Some Engineering Characteristics of Lime-Treated Soil of Semeel Region With Emphasis on Compaction Delay

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ABSTRACT

This research presents a laboratory study on the influence of different compactive efforts, curing and soaking periods at no-delayed and up to 4-hrs compaction delay periods on compaction, strength and swelling characteristics of untreated and 3%, 5% and 8% by dry weight of lime-treated Semeel soil.

The results of the tests without and with compaction delay of lime-treated soil show that for both of standard and modified compactive efforts, as the lime content % increases the Maximum Dry Density (MDD) decreases while the Optimum Moisture Content (OMC) increases. The decrease in MDD is occurred due to alteration of the material's gradation as a result of the flocculation and agglomeration of the soil particles upon lime addition. Whereas the increase in OMC is mainly referred to the more water required for the hydration of lime and cation exchange. It has been found that as the compaction delay period increases, the strength properties of lime-treated soil decrease for unsoaked and soaked conditions. This loss in strength therefore needs to be considered in design and construction and the durability of the UCS specimens should be assessed by evaluating their resistance to strength loss after 7-days curing followed by 4-days soaking. The swelling characteristics measured on remolded soil samples at no compaction delay show that Semeel soil is classified as highly expansive soil. While, at small lime contents %, as the compaction delay increases, swell percent and swelling pressure values are slightly increased from that at no compaction delay.

KEYWORDS: Compaction Delays, Expansive Soil, Lime-Treated Soil.

تأثير تأخير الرص على بعض الخصائص الهندسية لتربة سميل المثبتة بالنوره

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الخلاصـة

هذه الدراسة تضمنت عمل مختبري حول تأثير كل من طاقات الرص القياسية والمطورة, فترة الانضاج وفترة الغمر بالماء على خصائص الرص، مقاومة التربة للقص وضغط ونسبة الانتفاخ للتربة الطينية في منطقة سميل بحالتيها الطبيعية والمثبتة بالنورة بنسب مختلفة 3% ، 5% و8 % من الوزن الجاف للتربة الطبيعية في حالتي رص خليط التربة والنورة والماء مباشرة (بدون تأخير) إضافة الى تأخير عملية الرص لفترات زمنية مختلفة تصل الى 4 ساعات.

أظهرت نتائج تجارب الرص القياسي أو المعدل في حالتي عدم تأخير أو تأخير الرص للتربة المثبتة بالنورة والمرصوصة انه كلما إزدادت نسبة النورة تقل قيمة الكثافة الجافة العظمى بينما تزداد قيمة الرطوبة المثلى. إن النقصان في قيمة الكثافة الجافة العظمى يعزى الى تغير حجم حبيبات التربة نتيجة التكتل والتزغب بسب إضافة النورة بينما زيادة المحتوى الرطوبي المثلى يعود الى الحاجة لكمية أكبر من الماء لاتمام عمليتي إماهة النورة (Hydration) وتبادل الشحنات الموجبة. لقد وجد أن خصائص مقاومة القص للتربة المثبتة بالنورة تقل مع زيادة فترة تأخير عملية الرص في الحالتين الجافة والمغمورة بالماء. هذا النقصان في مقاومة التربة للقص يجب أن يوخذ بنظر الإعتبار في مرحلتي التصميم والتنفيذ باعتماد فحص ديمومة نماذج التربة من خلال إيجاد النقصان في مقاومتها للقص بعد إنضاحها لمدة 7 أيام في المختبر إضافة الى غمرها بالماء لمدة 4 أيام قبل الفحص. كذلك أظهرت نتائج خصائص الإنتفاخ والمقاسة على نماذج التربة المشوهه في حالة عدم تأخير عملية الرص أن تربة سميل ذات قابلية إنتفاخ عالية. ولكن عند نسب النورة القليلة وإزدياد فترة تأخيرعملية الرص كانت الزيادة في كل من نسبة وضغط الإنتفاخ ليست كبيرة مقارنة مع رص التربة بدون تأخير.

الكلمات الدالة: تأخير عملية الرص ، التربة الإنتفاخية ، **التربة المثبتة بالنورة.**

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1. INTRODUCTION

It is well known that the reaction of lime with soil is of a chemical nature. Such a reaction is not only a function of the reacting chemical agents, but also a function of time. Moreover, it is a time-consuming process due to the need of pulverization of the soil, uniform application and mixing of lime, moisture and density control at the time of compaction and curing. This procedure in the field, under normal conditions, takes any where from (2-4) hrs, which means that the compaction of a soil-lime mixture cannot be started in most cases before (2-4) hrs after mixing the soil with the lime. During this time period the reaction starts between the soil and the lime, and the reacting particles are left in loose state in comparison with the final compacted product.

It is expected that the delay in compaction in addition to soil type, construction method, and curing conditions may lead to a significant variation on soil-lime mixtures properties measured and prepared in the laboratory in comparison of those measured and prepared in the field. Therefore, this study is an attempt to identify the effects of compaction delays on the compaction, strength and swelling characteristics of Semeel lime-treated soil.

2. STUDIES RELATED TO EXPANSIVE SOILS

Vast areas of clay soils in the northern part of Iraq can be classified as expansive soils. These soils, such as Semeel soil, are problematic in nature due to the existence of Montmorillonite clay mineral, which has a high tendency to volume change upon a change in moisture content. The factors which affect swelling of clays can be classified into internal and external factors as shown in Figure (1), ([8] and [19]).

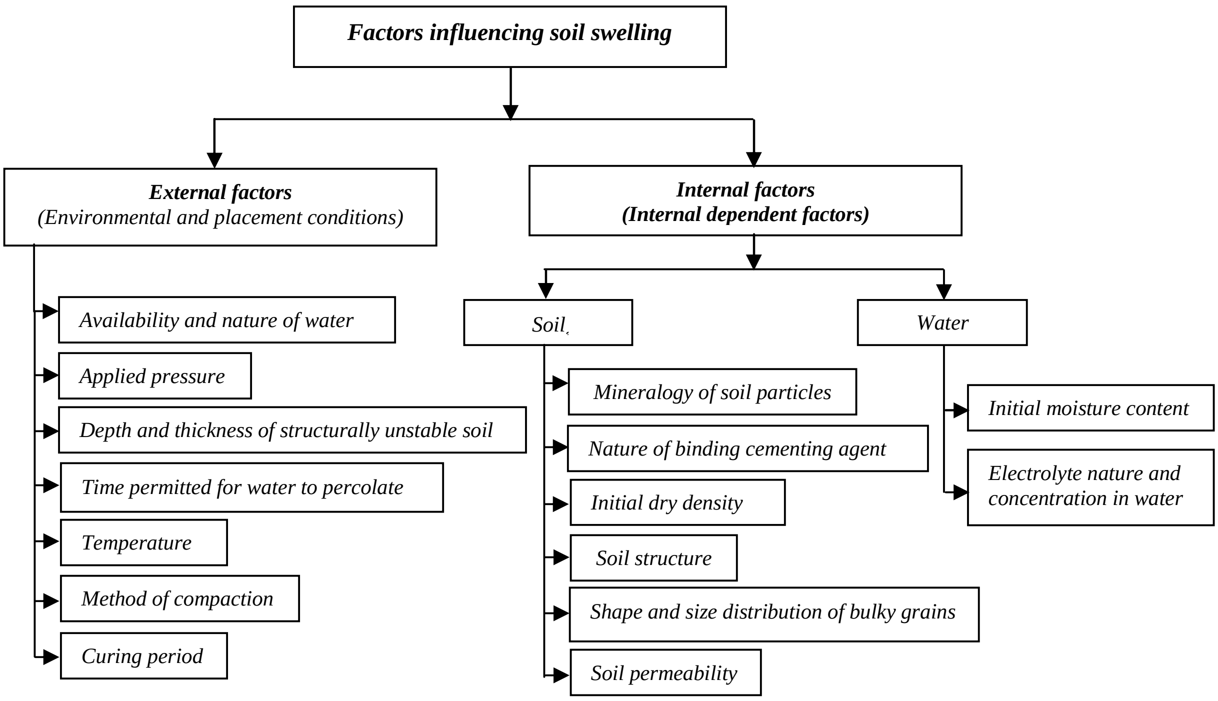

Figure (1): Factors affecting soil swelling (From [8] and [19]).

Many investigators have studied the expansive behavior of different soils. Abdullah et al. [1] conducted a physico-chemical study on expansive clay. Their investigation involved altering the adsorbed exchangeable cations from a heterogeneous untreated soil (having Na^{+}, Mg^{2+}, Ca^{2+} and K^{+} cations) to a homogenous one (with mainly one type of cations as that present on the clay). The results showed that the exchange complex decreased plasticity index, surface area, cation exchange capacity, free swell percent and swelling pressure.

Al-Shammam and Al-Nu'aimi [3] investigated the compaction and swelling characteristics of a highly expansive soil commonly known as “Shale” or “Red Marl” to improve its engineering properties. Initially by crushing the soil and then by mixing it with different percentages of fine to medium available local sand. The results showed significant changes in the soil behavior and its swelling tendency.

Katti and Shanmugasundaram [7] carried out a micro-structural analysis on the basis of x-ray diffraction tests during swelling of saturated bentonite samples that allowed to swelling to 0.50 and 75 % beyond their original volume. Their results showed an increase in swelling percent and a decrease in swelling pressure.

Erzin [5] predicted the swell pressures of clayey soils from some easily determined soil properties such as initial water content, initial dry density and plasticity index. For this purpose, bentonite-kaolinite clay samples with a wide range of plasticity indices were prepared and tested. The results showed that the swelling pressure increased as the initial dry density increased, while by increasing initial water content it decreased.

Bekkouche and Aissa [4] showed that estimation of swelling parameters without taking into account the physical soil properties led to over-estimate values and consequently had considerable effects on the stability of the structures.

3. STUDIES RELATED TO LIME-TREATED SOILS

Two main different types of lime reactions are usually believed to occur in soil-lime mixes. The first is a quick action and of interest primarily during the construction stage. It occurs immediately on addition of lime due to cation exchange and flocculation-agglomeration of soil clay particles. The second action is time dependent, important from a strength and durability standpoints and takes place over a long period during and after curing. This action is referred to the pozzolanic reactions with formation of cementation compounds [15].

The treatment of highly expansive soils with lime facilitates construction works in three major ways [13]: (i) the addition of lime to the soil decreases the liquid limit and increases the plastic limit resulting in a significant reduction in the plasticity index. Due to this reduction in PI, both of swell percent and swelling pressure are significantly reduced [9], (ii) a shift in the moisture-density relationship of a soil, which reflects a new behavior marked by a decrease in the maximum dry density and increase in the optimum moisture content, and (iii) immediate enhancement in soil strength and deformation properties.

Several researchers such as Osinubi [16] and Senol et al. [22] investigated the influence of compactive efforts and compaction delays on some characteristics of lime-treated soil. Their results showed that when the compaction was delayed, the maximum densities and the compressive strengths of lime-treated soil decreased in comparison of those obtained at no compaction delays.

4. RESULTS AND DISCUSSIONS

4.1 Physical and Geotechnical Properties

A summary of the physical properties of soil is shown in Table (1), while, the XRD analysis of the natural soil and 5% lime-treated soils is shown in Table (2). It is clear that the non-clay minerals of the native soil composed mainly of calcite, quartz and muscovite in descending order. But, the order of clay minerals is found to be semctite, kaolinite and palygroskite-illite. Table (2) also shows that soil treated with 5% lime result into a decrease in semctite amount and an increase in calcite amount. This may be attributed to the fact that the $Ca(OH)_2$ is expected to have been used to form CSH. However, formation of CSH can not be identified in the XRD pattern because of its amorphous nature [11].

Table (1): Physical and geotechnical properties of Semeel soil.

No.	Index property	Value
1	In-situ moisture content (w_n) %.	16.06*
2	In-situ unit weight (γ_{wet}), kN/m^3.	19.84
3	Specific Gravity (Gs).	2.76
4	Liquid Limit (L.L) %.	62
5	Plastic Limit (P.L) %.	26
6	Plasticity Index (PI) %.	36
7	Shrinkage Limit (S.L) %.	11
8	Linear shrinkage (LS) %.	19.5
9	% of clay fraction ≤ 0.002mm.	48
10	Activity = PI / (% of clay ≤ 0.002mm).	0.75
11	Free swell %.	7.75
12	Swelling pressure (kPa).	140.27
13	Unified soil classification system (USCS)	CH
14	AASHTO soil classification.	A-7-5

- *measured during spring, 2005.*

Table (2): XRD analysis of Semeel soil.

Clay minerals (%)			Non-clay minerals (%)		
Semctite	Palygorskite and Illite	Kaolinite	Quartz and Muscovite	Calcite	Dolomite
30.5 *	7.5	9	21	32	---
19 **	9	7	18	47	---

* *untreated natural soil (0 % lime).*
** *treated soil with (5 % lime).*

4.2 COMPACTION TEST RESULTS

4.2.1 Effects of No Delay between Instant Mixing and Compaction

Figure (2) shows the results of the compaction tests at no compaction delay (i.e., the compaction of the soil mixture is done immediately after mixing with water) of untreated and lime-treated soil at standard and modified compactive efforts. While, the variation of (MDD) and (OMC) of the soil with lime content % at no compaction delay for the two compactive efforts is shown in Figure (3). It is clear that the MDD decreases as the lime content % increases while the OMC increases. Such behavior is further supported by others ([2], [14] and [16]).

The decrease in MDD with an increase in lime content % may be attributed to the fact that after the lime, soil and water are mixed and compacted immediately, the change in compaction characteristics is primarily due to altering of the materials gradation i.e., a more friable structure is immediately created as a result of the flocculation and agglomeration of the soil particles upon the addition of lime. The higher reduction in MDD is obtained when 8% of lime content is added. This is valid for both standard and modified compactive efforts.

The rise in OMC upon the addition of lime is referred to the more water required for the hydration of lime and cation exchange. Since the lime is added to soil, the calcium cations Ca^{++} replace the sodium cations Na^{+} present in the clay until the latter becomes saturated with calcium which in turn rises the pH^{-}value to more than 12.4 [20].

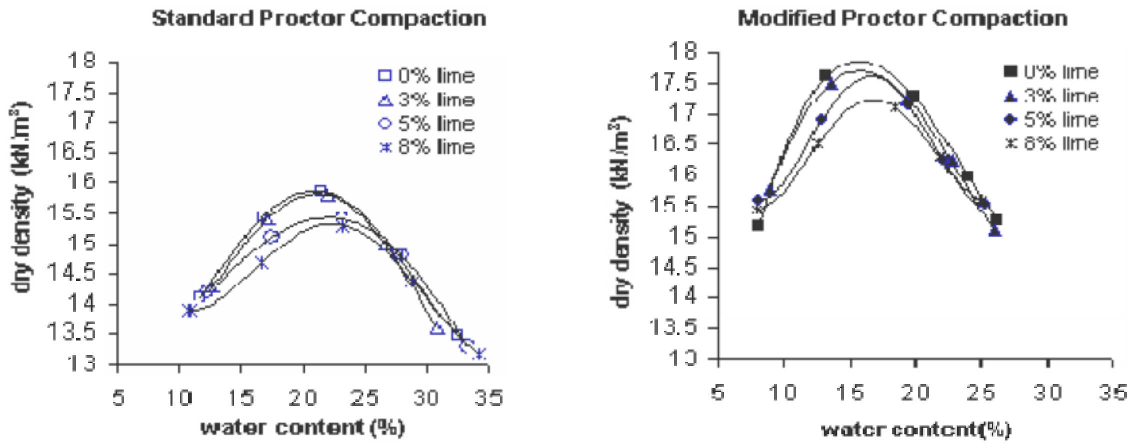

Figure (2): Dry density-water content relationships of untreated and lime-treated soil at (no compaction delay).

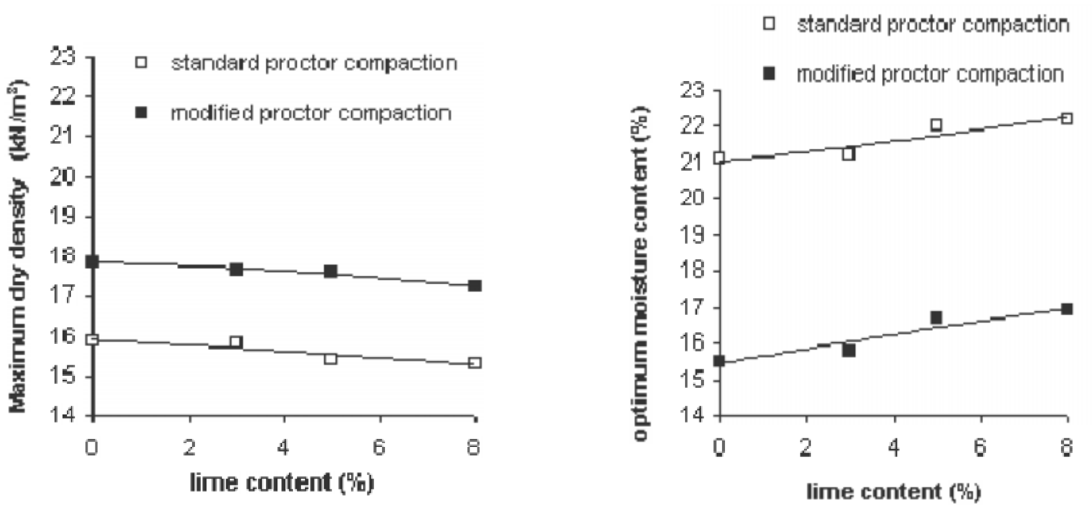

Figure (3): Variation of MDD and OMC with lime content % at (no compaction delay).

4.2.2 Effects of Compaction Delay Time Period

The influence of three compaction delay time periods (1 hrs, 2 hrs and 4 hrs) on the MDD and OMC of 3%, 5% and 8% lime-treated soil using standard and modified compactive efforts are shown in Figure (4). For ease of comparison, the figure also contains the dry density-water content relationships at no delayed compaction for the specified lime content percentage.

It is evident that for both standard and modified Proctor compactive efforts, the tendency for MDD is to decrease with an increase in compaction delays as shown in Figure (5). This behavior is mainly due to when compaction is delayed, hydration products begin to bond particles in a loose state and the disruption of these aggregates is required to the density of the soil. Therefore, a portion of the compactive energy is utilized in overcoming the cementation and the maximum densities are reduced with increased compaction delays. The amount of reduction is greater at higher lime contents and is dependent on the rate of hydration of lime. The losses in MDD of the soil after 4-hrs of delay compaction at 8% lime content are -5.79% with standard Proctor compaction and -12.77% with modified Proctor compaction.

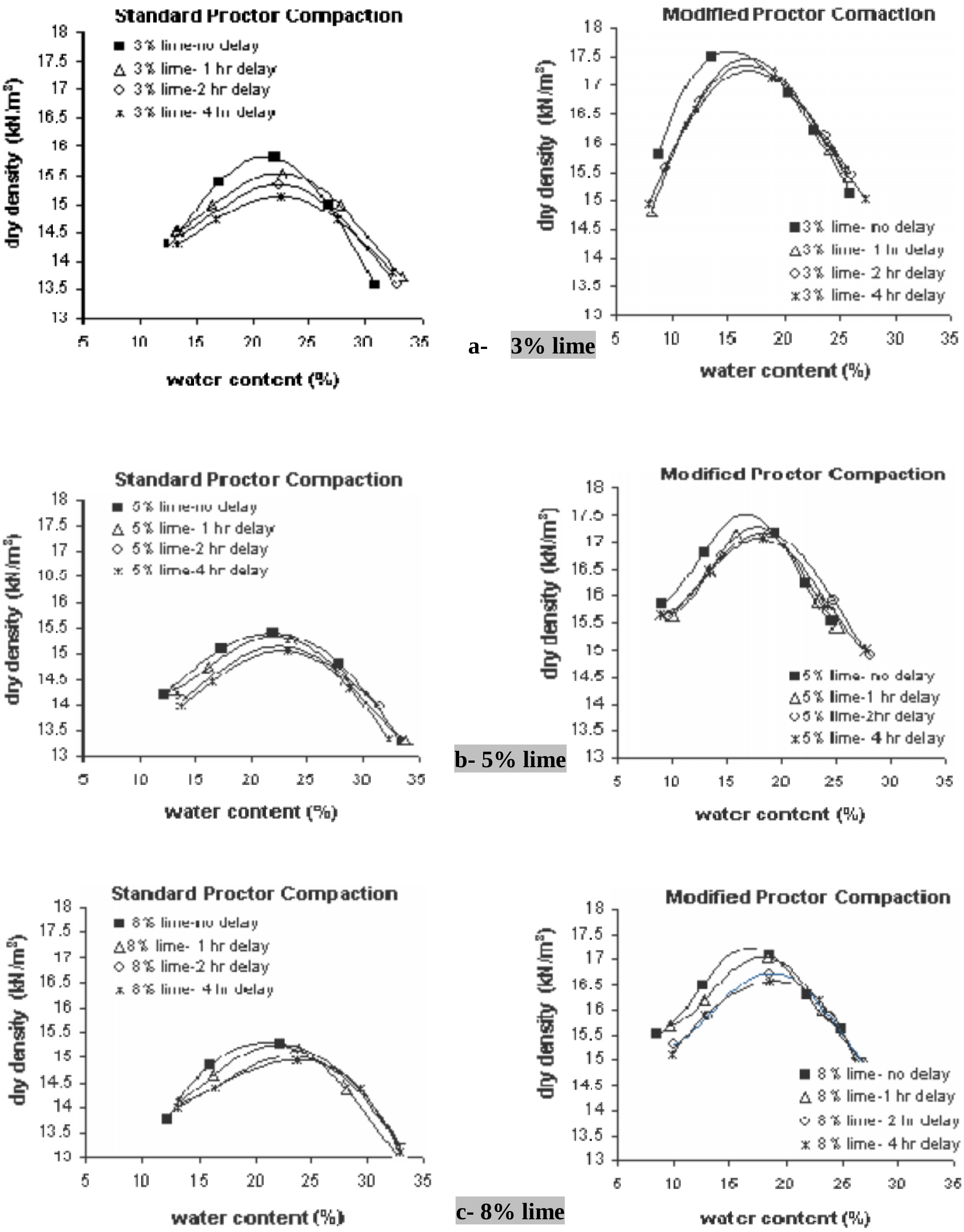

Figure (4): Dry density-water content relationships of lime-treated soil with compaction delay.

Figure (5) also shows the influence of compactive energies and compaction delays on the OMC of lime-treated soils. It can be noticed that the OMC increased with an increase in compaction delays at higher lime contents. This increase in OMC is attributed to the cations exchange and aggregation reactions taking place simultaneously, and thus taking up the available water in the system [22].

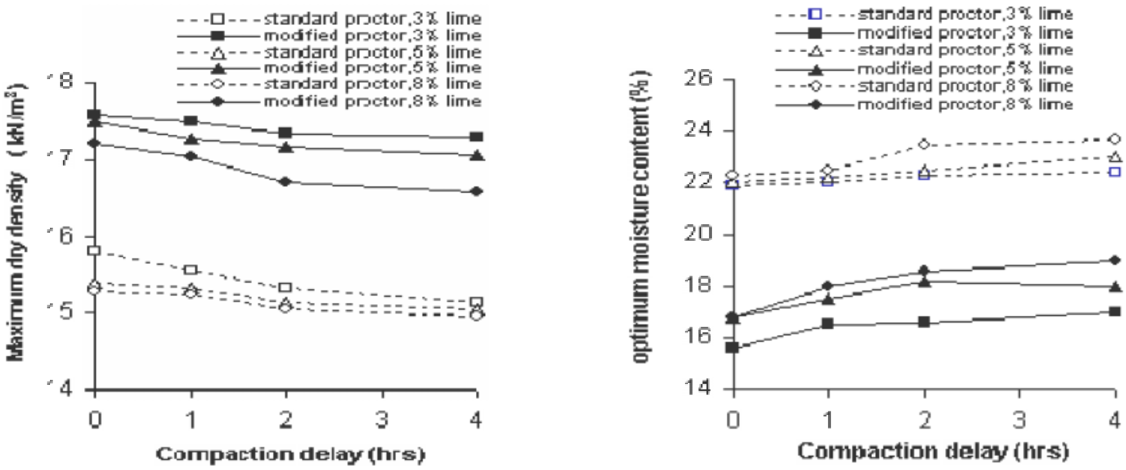

Figure (5): Variation of MDD and OMC of lime-treated soil with compaction delay.

4.3 Unconfined Compression Tests Results
4.3.1 Effect of Curing Time on the UCS at No Compaction Delay

The effect of curing time period on the strength characteristics of lime-treated soils for both unsoaked and soaked conditions is investigated. Two sets of soil specimens are prepared, the first set is cured and then tested at unsoaked condition while the second set is cured, then immersed in water for 4-days before testing. In both cases, the specimens of lime-treated soils are immediately compacted at OMC and MDD that obtained from modified Proctor compaction test. Then, the specimens are warped and allowed to cure for different periods of time (0, 7, 14 and 21days) in a wet room with temperature of (21±2Cº) before soaking and then, tested for unconfined compression strength (UCS) following ASTM D2166. These curing temperatures were used by many investigators such as Thomas [23] who stated that the reaction products C_4Ah_n, CSH(gel) and $CSH_{(II)}$ appeared at curing temperature of 5, 23 and 40Cº.

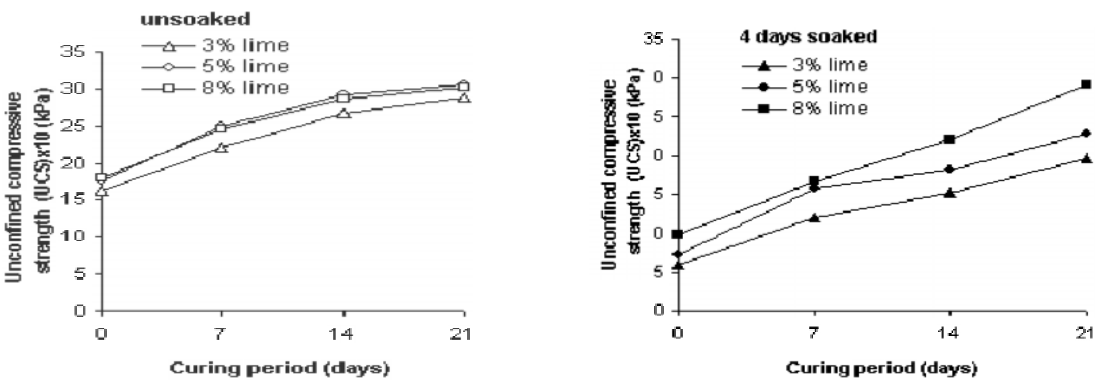

Figure (6): Effect of curing period on the UCS of unsoaked and soaked lime-treated soil at (no compaction delay).

Figure (6) shows the results of the tests of unsoaked and soaked lime-treated soil at no compaction delay. It is clear that as the curing period increases, the UCS values increases rapidly in comparison with that of uncured soil. However, after 7-days curing period the rate of increase decreases. This is mainly due to the effect of curing temperature and the pozzolanic reaction. Such behavior is supported by others ([17] and [23]). Therefore, the 7-days curing period is selected for all of the remaining tests.

The UCS gain of the lime-treated soil was primarily due to CAH (calcium aluminate hydrate) that is formed as a result of the pozzolanic reaction between lime and kaolinite ([15] and [16]). This behavior is further supported by Little [10] who showed on the basis of the Energy Dispersive X-Ray (EDX) Test Analysis that the pozzolanic reaction had already converted some of the clay minerals to (calcium silicate hydrate) CSH after 7-days cure period.

For easier comparison, the UCS values of untreated and lime-treated soils at different curing periods and no compaction delay for both unsoaked and soaked conditions are presented in Table (3). It is evident that soaking leads to a reduction in soil strength. Such decrease is mainly due to the chemical action of lime.

Table (3): UCS values of unsoaked and soaked untreated and lime-treated soil at different curing periods (no compaction delay).

Curing period (days)	Unconfined compressive strength (kPa)							
	Unsoaked condition				Soaked condition			
	Lime content %				Lime content %			
	0	**3**	**5**	**8**	**0**	**3**	**5**	**8**
0	139.7	148.6	147.7	163.8	9.3	59.5	71.6	98.2
		+6.0*	+5.0	+17		-57*	-49	-25
7		209.0	252.5	270.7		119.9	158.3	167.0
		+50	+81	+94		-14	+13	+19
14		210.5	291.0	295.5		152.1	182.1	220.5
		+51	+108	+112		+13	+30	+58
21		236.7	320.6	350.1		197.1	227.2	291.6
		+67	+129	+151		+41	+63	+109

All strength ratios are measured from uncured-untreated soil specimens at unsoaked conditions.
* *Improvement or loss in strength ratio (%),*
(+) signs mean improvement in strength, whereas (-) signs mean losses.

4.3.2 Effect of Lime Content % on the UCS at No Compaction Delay

The variation of the UCS values with lime content % of unsoaked and soaked treated soil at different curing periods at no compaction delay is shown in Figure (7) and presented in Table (4). It is clear that for any curing period, as the lime content % increases the UCS increases also. However, the rate of increase is rapid as the lime content % increased from 3% up to 5%, then beyond it the strength gain slightly increases and this may be attributed to the increasing amount of (unreacted) lime. This result agrees well with that noticed by ([2], [17] and [23]).

The UCS value of the natural (uncured) soil specimens at unsoaked test condition is (139.7) kPa. This value of strength increases with the addition of lime and increasing of curing period as listed in Table (3). It can be noticed that the improvement in UCS values of unsoaked-uncured soil specimens are (6%, 5% and 17%) for 3%, 5% and 8% lime contents, respectively. These ratios are increased due to lime and curing period to (50%, 81% and 94%) and (51%, 108% and 112%) for the same three lime contents of soil specimens cured at

7 and 14 days, respectively. However, for a specified percent of lime, the gain of strength upon increasing of curing period from 7 to 14 days seems to be small.

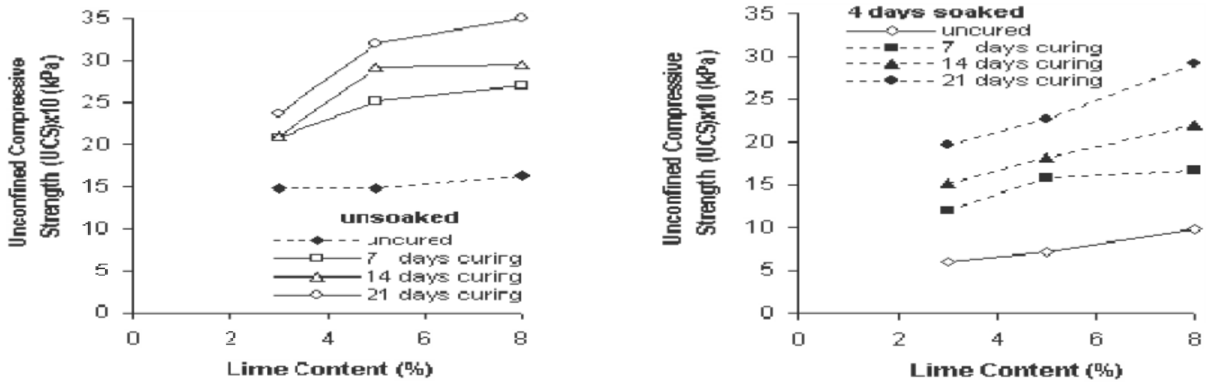

Figure (7): Variation of UCS with lime content % of unsoaked and soaked treated soil at different curing periods (no compaction delay).

It is obvious that the strength ratios are decreased upon soaking of soil specimens. The loss in strength of soil specimens when compared with that of unsoaked condition may be attributed to the adhesion failure or a weakening of the cohesive bonds between the lime products and the soil particles system.

4.3.3 Effect of Compaction Delay on the UCS

Figure (8) shows the influence of compaction delays on the UCS of lime-treated soil with 7-days curing period at unsoaked and soaked conditions. It is clear that the UCS is decreased in value with the increase in compaction delays. This can be explained that when compaction is delayed, the lime-reaction products begin to bond soil particles in a loose state and these bonds must be disrupted to densify the soil-lime mixture which in turn does not regain its full strength. Therefore, a portion of the compactive effort is used to overcome some of the cementitious bonds with the remaining energy to compact the mixture. Thus, in addition to altering compaction characteristics, the compaction delay also reduces the UCS of the lime-treated soil. Such behavior is further supported by other researchers ([12] and [17]).

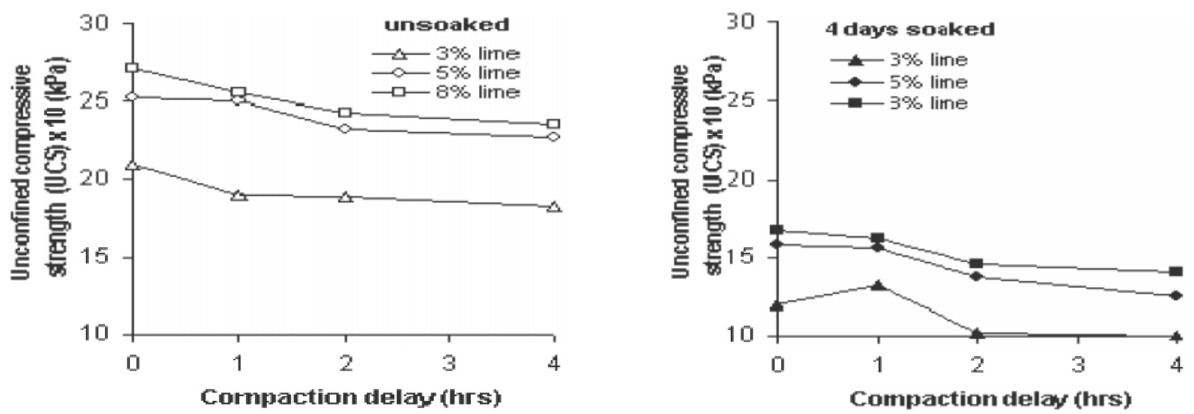

Figure (8): Effect of compaction delays on UCS of unsoaked and soaked lime-treated soil with 7-days curing period.

The UCS values at failure and their corresponding strains of lime-treated soil after 7-days curing period with delays compaction are presented in Table (4). The table also contains the ratios of losses in strength under unsoaked and soaked conditions which are expressed as:

$$\text{Loss in strength ratio (\%)} = \left(\frac{\text{UCS of soil specimen with specified lime \% at delayed compaction}}{\text{UCS of soil specimen with the same lime \% at no delay compaction}} - 1\right)x100$$

The losses in strength are measured from the corresponding lime content % at the unsoaked test condition and no compaction delay.

Table (4): UCS values at failure and the corresponding strains of lime-treated soil at 7-days curing period (with compaction delay).

compaction delay (hrs)	Stress at failure in (kPa) and the corresponding strain							
	Unsoaked condition				Soaked condition			
	Lime content %				Lime content %			
	0	3	5	8	0	3	5	8
0	139.7*	209.0	252.5	270.7	9.3	119.9	158.3	167.0
	3.59**	3.02	3.02	2.73	2.30	1.87	2.30	2.73
		0.00***	0.00	0.00		-42.63	-37.31	-38.31
1		190.0	250.1	254.7		132.1	156.4	162.1
		2.16	2.59	3.45		1.58	1.72	1.87
		-9.09	-0.95	-5.91		-36.79	-38.06	-40.12
2		189.0	232.0	243.2		102.5	137.0	145.6
		2.16	2.44	2.59		1.73	1.87	1.73
		-9.57	-8.12	-10.16		-51.82	-45.74	-46.21
4		182.0	227.0	235.0		100.0	125.2	140.3
		2.01	2.44	2.88		1.44	1.72	1.73
		-12.92	-10.10	-13.19		-55.45	-50.41	-48.17

: stress in (kPa), **: strain *10^{-2} and * : Loss (%) in Strength Ratio.*
All strength losses percentages are measured from unsoaked conditions and each specimen at delay from that with the same lime% at no delay.

For unsoaked test condition, the losses in strength ratios for a compaction delay of 4-hrs are found to be 12.92%, 10.10% and 13.19% for the soil treated with 3%, 5% and 8% lime contents, respectively. These losses in strength ratios after 7-days of curing and 4-days soaking are increased to 55.45%, 50.41% and 48.17% for the same three lime content percents, respectively. It is clear that these ratios of strength losses are more than the 20% maximum allowable loss in strength for a 7-days curing and 4-days soaking period specified by conventional specifications [6].

The variation of UCS with lime content % of treated soil at 7-days curing period with compaction delay as well as that at no delay for comparison is shown in Figure (9). It can be noticed that for any compaction delay time period as the lime content % increases, the UCS value increases. This conclusion is in coincidence with the results of several investigators ([17] and [23]).

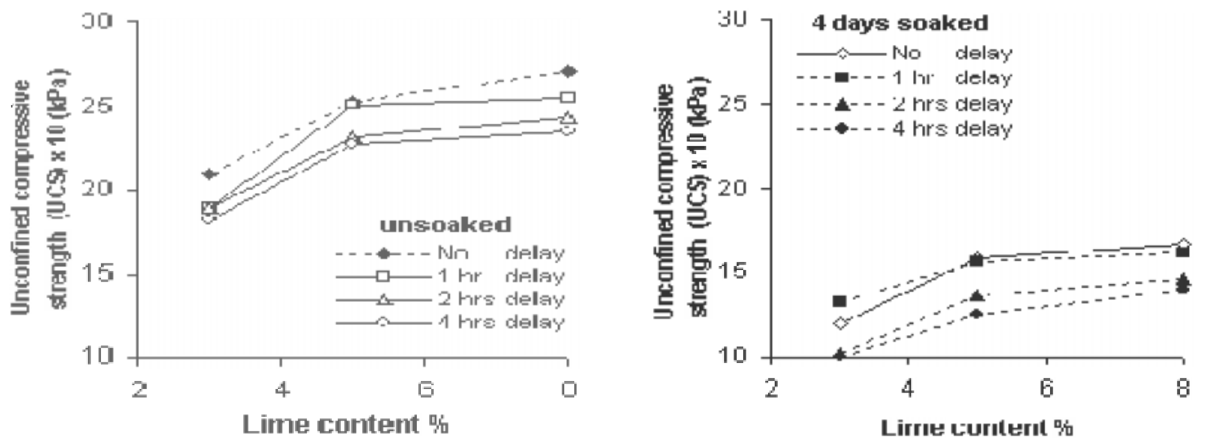

Figure (9): Variation of UCS with lime content % of treated soil at 7-days curing period (with compaction delay).

The increase in UCS value is obvious as a sharp change in the slope of the relationships curves, especially when the lime content % increased from 3% to 5%. Then after, the rate of increase is decreased. This trend is found to be applicable for unsoaked and soaked conditions. The improvement in strength due to the addition of 8% lime content is not so big over that of 5% lime; therefore, the 5% lime content may be considered as optimum lime content for stabilization design work.

4.4 Swelling Tests Results

4.4.1 Swell Parameters at No and with Compaction Delay

The effect of lime content% on both swell percent and swelling pressure of lime-treated soil at no compaction delay is shown in Figure (10). It is clear that as the lime content % increases, the swelling parameters are decreased in their amounts and rates. This is continued up to approximately (3-4) % of lime content, then after, all of the swelling characteristics are completely eliminated. This behavior is obvious due to the pozzolanic reactions which mainly converts some of the clay minerals to CSH (calcium-silicate-hydrate) after a 7-days cure period [9].

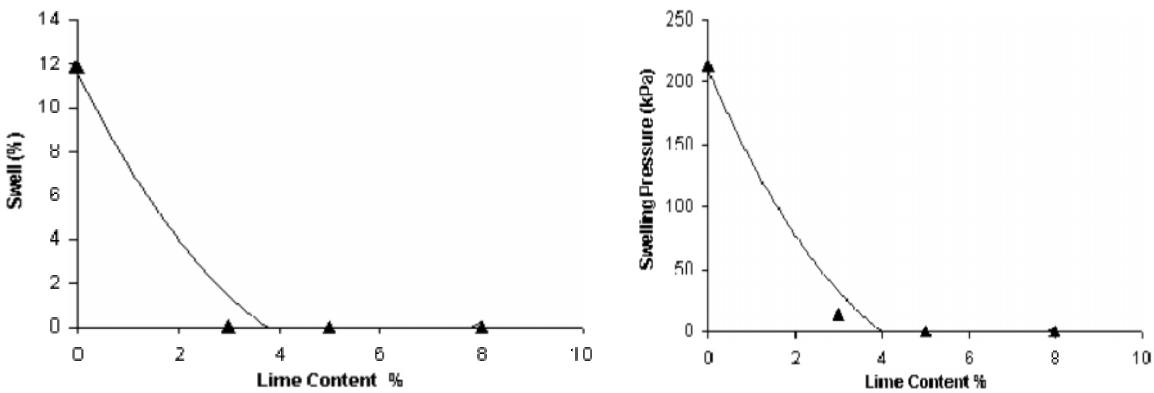

Figure (10): Effect of lime content on swell parameters of lime-treated soil at 7-days curing period (no compaction delay).

Figure (11) shows the effect of compaction delay time period on the swelling parameters of lime-treated soil with 7-days curing period and 4-days soaking. It is clear that with increasing compaction delay, both of swell % and swelling pressure values are slightly increase when the soil is treated with 3% or 5% lime contents. But, an addition of 8% lime shows no effect of time delay on swelling characteristics of the soil. This is due to that the addition of more lime % will produce an excess lime which leads to increase the pH-value of the soil-lime mixture related to the free hydroxyl ions OH^- produced from the lime. This, in turn, accelerates the solubility of the available silica and alumina of clay minerals to produce complex cementing materials as hydrated silicates and aluminates (CSAH).

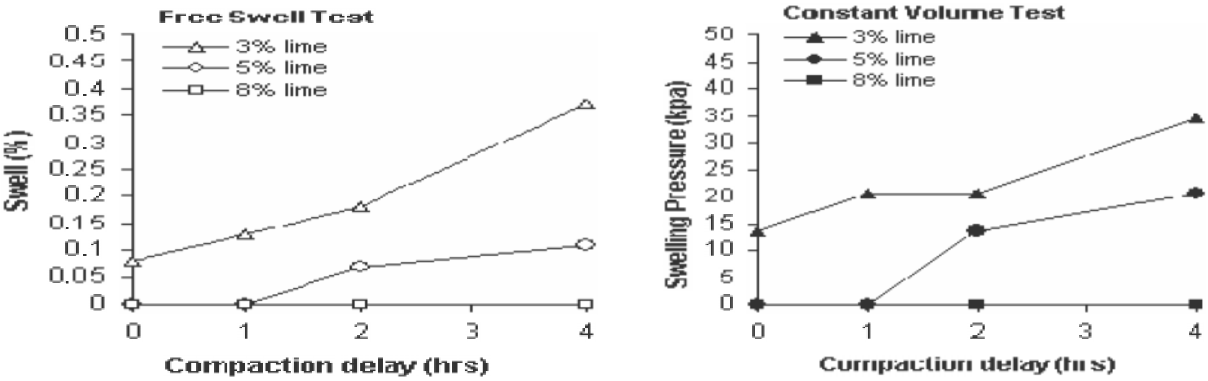

Figure (11): Effect of delays compaction on swelling parameters of lime-treated soil at 7-days curing period and 4-days soaking.

The swell percent and swelling pressure values of untreated and lime-treated soil at no and with compaction delay are presented in Table (5). The table also contains the decrease percents in swell parameters of lime-treated soil with 3%, 5% and 8% lime contents from that of untreated soil (0% lime). The swell % value of untreated (0% lime) soil is found to be 11.89% whereas the swelling pressure value is 213.27 kPa. These values of swell % and swelling pressure indicate that Semeel soil has a high tendency for imbibed water. This behavior is mainly dependent on the quantity of water entering the clay soil and its mineralogy, treatment during compaction, initial water content and plasticity index of clay soil ([18] and [21]).

Table (5): Swelling parameters of lime-treated soil at 7-days curing period at no and with compaction delay.

Compaction delay (hrs)	Swell percent %				Swelling pressure (kPa)			
	Lime content %				Lime content %			
	0	3	5	8	0	3	5	8
0	11.89	0.08	0	0	213.27	13.80	0	0
		99.33*	100	100		93.53**	100	100
1		0.13	0	0		20.70	0	0
		98.91	100	100		90.29	100	100
2		0.18	0.070	0		20.70	13.80	0
		98.49	99.41	100		90.29	93.53	100
4		0.37	0.11	0		34.50	20.70	0
		96.89	99.07	100		83.82	90.29	100

* *Decrease in swell percent from that of natural soil.*
** *Decrease in swell pressure from that of natural soil.*

The swell percent and swelling pressure values of lime-treated soil at no compaction delay are found to be (0.08% and 0%) and (13.80 and 0) kPa for 3% and 5% lime contents, respectively. But, after 4-hrs of compaction delay, these values are increased to (0.37% and 0.11%) and (34.5 and 20.7) kPa for the same lime contents mentioned above.

4.5 Direct Shear Tests Results

4.5.1 Shear stresses and Displacements at No and with Compaction Delay

The shear stress-shear displacement relationships of untreated and lime treated soil samples tested in unconsolidated undrained condition at no compaction delay and unsoaked condition are shown in Figure (12). It can be noticed that the stabilization of soil with lime increases its shear strength. This is due to the change in the soil skeleton by the addition of more lime and the possible reduction in voids content by plugging some voids with lime which improve the mechanical action of the soil particles. However, the curves for different lime contents are identical as they are closely spaced, indicating little difference in the stiffness of the soil through the majority of the test period.

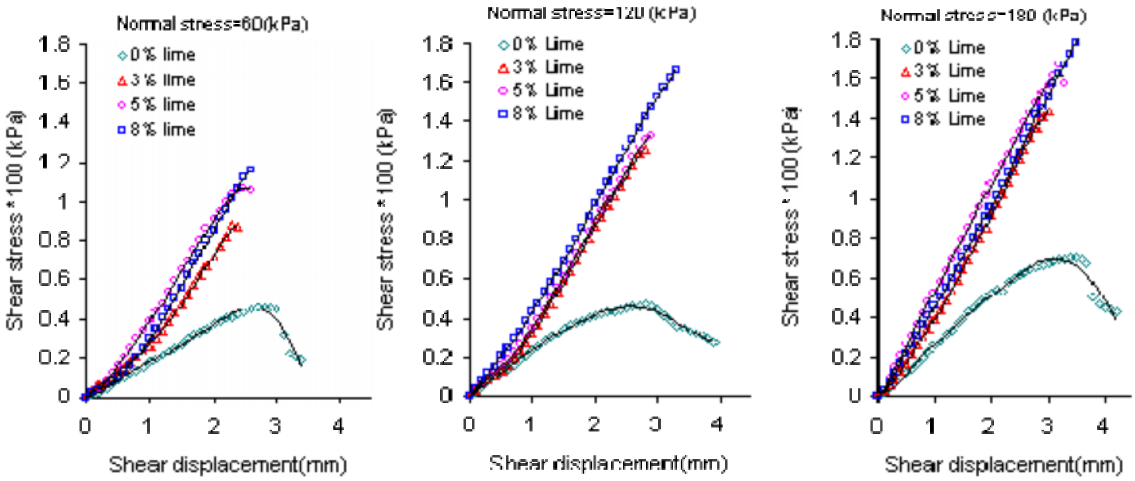

Figure (12): Shear stress-shear displacement relationships of untreated and lime-treated soil samples for unsoaked condition (at no compaction delay).

For easier comparison, the peak strength values at failure of lime-treated soil at unsoaked and soaked conditions with compaction delays are presented in Table (6). It is evident that soaking leads to a reduction in shear strength. This decrease in strength is influenced by the period of compaction delay and hydration characteristics of lime.

Table (6): Peak strength values (kPa) of lime-treated soil samples (with compaction delay).

Lime %	Delay time periods at normal stres s = 180 kPa			
	no delay	1-hr	2-hrs	4-hrs
3	143.88*	130.01	127.44	120.25
	38.02 **	34.12	36.69	31.86
5	166.50	155.70	144.91	145.94
	66.29	62.48	51.90	51.38
8	189.11	177.29	174.72	165.47
	77.08	76.56	75.02	65.77

**, ** Peak strength values for unsoaked and soaked conditions, respectively.*

4.5.2 Shear Strength Parameters at No and with Compaction Delay

The shear strength parameters for unsoaked and soaked conditions lime-treated soil with 1, 2 and 4-hrs compaction delays as well as those at no compaction delay as a base of comparison are presented in Table (7). The table shows that the stabilizer (lime) has a pronounced effect on both cohesion and angle of internal friction for unsoaked condition. The cohesion values for unsoaked soil specimens are found to be (2.1, 2.5 and 2.8) times that of pure soils for 3%, 5% and 8% lime contents, respectively. These ratios increase to (2.3, 2.5 and 3.0) with respect to the angle of internal friction. Whereas the shear strength parameters c and ϕ are greatly reduced due to soaking. The loss of strength due to soaking results from the destruction of weak interparticle hydration bonds that dissolve upon wetting and lead to a loss in the frictional strength components.

Also, it is seen that as the compaction delay period increases, the cohesion component of strength decreases. However, the change in angle of internal friction seems to be small for all soil specimens.

Table (7): Shear strength parameters of lime-treated soil samples (with delay Time Periods).

Lime %	Shear strength parameters for unsoaked and soaked conditions							
	C (kPa)				Φ (deg.)			
	No delay	1-hr	2-hrs	4-hrs	No delay	1-hr	2-hrs	4-hrs
3	63*	63*	42*	60*	14*	13*	15*	16*
	33 **	26**	19**	23**	7 **	7**	9**	6**
5	75	65	62	60	15	14	16	17
	22	21	26	21	24	24	16	18
8	85	77	86	75	18	17	15	15
	35	18	18	22	21	28	27	22

*, **

Shear strength parameters c and ϕ for unsoaked and soaked conditions, respectively.

5. CONCLUSIONS

The following conclusions can be drawn from this limited study:

1. The results of compaction tests at no compaction delay of lime-treated soil at standard and modified compactive efforts show that as the lime content % increases the MDD decreases while the OMC increases.
2. For both standard and modified proctor compactive efforts, as the compaction delay period increases the MDD decreases and the OMC increases. This behavior is mainly due to the hydration products and pozzolanic reactions of lime with clay fraction of the soil that begins to bond particles in a loose state and the disruption of the aggregates required for dense soil.
3. As the curing period increases, the soil specimens gain more strength. However, the rate of increase is rapid as the lime % is increased from 3% up to 5%, and then beyond it the strength gain remains approximately constant.
4. The strength properties of lime-treated soil decrease with increases in compaction delays. The strength loss due to compaction delay is significant and may be considered in design and construction. The maximum strength is reduced by approximately (10-15) % due to 4-hrs delayed compaction at dry condition. Whereas, this ratio increases due to 4-days soaking after the same compaction delay time period of 4-hrs.

5. The durability of the UCS specimens should be assessed by evaluating the resistance in strength loss of specimens cured for 7-days and later immersed in water for additional 4-days for soaking.
6. The results of swelling characteristics at no compaction delay show that Semeel soil is classified as highly expansive soil. But, as the lime content increases the swell parameters decrease in their amounts and rates. This is continued up to (3-5) % of lime content, then after, all of the swelling characteristics are completely eliminated. This behavior is due to the pozzolanic reactions which already convert some of the clay minerals to CSH after 7-days curing period. Further, the addition of 8% lime produces an excess lime which leads to an increase in pH-value of the soil-lime mixture as a result of the free hydroxyl OH^- produced from the lime.
7. As the compaction delay increases, both of the swell % and swelling pressure values increase. However, the increase from that at no compaction delay is not very big or limited.

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