHA}$ of 8.99 is obtained for the soil mixture with 4% lime and 8% RHA. For samples with curing time of 28 days, maximum $SIR_{Lime-RHA}$ of 16.29 is achieved. To verify the effect of RHA on strength of soils stabilized lime, a new soil improvement factor SIR_{LRHA-L} indicating the unconfined compressive strength of the soils stabilized with lime and RHA, with respect to unconfined compressive strength of the soil stabilized with lime is introduced as

$$SIR_{LRHA-L} = \frac{UCS_{Lime-RHA}}{UCS_{Lime}} \tag{4}$$

The quantitative comparison of unconfined compressive strength results for different combination of additives used in the stabilized soil for curing time of 7 and 28 days is provided in Table 9 and Figures 5, 6 and 7. As can be seen from Table 9, for curing time of 7 days for the soil stabilized with 4% lime and 8% RHA, the value of SIR_{LRHA-L} is found to be 2.5 showing the significant effect of adding RHA in soils stabilized with lime. As can be observed from Table 9 and Figures 5, 6 and 7 the improvement measured when using the mixture of RHA and lime is much more efficient than the sum of the improvements when using each individual additive in the same proportion.

Swelling potential of the stabilized gypseous clay using CBR tests

To determine the swelling potentials of the gypseous clay and the gypseous clay stabilized with lime and RHA, CBR tests were conducted. Specimens were cured for 7 and 28 days and then were immersed in water for 4 days. In these 4 days, samples' swelling potential was measured in every 24 hours. In the next sub-sections, the results obtained for swelling potential of samples are presented and discussed.

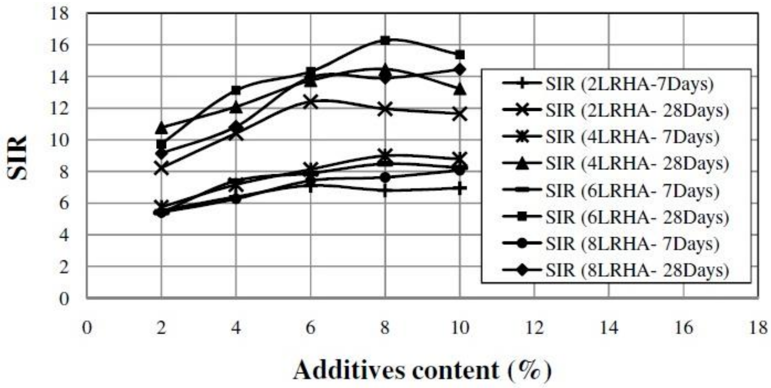

Figure 5. Soil improvement ratio for a gypseous clay stabilized with lime and RHA

Stabilized gypseous clay with lime and RHA with 7 days curing time

The results of the experiments used to obtain swelling potential of the gypseous clay stabilized with lime and RHA after 7 days of curing

Table 9. Quantitative comparison of unconfined compressive strength for different combination of additives used in stabilized soil for curing times of 7 and 28 days

Indication	Curing time	Additive contents (%)				
		2	4	6	8	10
SIR_L	7	3.25	3.59	3.74	3.63	3.50
	28	3.62	4.20	4.97	5.22	5.12
SIR_{RHA}	7	1.91	2.15	2.16	2.27	2.00
	28	2.14	2.42	2.63	2.65	2.66
$SIR_{2L\text{-}RHA}$	7	5.55	6.40	7.11	6.81	6.95
	28	8.23	10.41	12.41	11.95	11.65
$SIR_{4L\text{-}RHA}$	7	5.76	7.17	8.13	8.99	8.79
	28	10.78	12.09	13.74	14.46	13.24
$SIR_{6L\text{-}RHA}$	7	5.39	7.41	7.89	8.49	8.25
	28	9.74	13.12	14.31	16.29	15.39
$SIR_{8L\text{-}RHA}$	7	5.41	6.27	7.42	7.63	8.08
	28	9.15	10.84	13.95	13.90	14.45
$SIR_{2LRHA\text{ - }2L}$	7	1.71	1.97	2.19	2.10	2.14
	28	2.27	2.88	3.43	3.30	3.22
$SIR_{4LRHA\text{ - }4L}$	7	1.61	2.00	2.26	2.50	2.45
	28	2.57	2.88	3.27	3.44	3.15
$SIR_{6LRHA\text{ - }6L}$	7	1.44	1.98	2.11	2.27	2.21
	28	1.96	2.64	2.88	3.28	3.10
$SIR_{8LRHA\text{ - }8L}$	7	1.49	1.72	2.04	2.10	2.22
	28	1.75	2.08	2.67	2.66	2.77

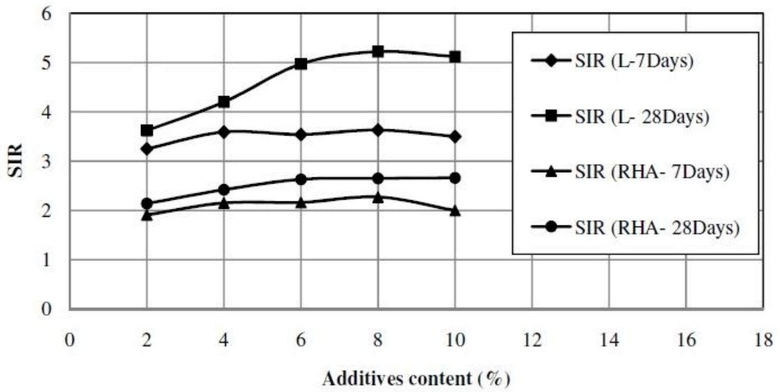

Figure 6. Soil improvement ratio for a gypseous clay stabilized with lime-RHA

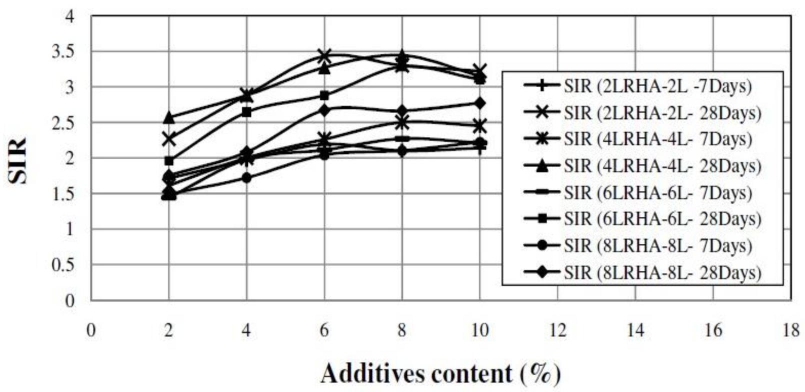

Figure 7. Soil improvement ratio for a gypseous clay stabilized with lime-RHA with respect to the gypseous clay stabilized with lime.

are shown in Figure 8. Figure 8(a) demonstrates the results for soils stabilized with lime. Swelling potentials of soils stabilized with 2%, 6% and 10% lime content and 2%, 4%, 6%, 8% and 10% RHA content are depicted in Figures. 8(b), 8(c) and 8(d), respectively. As is portrayed in Figure 8 (a), it is found for specimens with 7 days of curing period, with the increase of the lime percentage, swelling potential increased which is because of the presence of sulphate in the clayey soil, and the Ettringite formation. In general, swelling potential for stabilized samples with lime is less than swelling potential of natural clays. Ettringite is a swelling mineral that absorbs the environment water and increases the soil strength. With the absence of water from the samples, the more detrimental effects of the Ettringite were prevented. However, as soon as water reached the samples, this mineral is activated and swelling potential increases.

The steep slope of the swelling potential curves shown in Figure 8 for samples stabilized with lime and RHA within first 24 hours of immersion in water, shows that high percentage of swelling is obtained in the first 24 hours after immersion of samples in water. Also, from Figures. 8(b), 8(c) and 8(d) it can be seen that the lowest swelling potential in all percentages of lime is obtained in the highest percentage of RHA. The swelling potential in all samples decreased with the increase in the RHA content. It is noteworthy that with the increase of the percentages of RHA from 8 to 10%, swelling potential has not been reduced significantly indicating the optimum percentage of RHA being 8%. It is also observed from comparison of Figures 8(b), 8(c) and 8(d) that at the end of day 4, the lowest swelling percentage in the stabilized gypseous clay with lime and RHA exists in samples with the lime content of 6%. Swelling potential in samples with the lime content of 2% was higher than samples with the lime of 6% due to the lack of sufficient lime for pozzolanic reaction with RHA. On the other hand, due to surplus lime in the environment and lime reaction with gypsum, swelling potential in samples with the lime percentage of 10% was higher than samples with the lime of 6%. Figure 8 demonstrates the remarkable effect of RHA on reduction of swelling potential of the gypseous clayey soil stabilized with lime.

[DOR: 20.1001.1.22286837.1396.11.3.7.8]
[DOI: 10.18869/acadpub.jeg.11.3.23]

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Stabilized gypseous clay with lime and RHA with 28 days curing time

The results for the swelling potential of the gypseous clay stabilized with lime and RHA after 28 days of curing are shown in Figure 9. Figure 9(a) shows the swelling potential of the stabilized gypseous clay with different lime contents after 28 days of curing time. Compared with Figure 8(a) (with the curing time of 7 days), curing time of 28 days results in a significant reduction in the swelling potential. This is due to more completion of pozzolanic reaction between lime and the gypseous clay in 28 days, and also because of the formation of crystalline structure in Ettringite. For the cases when RHA has been added to the soil-lime mixture, as is shown in Figures. 9 (b), 9(c) and 9(d), after 28 days of curing time pozzolanic reaction between the gypseous clay, lime and RHA have been more completed and the strength of the soil mass increased. Thus, samples' swelling potential decreased greatly.

In all experiment combinations, swelling potential decreased with the increase of the RHA, such that in high contents of RHA, swelling potential was almost zero. Again compared with Figures. 8(b), 8(c) and 8(d), the effect of increase of curing time on reduction of swelling potential of the gypseous clay stabilized with lime and RHA is clearly observed.

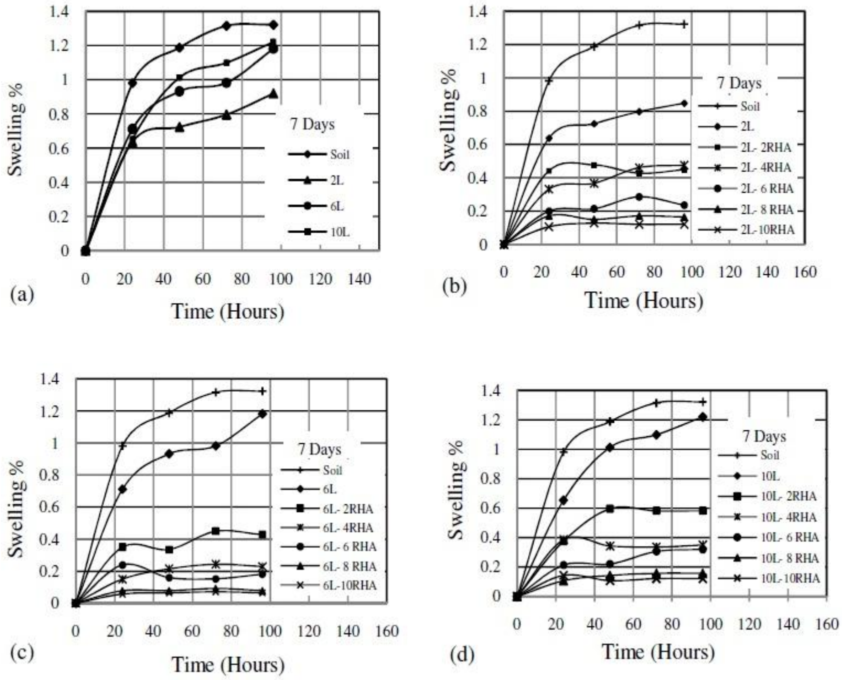

Figure 8. Swelling potential of the stabilized gypseous clay with 7 days of curing time: (a) samples stabilized with lime; (b) samples stabilized with the lime content of 2% and RHA; (c) samples stabilized with the lime content of 6% and RHA; (d) samples stabilized with the lime content of 10% and RHA

Quantitative comparison of swelling potential of the gypseous clay stabilized with lime, RHA and both lime and RHA

To quantitatively investigate the effect of both lime and RHA on swelling potential of gypseous clays, Swelling Reduction Ratio (SRR) presenting the amount of reduction in swelling of stabilized soils with respect to the clayey soil after 96 hours is defined:

$$SRR_{(L)} = \frac{Swelling_{Lime}}{Swelling_{Soil}} \tag{5}$$

$$SRR_{(LRHA)} = \frac{Swelling_{Lime-RHA}}{Swelling_{Soil}} \tag{6}$$

$$SRR_{(LRHA-L)} = \frac{Swelling_{Lime-RHA}}{Swelling_{Lime}} \tag{7}$$

To have a beneficial effect of lime and RHA on reduction in swelling potential of the gypseous clay, SRR should be smaller than 1. The results of the experiments for soil swelling in terms of swelling reduction ratio are depicted in Figures. 10, 11 and 12. As can be observed from Figure 10 for soils stabilized with lime, the values of $SRR(L)$ is increased up to 0.9 with the increase of lime contents to 10% for samples cured for 7 days. It shows the effect of sulphate in increasing the swelling potential of clayey soils stabilized with lime. In contrast, with the increase of curing time to 28 days, the values of $SRR_{(L)}$ is reduced but the decrease is not substantial. The values of $SRR_{(LRHA)}$ defining the ratio of the swelling of the clayey soils stabilized with both lime and RHA with respect to the swelling of the clayey soil are plotted in Figure 11. As it can be seen clearly, with the increasing the content of RHA, the swelling potential of the stabilized soil is reduced significantly highlighting the beneficial effect of RHA on the reduction of the swelling of the stabilized soil. This effect is due to pozzolanic reaction between soil, RHA and lime that is a cementation process and makes the soil stringer and cemented skeleton of soil prevent from swelling.

Values of (in 7 days curing time), ~~for~~ lime content of 2, 6 and 10 percent, are decreased down to 0.1, 0.06 and 0.04, respectively. It demonstrates that by using 6% lime and 8% RHA, and reduction of

[DOR: 20.1001.1.22286837.1396.11.3.7.8]
[DOI: 10.18869/acadpub.jeg.11.3.23]

about 95% in the swelling of the clayey soil is achieved. The values of $SRR_{(LRHA-L)}$ presenting the ratio of the swelling of the stabilized clayey soil with both lime and RHA with respect to the swelling of the clayey soil stabilized with lime are portrayed in Figure 12. Again the significant effect of RHA in the reduction of swelling potential of the mixture of soil and lime is shown. From Figure 12 it is found that using 6% lime and 8% RHA, leads to a reduction of 94% in swelling of soils stabilized with lime. Again as it is demonstrated from Figures 10, 11 and 12, the improvement obtained when using the mixture of RHA and lime is much more beneficial than the sum of the improvements when using each individual additive in the same proportion.

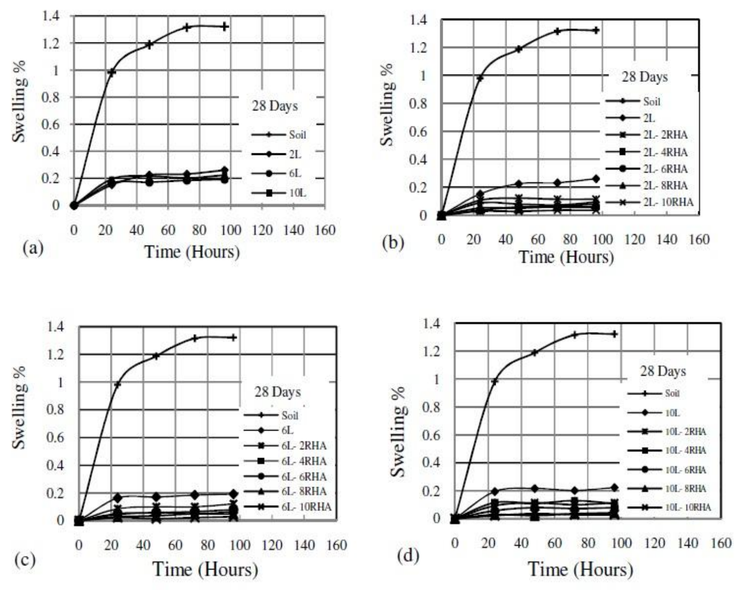

Figure 9. Swelling potential of the stabilized gypseous clay with 28 days of curing time: (a) samples stabilized with lime; (b) samples stabilized with lime content of 2% and RHA; (c) samples stabilized with lime content of 6% and RHA; (d) samples stabilized with lime content of 10% and RHA

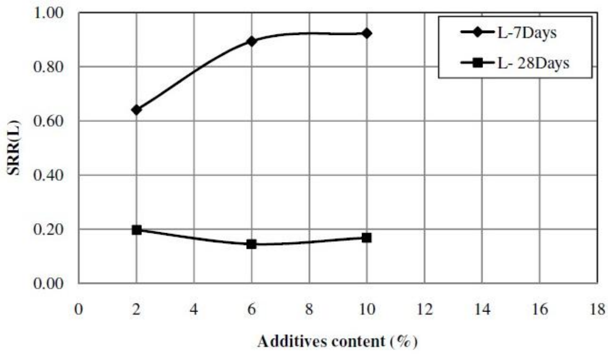

Figure 10. The variation of $SRR_{(L)}$ with lime content after 96 hours

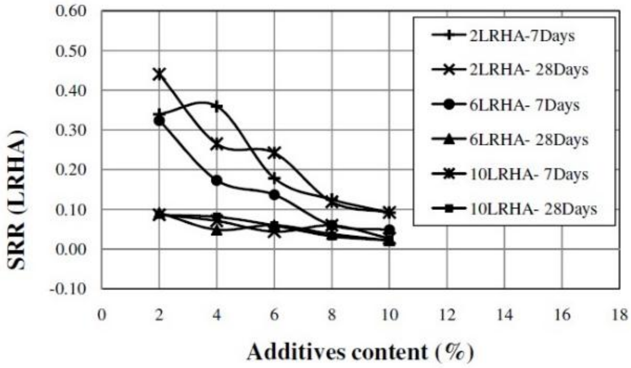

Figure 11. The variation of $SRR_{(LRHA)}$ with additive contents after 96 hours

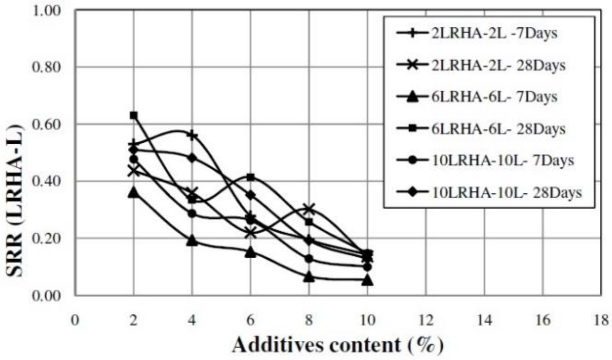

Figure 12. The variation of $SRR_{(LRHA-L)}$ with additive contents after 96 hours

Conclusions

In this paper, a gypseous clay was chemically stabilized using lime and RHA. Mechanical properties of the stabilized soil were investigated using compaction, uniaxial and CBR tests. The results of this study indicate that RHA has a positive impact on both increasing the unconfined compression strength and on reducing the swelling potential of gypseous clays stabilized with lime. The following conclusions can be drawn based on the results obtained in this study:

1. A soil improvement ratio of 3.72 in UCS of the gypseous clay with addition of 6% lime after 7 days of curing is determined. The soil improvement ratio increased to 5.22 with addition of 8% lime after 28 days curing. It shows that the increase of curing time from 7 to 28 days leads to increase in both optimum lime content and UCS.
2. A soil improvement ratio of 9 in UCS of the gypseous clay was obtained with addition of 4% lime and 8% RHA after 7 days of curing. That value increased to 16.3 by adding 6% lime and 8% RHA after 28 days. Increasing the curing time greatly increased UCS of the soil.
3. Swelling potential of the gypseous clay has decreased with the increase of the RHA after 7 days of curing. A swelling reduction ratio of 6% in samples stabilized with 6% lime and 8% RHA is obtained showing 94% reduction in the swelling of the clayey soil. On the other hand, due to surplus lime in the environment and lime reaction with gypseous clay, swelling potential in

samples with the lime of 10% was higher than samples with the lime of 6%.

4. It was also observed that increasing the curing time decreased swelling potential of the gypseous clay greatly so that in high percentages of RHA, it almost became zero after 28 days of curing.
5. From the mechanical property point of view, addition of 6–8% lime and 8-10% RHA is suggested in stabilization projects. RHA would be beneficial in reducing the amount of lime necessary to stabilize the clayey soils, speeding up the effects of lime treatment and reducing the swelling problems of clayey soils.

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