Effect of Lime on Plasticity, Compaction and Compressive Strength Characteristics of Synthetic Low Cohesive (CL) and High Cohesive (CH) clayey soils.

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ABSTRACT

Proper application of lime to poor subgrade soils, platform of pavement systems, do significantly reduce its damaging impact on the pavement and the escalated costs required to import superior soils. However, the amount of published information on lime stabilized clay is localized since natural soils vary a great deal from one location to the other. There have not been any study allowing direct comparisons between maximum dry density (mdd) and optimum moisture content (omc) of lime stabilized high and low plasticity clays and to ascertain why the maximum dry density decrease as the lime content increase. There is a need to conduct a unified study with blended synthetic commercially available clay minerals to produce a reproducible controlled low plastic cohesive soil (CL) and a high plastic cohesive soil (CH) in the laboratory. These synthetic cohesive soils can represent the "ideal" low and high cohesive clay soil in the global village. The objectives of this research work include:

- Investigating the effect of lime on plasticity and compressive strength of CL and CH cohesive soils.
- Evaluating the factors which affect MDD AND OMC such as the amount of kaolinite and sodium montmorrilonite clay minerals, amount of lime present and curing period.

Two commercially available clay minerals were blended in the laboratory to produce a CL and a CH soil. Compaction and stabilization were performed on these synthetic soils with lime contents to establish appropriate mix design. Afterwards, specimens prepared with selected stabilization contents were tested for compressive strength.

The liquid limit and the plasticity index for the sodium montmorrilonite clay minerals were 460 and 447 respectively, the addition of 5 percent sodium montmorrilonite to the kaolinite significantly raised the plasticity index (PI) of kaolinite clay mineral from 13 to 20. Plasticity index (PI) showed a remarkable decrease for CL and CH soils from 20 to 12 and 44 to 18 respectively. Higher compaction densities were obtained in the CL soil treated with lime than the CH soil treated with lime. The unconfined compressive strength of the pulverized fine grained low plastic CL soil compacted at optimum moisture content and maximum dry density was 663.60 kN/m^2. The increase in compressive strength for CL soil ranged from 1493.10 kN/m^2 for the 2 percent lime to 2626.75 kN/m2 for the 6 percent lime. The untreated CH soil compressive strength was 276.5kN/m^2.

From the research, it was concluded the type of clay mineral present influences the geotechnical properties of the soil.

Curing time has no significant effect on plasticity index (PI).
The soil-lime mixture has a lower maximum density than the untreated CL and CH soils for a given compactive effort.
The soil-lime mixture of the CL soil has a higher density than the soil-lime mixture of CH soil at the same lime content.
As the percentage of lime increased, the percentage reduction of the maximum density also increased.
The optimum moisture content increased with increasing lime content due to hydration of calcium cations.
Lime flocculated CL and CH clay soil produced larger particles with large void spaces between them culminating into lower maximum density.
The unconfined compressive increment of more than 277kN/m^2 after the addition of lime to the CL andCH soils indicated that pozzolanic reaction has taken place.
KEYWORDS : Lime Stabilization; Synthetic Cohesive soils; Maximum Dry Density; Optimum Moisture Content; Plasticity Index; Compressive strength; Kaolinite; Sodium montmorrilonite.

INTRODUCTION

Subgrade soils which are the ‘platform’ of highway and runway pavement systems do impact on the design, construction, structural response and performance (Thompson, 1989). A major concern of the pavement systems is the depletion of acceptable natural subgrade soils. In areas where high quality soils have been depleted, poor subgrade soils with expansive clay minerals exist.

Addition of lime to clayey soils to improve their engineering properties is a well –established practice. Historically, the ancient Mesopotamians and Egyptians as well as the Greeks and Romans used lime additives to stabilize earth roads (McDowell, 1959). Contemporary usage of lime stabilization was carried out in the United States of America in 1924 (McCaustland, 1925,quoted from Bell, 1996)

Proper application of lime to poor subgrade clayey soils do significantly reduce its damaging impact on the pavement and the escalated costs required to import superior soils. The mechanisms by which lime improves the properties of cohesive soils are well documented in the literature (TRB, 1987). It is known that with the addition of lime, cation exchange and flocculation-agglomeration reactions produce rapid changes in the soil’s plasticity and workability with accompanying improvement in strength and load deformation properties. Time dependent pozzolanic reactions further produce varying degrees of strength and durability depending on the soil type, the relative humidity, temperature and the pH of the curing environment.
Extensive research has been conducted on the effects of lime stabilization on the engineering properties of natural clayey soils (Allen et. Al., 1977; Sabry and Parcher, 1979; Kenedy, et. Al., 1987).
However, the amount of published information on lime stabilized clay is localized since natural soils vary a great deal from one location to the other. There have not been any study allowing direct comparisons between maximum dry density (MDD) and optimum moisture content (OMC) of lime stabilized high and low plasticity clays. There has not been any detailed research to ascertain why the maximum dry density decrease as the lime content increase. There has not been any hypothesis to explain why the optimum moisture content increases with increase in lime content.
There is a need to conduct a unified study with blended synthetic commercially available clay minerals to produce a reproduciblecontrolled low plastic cohesive soil (CL) and a high plastic cohesive soil (CH) in the laboratory. These synthetic cohesive soils can represent the “ideal” low and high cohesive clay soil in the global village.

Objectives of the study

The major goal of this study was to provide more insight on the effects of lime stabilization on the maximum dry density (MDD) and optimum moisture content (OMC), plasticity, and compressive strengths of the CL and CH soils.
The specific objectives covered the following:

- Investigating the effect of lime on plasticity of CL and CH cohesive soils.
- Evaluating the factors which affect MDD AND OMC such as the amount of kaolinite and sodium montmorrilonite clay minerals, amount of lime present and curing period.
- Investigating the effect of lime content on the compressive strength of CL and CH soils

Previous Studies

Lime as a Stabilizer

Lime is widely used as a stabilizer to expedite construction on weak subgrade soils and to improve the engineering properties especially the strength and durability of fine grained soils. National Lime Association (NLA) reported in 2001 that lime is an unparallel aid in the modification and stabilization of soil beneath road and similar construction projects. The most commonlyutilized limes are slaked lime ($Ca(OH)_2$) and calcitic quicklime (CaO). When lime is added to a fine grained soil, a number of complex reactions take place. Lime which is a source of free calcium reacts with all fine-grained soils in the presence of water. The reactions are rapid cation-exchange and flocculation-agglomeration. Tuncer and Basma (1991) reported that reactions between lime and soils within a few minutes to an hour are colloidal in nature which involve cation exchange and agglomeration-flocculation reactions because of varying double layer characteristics of individual clay particles.

A cation exchange reaction causes a change in the relationship between clay particles, from state of mutual repulsion to one of mutual attraction; this results from the excess Ca^{2+} replacing dissimilar Cations from the exchange complex of the soils.
A soil-lime pozzolanic reaction can occur to form various cementing agents that increase compacted mixture strength and durability.Lime, water, soil silica, and alumina react to form various cementatious compounds. When a large amount of lime is added to a soil, the pH of the soil-lime mixture is increased to about 12.4, which is the pH of saturated lime water. At high pH levels, the solubility of silica and alumina are enhanced, which in turn, promotes the soil-lime reaction. Eades (1962) quoted from TRB (1987) postulated that the high pH causes silica from the clay minerals to dissolve and in combination with Ca^{2+} to form calcium silicate. This reaction continues as long as $Ca(OH)_2$exists in the soil and there is available silica. It is also possible for the lime to react directly with clay crystal edges, producing accumulation of cementitious materials. These reactions cause a decrease in plasticity, dispersion, compressibility, volume change potential, and increase in particle size, permeability and strength. The properties of lime-soils mixtures are dependent on the following:

- Soil type
- Lime type and lime percentage
- Curing conditions, which include time, temperature and moisture.

In general, strength increases as the lime content is increased, but for a given curing period, O'Flaherty (1988) pointed out there might be an optimum lime content. The exact optimum lime content is influenced by the amount and type of clay minerals present. Quick lime are more effective than hydrated lime in producing strength increases due to the greater amount of Ca^{2+}available from a given mass of quicklime as compared with the mass of hydrated lime.

Compaction Characteristics

Maximum density and optimum moisture are needed for field control during compaction so as to

achieve satisfactory results. With a given compaction effort, soil-lime mixtures have a lower maximum density than the original untreated soil. The maximum density normally continues to decreased as the lime content is increased. The optimum moisture content increases with increasing lime content (TRB 1987).
Mixing clayey soils below the optimum moisture content encourages formation of clay balls and clods, whereas mixing at or slightly above optimum eases pulverization and helps break down clods. Above optimum moisture contents, clayey soils become sticky and difficult to mix (Rollings and Rollings, 1996). The addition of lime reduces plasticity and improves workability, thereby, alleviating most of the compaction problem

Compressive Strength

The unconfined compression test is the most popular procedure to evaluate the strength of lime-soil mixture but it is not necessarily the most appropriate test for all purposes (Sabry and Parcher, 1975). The addition of lime can generate immediate improvement in strength and stability because of cation exchange flocculation, and agglomeration. These immediate effects are beneficial when soft, highly plastic cohesive soils create mobility problems for wheeled vehicles during pavement construction operations (TRB, 1987)
The strength of soil-lime mixture continues in excess of 10 years. The difference between the compressive strengths of the natural and lime-treated soil is an indication of the soil-lime pozzolanic reaction (TRB, 1987). When the increase in strength of lime-soil mixture is greater than 340 kN/m^2 (50 psi), Thompson (1966) suggested that the soil is reactive with lime and can be stabilized to produce a quality paving material.
Kennedy et. al (1987) observed an increase in the unconfined compressive strength with the addition of lime to some clay soils.
Allen, et. al., (1977) reported that higher than normal temperature activate the strength producing pozzolanic reactions of lime –soil mixtures.

Experimental Program

Materials

Two commercially available clay minerals, Hydrite R (a synthetic kaolinite clay mineral) and sodium bentonite (predominantly sodium montmorillonite) were used. Hydrite R was in the form of a pulverized white insoluble odorless powder. Sodium Bentonite, a commercial clay was mined at Billings, Montana. It was in the form of pellets and was pulverized before it was incorporated in the experimental study.
A blending study was initially done to establish the material combinations that would produce synthetic soils classified as CL and CH. Various proportions of Hydrite R and sodium bentonite were blended and tested for Atterberg limits. The results are shown in Table 2.Based on the test results, a blend of 95 percent Hydrite R and 5 percent sodium bentonitewas selected as the CL soil, and an 80 percent Hydrite R and 20 percent sodium bentonite blend was established as the CH soil. These synthetic soils were used in the rest of the experiments. The physical properties and chemical composition of these two materials and the blended CL and CH soils are indicated in Table 1.

Table 1. Properties of raw and blended synthetic CL and CH soils

Materials properties	Hydrire R	Bentonite	CL	CH
-# 40	100%	100%	100%	100%
LL, %	43	480	48	70
PL, %	30	33	28	26
PI, %	13	447	20	44
SG	2.620	2.700	2.623	2.636
Minerological composition	97% kaolinite 3% other	90% Mont. 7% Feld. 3% Quartz	92% Kaolinite 4.5% Mont. 1% Feld. 2.5%Quartz	77% Kaolinite 18% Mont. 2% Feld. 3% Quartz

Hydrated lime, a commonly used soil admixtures was selected for the study. The lime conformed to ASTM C 977-89 specifications with regard to soil stabilization.

Mix Design and Stabilization Study

A mix design was conducted with the synthetic CL and CH soils and the stabilizer to determine the appropriate ranges of lime for preparation of specimens to be included in the experimental program. Because subgrade improvement is the main focus of this research, Illinois procedure for mix design which is primarily applicable to soil modification were adopted. The same procedure was extended to the relatively higher stabilizer contents to study plasticity characteristics of the CL and CH soils. However, unconfined compressive strength tests were also done to monitor the effectiveness of the stabilization. The design lime content was designated as the lime content above which no further significant reduction in plasticity index (PI) occurs or if the PI of the stabilized soils drops below 15. The CL soil was treated with 2, 3, 4, 5, and 6 percent hydrated lime; the CH was treated with 2, 4, 6, 8, and 10 percent hydrated lime. The lime treated mixture were allowed to mellow I hour before liquid and plastic limit tests were performed on the samples. Based on the test results, 2, 4, 6 percent lime contents were adopted for the stabilization program. Although, 2 percent lime content reduced the PI to below 15, the 4 percent lime content reduced the PI of both the CL and CH soils below 15. There was no further significant reduction in PI when the lime content exceeded 6 percent.

Compaction Study

A compaction study was undertaken to establish the optimum moisture content (OMC) and maximum dry density (MDD) for the specimens to be subjected to compressive strength testing. The effect of 2, 4, and 6 percent lime content on both

MDD and OMC for the CL and CH were investigated. Unstabilzed CL and CH soils were also tested as control specimens. The mixtures were compacted dynamically in a Harvard miniature mold. To accomplish the standard Proctor compactive effort of 198629.4 kg/m^3 (12,399.8 1b/ft^3), a hammer of 15.2mm (0.6 in) diameter and weighing 0.43 kg(0.95 lb) was dropped 213.4 mm (8.4 in) to compact the specimens in three layers with 18 blows on each layer.
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Unconfined Compressive Strength

Specimen size

In this research, a specimen size of 31.3 mm (1.25 in) diameter and 68.8 mm (2.75 in) high was chosen because of the small quantity of available hydrite R and the ease and speed of sample preparation. Moreover, the small quantity of the material involved ensured a very high probability of obtaining uniform specimens.

Specimen Preparation

Triplicates specimens for the unconfined compressive strength testing was prepared according to ASTM D1633. The untreated CL and CH soils were mixed at optimum moisture content and were compacted immediately in the Harvard miniature mold. The extruded samples were wrapped in a rubber membrane and placed in a zip-lock bag for a period of 24 hours in the humidity chamber to insure a uniform moisture distribution.

Triplicates samples of lime treated CL and CH soils were also made at the optimum moisture content according to AASHTO Designation T-220. The soil- lime mixture contained 2 %, 4% and 6 % hydrated lime. The samples were accelerated cured in an oven for 7 days at 105 ^oF

Results and Discussion

Relationship between Mineralogy and Geotechnical properties of Cohesive soils

The results of the consistency (Atterberg's) limits tests of clay minerals i.e., kaolinite (hydrite R), sodium montmorrilonite and the various combinations of kaolinite and sodium montmorrilonite cohesive soils are tabulated in table 2 and plotted graphically in figure 1. The liquid limit (43) and the plasticity index PI (13) of the kaolinite clay mineral indicated that it is non-cohesive soilwhile that of sodium montmorrilonite demonstrated a very high cohesiveness. The liquid limit and the plasticity index for the sodium montmorrilonite clay minerals were 460 and 447 respectively.
From the plot, itwas deduced that the type of clay mineral present influences the geotechnical properties of the soil. The addition of 5 percent sodium montmorillonite to the kaolinite significantly raised the plasticity index (PI) of kaolinite clay mineral from 13 to 20. It should be noted that subgrade soils with PI greater than 18 are considered marginal to poor subgrade soils.
Clay surfaces have residual negative charges due to isomorphous substitution of Si^{4+} and $Al^{3+}$by other lower valence ions such as Mg^{2+} cation. Montmorrilonite clay mineral is very reactive because of its very high specific surface area (800 m^2/g)and affinity for adsorbed water which are held tightlyat the surface. Comparatively, kaolinite clay mineral has low specific surface area (10 -20 m^2/g) and affinity for adsorbed water.
The results are consistent with Attewell and Taylor findings in 1973. They asserted that increasing montmorillonite content for different North American cohesive soils greatly influenced the geotechnical properties such as raising the liquid limits of the various soils.

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Table 2. Atterberg limits of the blended soils

Sample #	Hydrite R %	Bentonite %	LL	PL	PI
	100	0	43	30	13
KB1	95	5	48	28	20
KB2	90	10	59	29	30
KB3	80	20	70	26	44
KB4	70	30	99	25	74
KB5	60	40	119	26	93
KB6	50	50	132	27	105
KB7	40	60	162	28	134
KB8	30	70	197	30	167
KB9	20	80	210	31	179
KB10	10	90	309	31	278
	0	100	480	33	447

LL= Liquid Limit **PL= Plastic Limit** **PI= Plasticity Index**

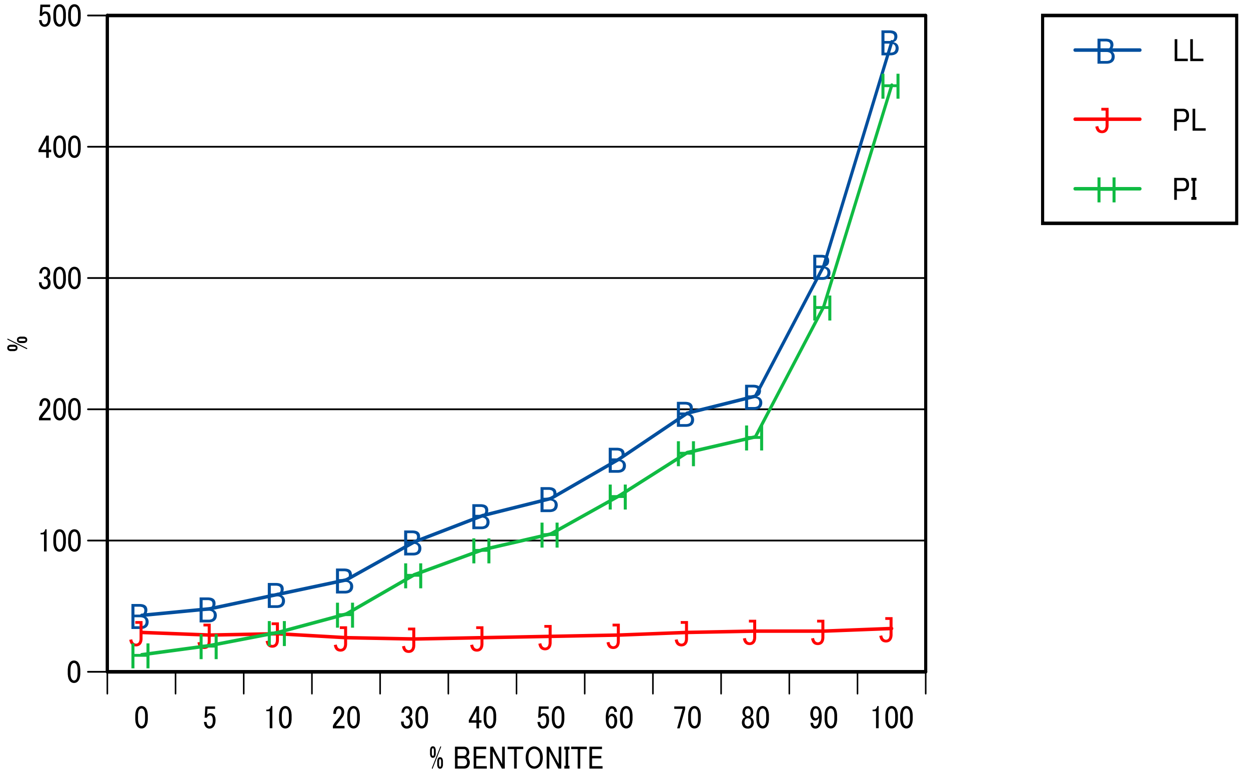

Fig 1.Influence of Bentonite on Atterberg Limits. (% Moisture verses % Bentonite)

Effect of Lime and Curing Time on Atterberg's Limits

Tables 3 (a) and (b) were summary of results and Figures 3 (a), 3 (b), 3 (c), 3 (d) 3 (e), 3 (f) showed plots of the effect of lime and curing on Atterberg's limits.

From the results, there was a marked decrease in liquid limits and a significant increase in plastic limits on the CL and CH soils with the addition of lime. Plasticity index (PI) which is a composite parameter also showed a remarkable decrease. Specifically, with the addition of 2 percent lime, the plasticity index (PI) for the CL soil was reduced drastically from 20 to 12. This made the CL soil suitable as a subgrade soil. 4 percent lime reduced the PI of the CH soils from 44 to 18. However, as more lime was added to the CL and CH soils, the rate of reduction of the PI decreased.

Jan and Walker (1963) also observed that the first increments of lime addition are generally most effective in reducing plasticity, with subsequent additions being less beneficial. Sabry and Parcher (1979) examined the effect of lime treatment on Atterberg's Limits of Camargo bentonite and found a substantial decrease in liquid limit and an increase in plastic limit. The current research support the findings.

Figures 3 c and 3fclearly showed that curing time has almost negligible effect on plasticity index (PI). The student t test run on the results showed that there was no significant difference among samples cured at 2 hours, 7 days or 28 days. This was attributed to the fact that lime is an active admixture which initiated several reactions with the clay soils almost as soon as they were mixed.One of such reaction was the cation exchange which began immediately between the metallic ions associated within the diffuse hydrous double layer surfaces of the clay particles and the calcium ions of the lime.This altered the density of the electrical charge around the clay particles which led to their being attracted to each other to form flocs, the process being termed flocculation and

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agglomeration. The above reactions lead to a reduction of plasticity within 1 or 2 hours after mixing (Diamond and Kinter, 1965;Bell, 1996)

Basmer and Tuncer (1991) also reported that there is nosignificant effect of curing time on the reduction of liquid limit or plasticity index

Table 3a. Effect of lime on low Plastic Soils (CL)

Sample #	% Lime	LL (Curing)			PL (Curing)			PI (Curing)		
		2Hr	7D	28D	2Hr	7D	28D	2Hr	7D	28D
KB1	0	48	48	48	28	28	28	20	20	20
KB1	2	46	45	45	32	33	33	14	12	12
KB1	3	44	44	44	34	34	35	10	10	9
KB1	4	44	44	44	36	37	37	8	7	7
KB1	5	45	44	44	38	38	38	7	6	6
KB1	6	44	45	45	38	38	39	6	7	6

LL = Liquid Limit **PL= Plastic Limit** **PI= Plasticity Index**

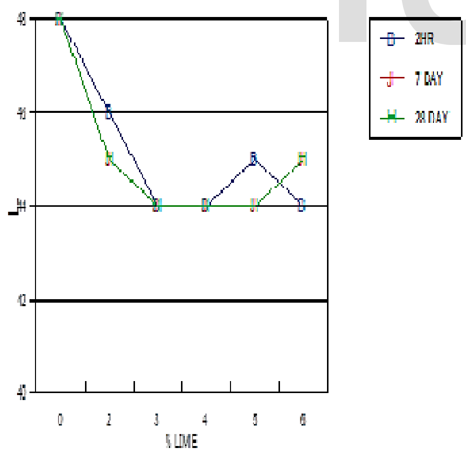

Figure 3a. Effects of Lime and curing time on the LL of CL soil.

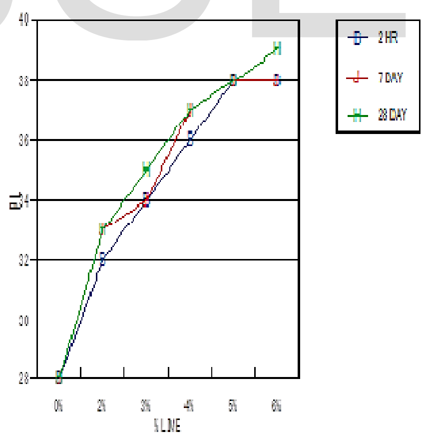

Figure 3b. Effects of Lime and Curing timeon the PL of CL soil.

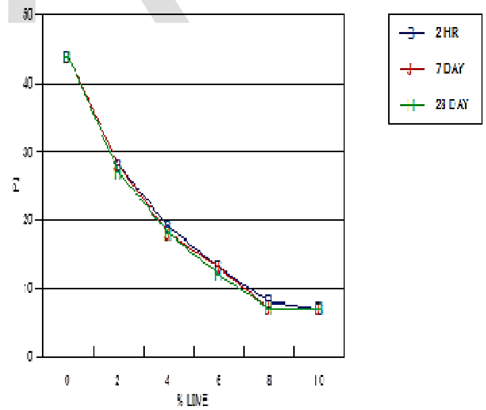

Figure 3c. Effect of Lime and Curing time on the PI of CL soil.

Table 3b. Effect of Lime on High Plastic Soils. (CH)

Sample #	% Lime	LL (Curing) 2Hr	LL (Curing) 7D	LL (Curing) 28D	PL (Curing) 2Hr	PL (Curing) 7D	PL (Curing) 28D	PI (Curing) 2Hr	PI (Curing) 7D	PI (Curing) 28D
KB3	0	70	70	70	26	26	26	44	44	44
KB3	2	63	63	63	35	35	36	28	28	27
KB3	4	57	57	57	38	39	39	19	18	18
KB3	6	55	55	54	42	42	42	13	13	12
KB3	8	53	53	53	45	46	46	8	7	7
KB3	10	52	52	52	45	45	45	7	7	7

LL= Liquid Limit PL= Platic Limit PI= Plasticity Index Hr= Hour D= Day

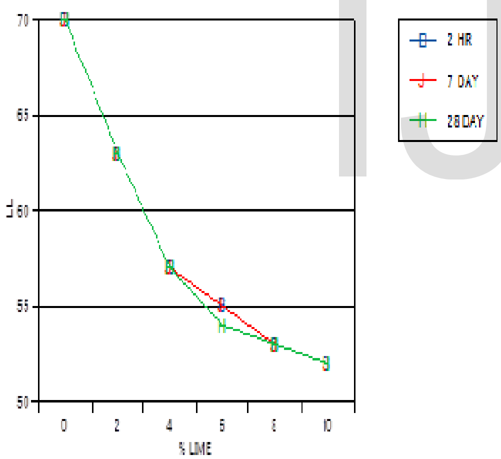

Figure 3d. Effect of Lime and Curing time on the LL of CH Soils

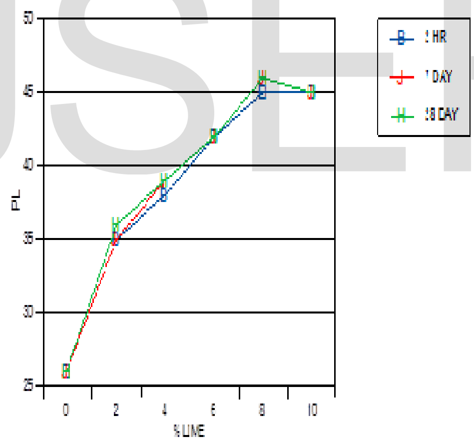

Figure 3e Effect of Lime and Curing time on the PL of CH soil.

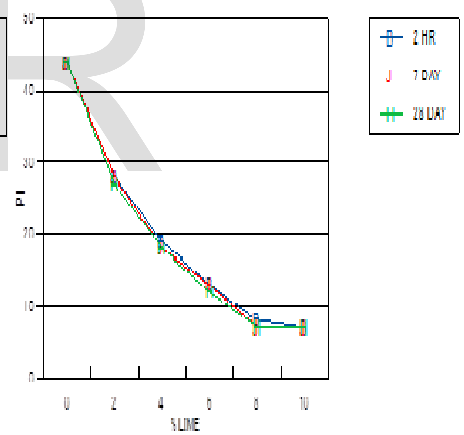

Figure 3f Effect of Lime and Curind time on the PI of CH soil.

Effect of Lime on Dry Density and Optimum Moisture Content

Dry density and moisture contents values obtained from the Harvard Miniature mold on CL and CH soils and soil-lime mixtures are summarized in Tables 4a and 4b.Figures 4a and 4b show the plots of the moisture density relationship of the CL, CH and the soil-lime mixtures. Figure 5 also shows the effect of lime on the density and soil type. From the figures, the following observations were made.

- A broad peaked compaction curve was generated for all the samples (treated and untreated)
- The soil-lime mixture has a lower maximum density than the untreated CL and CH soils for a given compactiveeffort.

- The soil-lime mixture of the CL soil has a higher density than the soil-lime mixture of CH soil at the same lime content.
- As the percentage of lime increased, the percentage reductionof the maximum density also increased.
- The optimum moisture content increased with increasing lime content.

The practical significance of the above findings is that a large range of molding moisture contentcould effectively achieve a relatively high density. Moisture content adjustment, either increase or decrease, is very difficult with sticky and low-permeability CH clays (Rollings and Rollings, 1966). However, the reduction in density as the lime content increases present a major challenge in determining the accurate field density during construction. For example, if the contractor's lime application rate in the field exceeds the specified amount, then calculating percentage relative density based on the compaction curve for lower lime content unfairly penalizes the contractor. Conversely, if the contractor's lime application rate is lower than specified, it may give an erroneous impression that high density has been achieved.

Wang et. al. (1963) reported that the addition of lime to a soil lowered its maximum density for the same compactive effort,They stated that the greatest decreasing rate in the maximum density was for small amounts of additives. TRB (1987) asserted that the maximum density decreased and optimum moisture increased as the lime content increased in soil-lime mixtures. The current research support the findings of TRB. Jan and Walker (1963) studied the effects of lime on moisture density relations and observed no significant reduction in maximum density and a slight reduction of moisture content after the addition of lime. Au and Chae (1980) found that lime treatment decreased the maximum density without appreciable change in optimum moisture content. They hypothesized that the decrease in maximum dry density with increasing lime content was due to the higher degree of flocculated book house soil structure.

When lime is added to clayey soils, the monovalent cations generally associated with clays are replaced by the divalent calcium ions. From Table 5, it can be seen that calcium cation is a good flocculator and has a relative flocculating power of 41 times that of sodium ion.

Table 4a. Moisture Density Relations for CL Soils (Lime Treated)

KB1 + 0% Lime		KB1 + 2% Lime		KB1 + 4% Lime		KB1 + 6% Lime	
MC%	Density.Kg/M^3	MC %	Density Kg/M^3	MC%	Density Kg/M^3	MC%	DensityKg/M^3
20	1392.87	20	1472.92	20	1282.401	20	1274.396
22	1568.98	22	1524.152	22	1450.506	22	1357.648
24	1617.01	24	1543.364	24	1492.132	24	1397.673
26	1552.97	26	1578.586	26	1520.95	26	1471.319
28	1504.94	28	1504.94	28	1562.576	28	1508.142
30	1440.9	30	1447.304	30	1477.723	30	1528.955
				32	1432.895	32	1474.521
						34	1474.521

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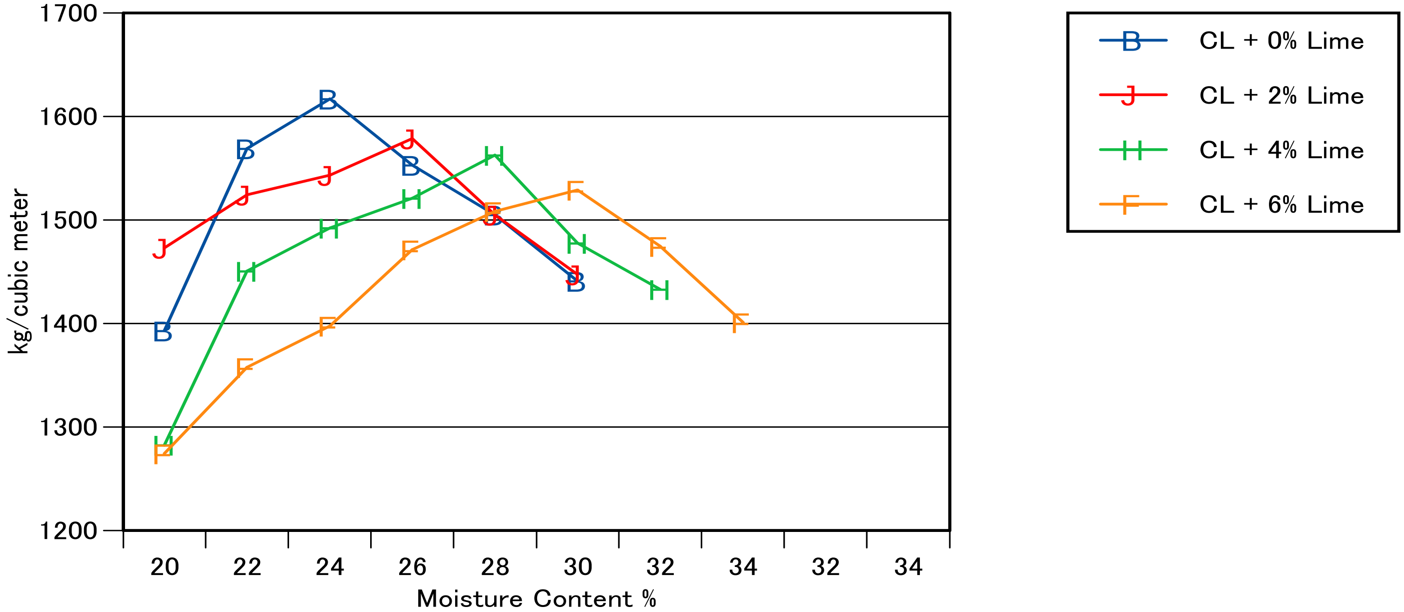

Figure 4a. Moisture Density relationship of CL + LIME

Table 4b. Moisture Density Ralations for High Plasticity Soils (Lime- Treated)

KB3 + 0% Lime		KB3 + 2% Lime		KB3 + 4% Lime		KB3 + 6% Lime	
MC%	Density. Kg/M³	MC%	Density. Kg/M³	MC%	Density. Kg/M³	MC%	Density. Kg/M³
20	1424.89	20	1360.85	20	1388.067	20	1282.401
22	1525.753	22	1416.885	22	1482.526	22	1324.027
24	1568.98	24	1477.723	24	1508.142	24	1344.84
26	1520.95	26	1551.369	26	1528.955	26	1420.087
28	1488.93	28	1474.521	28	1520.95	28	1440.9
30	1440.9	30	1407.279	30	1452.107	30	1456.91
				32	1432.895	32	1408.88
						34	1376.86

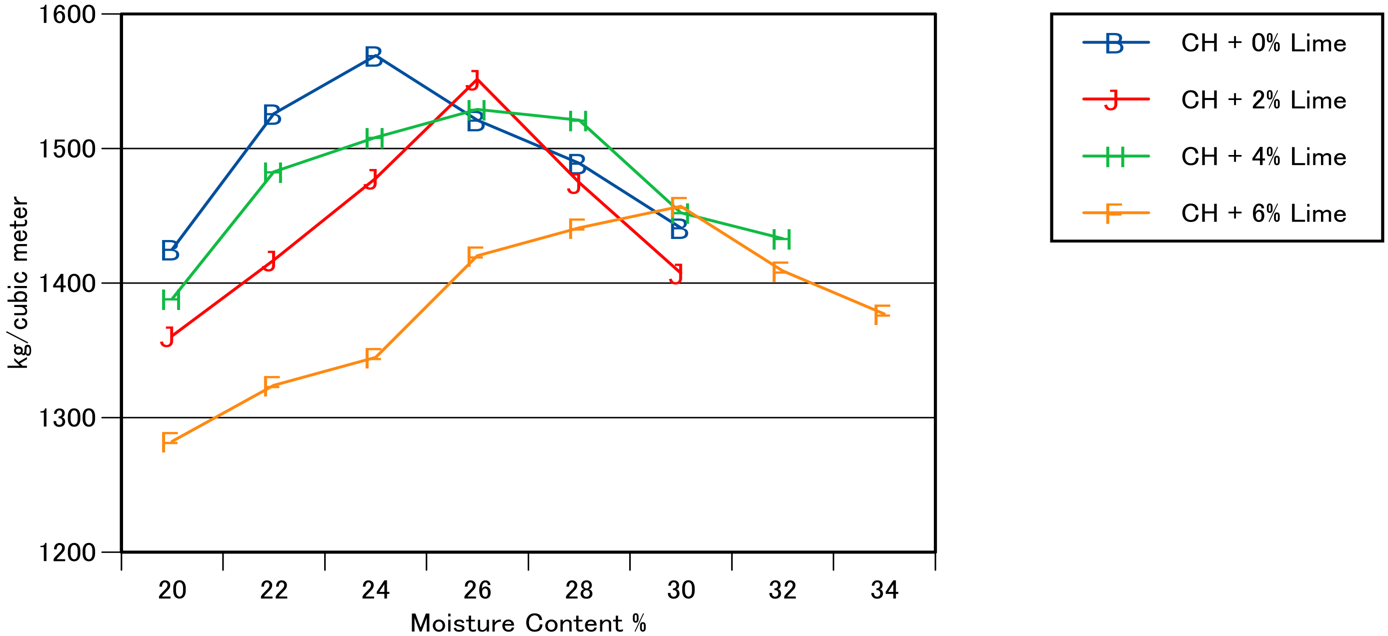

Figure 4b. Moisture Density relationship of CH + Lime

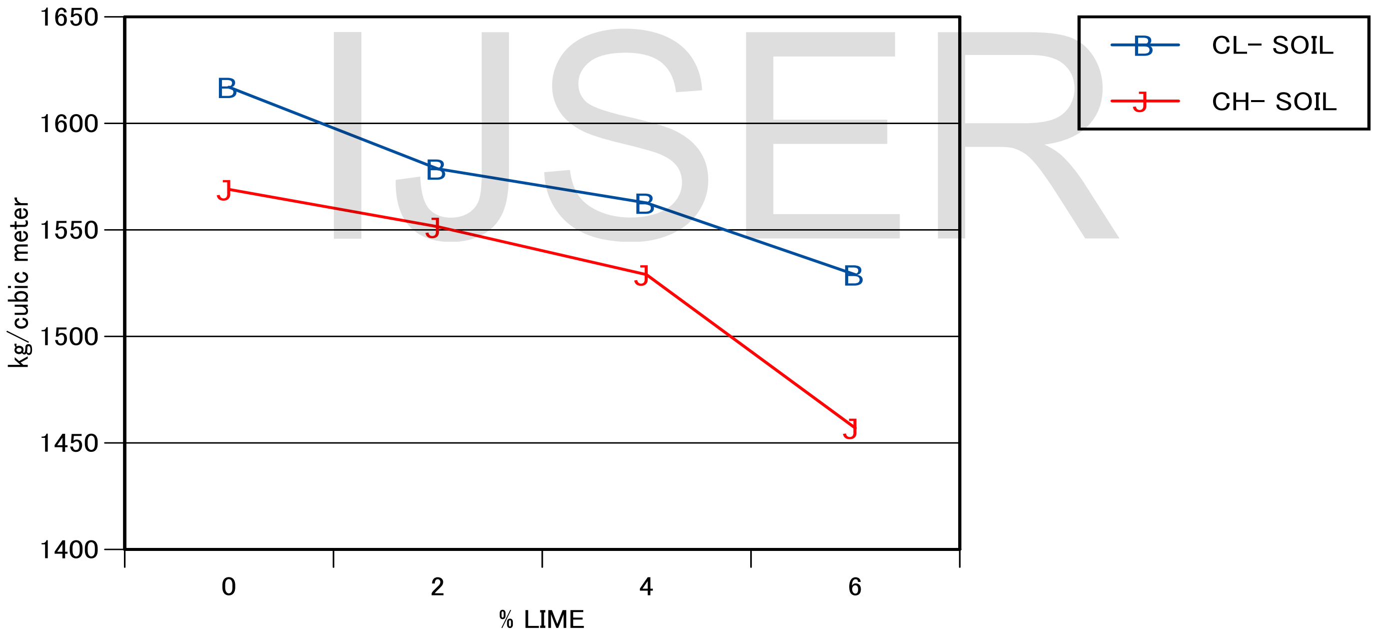

Figure 5.Effect of lime on Density of CH and CL soils.

As the lime content increases, more hydrated calcium ions are released into solution resulting in more flocculation and agglomeration of clay particles. As reported earlier, flocculation produces change in the texture of clay soils. The clay particles form larger particles with large void spaces between them culminating into lower maximum density. Nagaraj (1964) suggested that the decrease in maximum dry density of the lime treated soil is a reflection of increased resistance offered by the flocculated soil structure to the compacted effort. The reduction in maximum drydensity according to Bell (1996) could be due to an immediate formation of cementitious products which reduce compactibility and hence the density of the treated soil.

Higher compaction densities were obtained in the CL soil treated with lime than the CH soil treated with lime. The CH soils contained 20 percent sodium montmorillonite compared to 5 percent of sodium montmorrilonite in the CL soil. Croft (1964) suggested that this was due to the higher demand of expandable clay minerals (sodium montmorillonite) for adsorbed and lubrication water. Sodium montmorillonite is a reactive clay mineral with very large specific surface area which can easily get saturated by adsorbing water. The author agrees with Croft suggestion.

Little (1996) believed that optimum moisture content increased with increasing lime content because more water was needed for the soil-lime chemical reactions.

Table 5: Relative flocculating Powers of Cations (Dr. Jim Walworth (2006))

Cation	Chargers per atom	Hydrated radius (nm)	Relative Flocculating Power
Sodium (Na^+)	1	0.79	1.0
Potassium (K^+)	1	0.53	1.7
Magnesium (Mg^{2+})	2	1.08	27.0
Calcium (Ca^+)	2	0.96	43.0

Effect of Lime on the Unconfined Compressive Strength

The unconfined compressive strength of the pulverized fine grained low plastic CL soil compacted at optimum moisture content and maximum dry density was 663.6kN/m^2. The lime treated CL soil showed a remarkable increase in compressive strength. The increase in compressive strength ranged from 1493.10 kN/m^2 for the 2 percent lime to 2626.75 kN/m^2 for the 6 percent lime as tabulated in table 6 below.

Table 6also demonstrates a similar trend for the CH soils where the unconfined compressive strength increased with the amount of the lime present. The untreated CH soil compressive strength was 276.5kN/m^2.

The differences between the compressive strengths of the untreated compacted fine grained CL and CH soils and the lime-treated soils give an indication that soil-lime pozzolanic reaction has taken place. Pozzolanic reaction between soil and lime involves a reaction between lime and the silica and alumina of the soil to form cementing material.

$Ca(OH)_2 + SiO_2 = CSH$ where $C = CaO$; $S = SiO_2$; $H = H_2O$

The pozzolanic reaction may continue for a long time.

If the increase in strength is greater than 276.5 kN/m^2, then the soil –lime mixture has undergone pozzolanic reaction (Thompson, 1966).

From the results, both the CL and CH soils underwent pozzolanic reaction. However, the strength gains in the CL soils were greater than the CH soils. As stated earlier, the CH soils contained 20 percent of sodium montmorillonite while the CL soil contained only 5 percent of sodium montmorillonite. Much of the lime in the CH soils was apparently used to break down or degrade the large specific surface area of the montmorillonite clay minerals. The lime treatment created flocculated structure but the reaction products which were produced by the through solution process become less effective because the surface area was too large for the cementitious material to create significant increases in the unconfined compressive strengths. Hence the lower strengths gain in the CH soils (Ford et. al., 1982);

Table 6. Effect of Lime on Unconfined Compressive Strength of CL and CH Soils

% LIME	Unconfined Compressive Strength CL / KiloPascal	CH / KiloPascal
0	663.60	276.5
2	1493.10	1106.00
4	2322.60	1216.60
6	2626.75	1741.95

CONCLUSION

From the research, it was concluded the type of clay mineral present influences the geotechnical properties of the soil. The addition of 5 percent sodium montmorillonite to the kaolinite significantly raised the plasticity index (PI) of kaolinite clay mineral from 13 to 20.
The addition of 2 percent lime drastically reduced the plasticity index (PI) for the CL soil from 20 to 12. This made the CL soil suitable as a subgrade soil. 4 percent lime reduced the PI of the CH soils from 44 to 18. However, as more lime was added to the CL and CH soils, the rate of reduction of the PI decreased.
Curing time has no significant effect on plasticity index (PI).
The soil-lime mixture has a lower maximum density than the untreated CL and CH soils for a given compactive effort.
The soil-lime mixture of the CL soil has a higher density than the soil-lime mixture of CH soil at the same lime content.
As the percentage of lime increased, the percentage reduction of the maximum density also increased.
The optimum moisture content increased with increasing lime content due to hydration of calcium cations.
Lime flocculated CL and CH clay soil produced larger particles with large void spaces between them culminating into lower maximum density.
The unconfined compressive increment of more than 277 kN/m^2 after the addition of lime to the CL andCH soils indicated that pozzolanic reaction hastaken place.

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