Lime Stabilization of Clay-Sand Mixtures

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Laboratory-prepared, lime-treated, clay-sand mixtures were studied. A 5 percent lime-treatment level was chosen for the major part of this investigation; however, a limited number of samples were mixed with 3 and 7 percent lime. The percentages of lime specified here were based on the weight of the whole soil mixture. Essentially, 2 types of clay-sand mixtures were investigated: a Hydrite UF-sand mixture and a Grundite-sand mixture. Within each type of mixture, there were different clay-sand ratios. Different compactive efforts were applied to fabricate cylindrical samples of various clay-sand ratios to the desired dry densities, which were taken as 95 percent of the maximum dry density of a specified compactive effort of the corresponding untreated samples. Unconfined compressive strengths and pH values were determined on samples cured for 1 to 12 weeks. The results of this investigation show that the effectiveness of lime-soil stabilization appears to be related to the fine-grain fraction/lime ratio (FGF/L) of a soil mixture. For the 2 types of clay-sand mixtures studied, the optimum FGF/L ratios for maximum strength range from 14 to 12 depending on curing period. The rate of strength gain is affected by the lime-treatment level; however, the optimum FGF/L ratio is only slightly affected. The magnitudes of maximum strength for a given FGF/L ratio vary with the coarse-grain fraction content in a soil mixture—the lower the coarse-grain fraction content is, the higher the strength. It is believed that the FGF/L ratio is a more indicative parameter for dealing with lime-soil stabilization than the lime percentage specified on the basis of either total weight or total volume of the whole soil mixture.

•LIME HAS BEEN USED extensively to modify the engineering characteristics of fine-grained soils. The beneficial effects of lime stabilization on the plasticity, shrinkage, workability, and strength properties of a soil are well known. In general, most of these properties are altered by the addition of 3 to 7 percent lime by weight. The strength increase observed in soils by the addition of lime, however, is variable. This variation of strength increase has been attributed to the degree of accomplishment of lime-soil reactions, namely, cation exchange, flocculation, carbonation, and pozzolanic reaction. The last reaction is considered to be primarily responsible for the long-term strength increase in lime-soil mixtures.

The effectiveness of lime stabilization depends on many factors. Works by groups from M.I.T., Iowa State University, University of Illinois, and many others have contributed greatly to the understanding of the engineering behavior, the chemical reactions, and the mineralogical aspect of lime-soil stabilization. In recent years, a qualitative approach based on pedological classification has been adopted by Thompson (1) to establish some guidelines for the evaluation of lime reactivity of Illinois soils. He reported that lime-soil reactions are dependent on the nature and character of the soil being stabilized. Hilt and Davidson (2) reported that lime fixation in clayey soils depends on

Paper sponsored by Committee on Lime and Lime-Fly Ash Stabilization and presented at the 49th Annual Meeting.

the type of clay minerals. The quantity of lime used for lime fixation contributes to the improvement of soil workability but not to the increase in strength. Additional amounts of lime added above the lime fixation capacity cause the formation of cementing materials within clayey soils.

X-ray diffraction and electron microscopic studies made on lime-soil stabilization (3, 4, 5) have indicated that pozzolanic reaction can be described as a slow and continuous reaction in the presence of $Ca(OH)_2$ and soluble silica or alumina. It causes the breakdown of clay particles and the formation of new crystalline phases, or it attacks the clay particles and deteriorates the whole clay mineral structure. Because of these processes the conductivity of the system decreases, indicating that soluble salts in the lime-soil mixture are converted to less soluble compounds that may serve to bond particles together. This phenomenon is irreversible.

Eades and Grim (6) more recently have proposed that the optimum lime content for strength increase for lime stabilization can be determined by pH readings of the lime-soil mixture. Hilt and Davidson (2) reported that the lime fixation capacity of a montmorillonitic or kaolinitic soil is the same as the optimum lime additive for maximum increase in the plastic limit of the soil. Arulanandan and Shen (7) have used the nondestructive electrical response characteristics measurements to monitor the continuous structural change of a lime-soil mixture. This technique makes possible the examination of the various lime-soil reactions and the determination of the approximate lime percentage required for long-term strength increase.

It is interesting to note that most of the work done in lime-soil stabilization specifies the amount of lime added to the mixture as a percentage of either the total weight or the total volume of the soil mixture. However, it is generally recognized that lime reacts primarily with the fine-grain fraction (passing No. 200 sieve) of the soil mixture, whereas the coarse-grain fraction does not react chemically with lime. Therefore, it is worthwhile to specify the lime content for stabilization on the basis of the fine-grain fraction of the soil mixture rather than the mixture as a whole and relate the effectiveness of lime stabilization to the ratio of fine-grain fraction to lime content. It would also be interesting to examine how the chemically nonreactive part of the soil mixture affects the overall physical properties of lime stabilization. This approach appears to be more realistic in dealing with natural soils that are in most cases composed of various amounts of sand, silt, and clay.

This paper presents the results of a preliminary study made on laboratory mixed clay-sand mixtures treated with lime.

EXPERIMENTAL PROGRAM

Materials

The sand used in this study was a No. 20 Del Monte sand of uniform subrounded to subangular particles. The gradation curve of this sand is shown in Figure 1. Also shown in Figure 1 are the grain-size distribution curves of the 2 types of commercial clays used in this study. They are Hydrite UF, a product from George Kaolin Company, and Grundite, a product from Illinois Clay Products Company. The Hydrite UF is a pure kaolin clay of very fine particles, and the Grundite contains primarily illitic clay minerals with substantial amounts of silt-size particles. The physical properties of these commercial clays are given in Table 1. A hydrated, high-calcium lime containing 90 percent available $Ca(OH)_2$ was used in all the mixtures.

Lime-Treatment Level

A 5 percent lime-treatment level was chosen for the major part of this investigation; however, a limited number of samples were treated with 3 and 7 percent lime. The percentages of lime specified here were based on the weight of the whole soil mixture.

Preparation of Specimens

Composition of Specimens—Figure 2 shows the compositions of the specimens fabricated and tested in this investigation. Essentially, there were 2 types of mixtures:

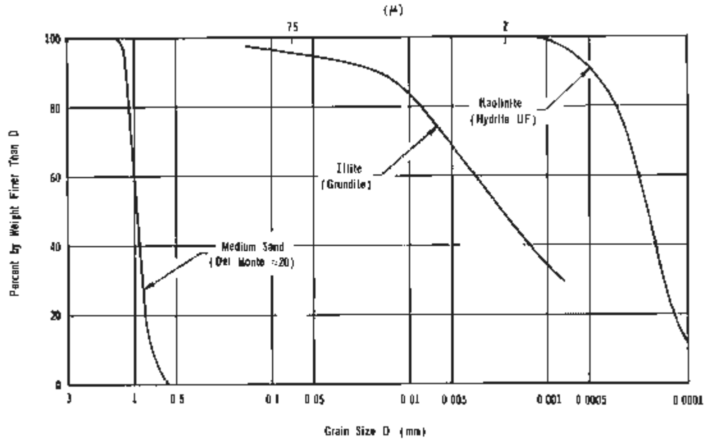

Figure 1. Grain size distribution curves for experimental clays and sand.

a Hydrite UF-sand mixture (K-S), and a Grundite-sand mixture (I-S). Samples were labeled as, for instance, 5K100, which meant 100 percent Hydrite UF and no sand treated with 5 percent lime, or 3G60, which meant 60 percent Grundite and 40 percent sand treated with 3 percent lime.

Mixing—The appropriate amount of clay, sand, and lime were first mixed in an air-dry condition; the necessary amount of water was then added to the mixture and thoroughly mixed for about 5 minutes. The time lapse between mixing and compaction was kept constant for all samples. The amount of water-soil-lime mixture mixed each time was enough for 2 specimens, and the time lapse from after mixing to the completion of compaction was approximately 15 minutes.

Compaction—Cylindrical samples were compacted in pairs by static compaction in 1.4-in. diameter steel molds. Different compactive efforts were employed to fabricate samples of various clay-sand ratios to the desired dry densities, which were

TABLE 1
CHARACTERISTICS OF COMMERCIAL CLAYS

Characteristic	Kaolinite (Hydrite UF)	Illite (Grundite)
Liquid limit	63	51
Plasticity index	34	30
Percentage finer than No. 200 sieve	100	95
Percentage finer than 2μ	100	47
Mineral composition, percent	100 Kaolinite	55 Illite (9) 10 Kaolinite 20 Quartz 15 Mixed layer clay

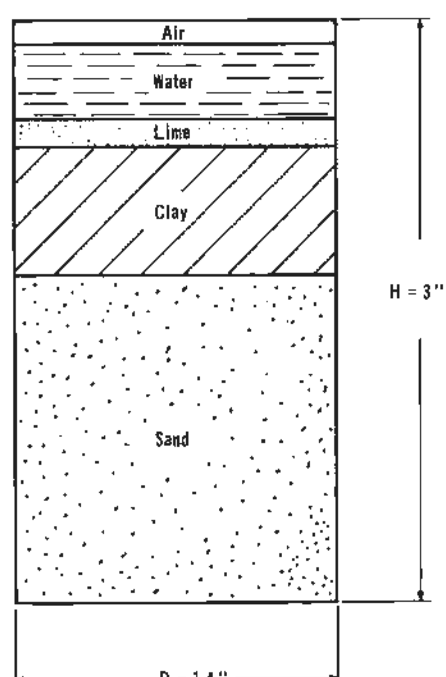

Figure 2. Composition of a specimen.

taken as 95 percent of the maximum dry density of a specified compactive effort of the corresponding untreated samples. The molding moisture contents were taken as 112, 120, and 128 percent of the optimum moisture contents of the untreated samples for 3, 5, and 7 percent lime-treatment levels respectively. The maximum dry densities and the optimum moisture contents of the untreated samples are given in Table 2.

TABLE 2

MAXIMUM DRY DENSITIES AND OPTIMUM MOISTURE CONTENTS OF UNTREATED MIXTURES

Mixture	Dry Density (g/cm^3)	Moisture Content (percent)
K 100	1.27	36.0
K 80	1.42	26.5
K 60	1.61	21.0
K 40	1.82	15.2
K 20	1.97	10.5
I 100	1.66	20.0
I 80	1.76	17.0
I 60	1.85	14.5
I 40	1.98	12.5
I 20	1.98	10.0

Curing—All samples were stored in a moisture room of 72 F and 95 percent humidity for curing. These samples were wrapped in 2 rubber membranes with a thin film of silicon grease in between. O-ring seals were applied around both lucite bases to prevent change in moisture content and the entry of CO_2 gas during curing.

The 5 percent lime-treatment samples were cured for 1, 2, 4, 8, and 12 weeks prior to testing. A 4-week curing period was chosen for I-S mixtures of 3 and 7 percent lime treatment. The untreated samples were also cured for one week before testing to eliminate possible thixotropic effect in compacted clay.

Testing

Unconfined Compression Tests—The unconfined compression tests were carried out on the TO testing machine. The loads and deformations throughout the test were automatically recorded. All tests were performed at a strain rate of 0.05 in. per minute.

pH Value Measurements—The Backman pH-meter was used to measure the pH of all samples. As recommended by Eades and Grim (6), a 1:5 soil to CO_2-free distilled water slurry was used. The slurry was stirred at regular intervals for one hour before measurements were taken.

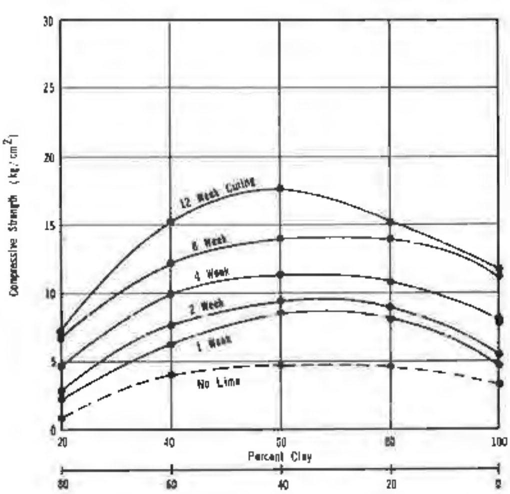

Figure 3. Compressive strength of kaolinite-sand mixtures with 5 percent lime.

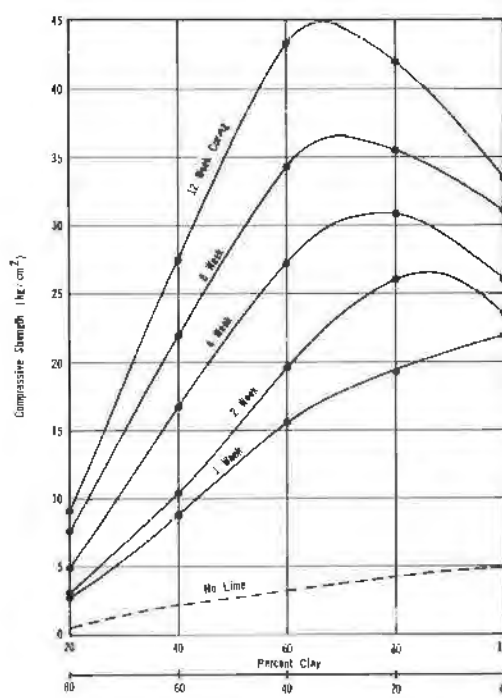

Figure 4. Compressive strength of illite-sand mixtures with 5 percent lime.

TABLE 3

UNCONFINED COMPRESSIVE STRENGTH DATA (kg/cm^2)

Specimen	Untreated	5 Percent Lime Treatment				
		1W	2W	4W	8W	12W
K 20	1.0	2.4	2.5	4.7	6.8	7.1
K 40	4.1	6.2	7.6	10.1	12.2	15.1
K 60	4.8	8.6	9.4	11.0	13.9	17.9
K 80	4.7	8.1	8.9	11.0	14.6	15.0
K 100	3.3	4.7	5.4	8.2	11.5	11.3
I 20	0.6	2.8	3.1	4.9	7.6	9.0
I 40	2.3	8.9	10.6	16.7	21.9	27.6
I 60	3.0	16.1	19.7	27.1	34.4	43.5
I 80	4.4	19.3	26.1	30.9	35.5	42.0
I 100	5.2	22.0	23.5	26.0	31.0	33.3

TEST RESULTS

Strength Tests

After a predetermined period of curing, samples were tested to failure, and the unconfined compressive strengths of the samples were determined. The results of strength tests plotted against the sand-clay ratio for K-S and I-S mixtures are shown in Figures 3 and 4 respectively. The dotted curve on the lower part of each plot shows the compacted, untreated soil strengths of different C/S ratios. It can readily be seen that lime treatment can increase the strengths of the mixtures (compared with 12-week curing strength at same densities) from 4 to 7 times their respective untreated strengths for K-S mixtures and about 6 to 16 times for I-S mixtures. The strength test results are given in Table 3.

Figures 5 and 6 show the variations of axial strains at failure for the 5 percent lime-treatment samples. These results indicate that in general the strain at failure decreases with increasing curing time and decreasing fine-grain fraction content in a sample.

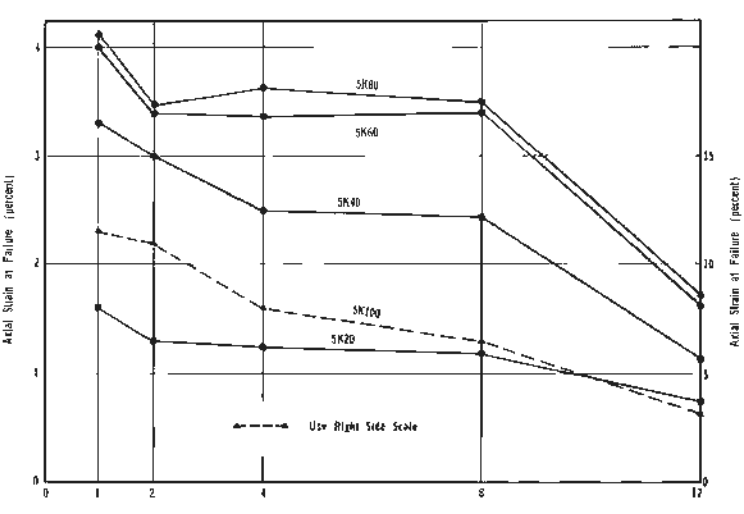

Figure 5. Axial strain at failure of kaolinite-sand mixtures with 5 percent lime.

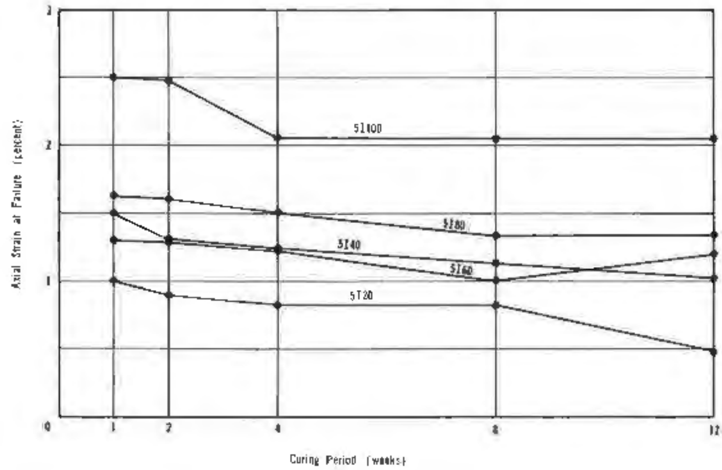

Figure 6. Axial strain at failure of illite-sand mixtures with 5 percent lime.

pH Measurements

Upon completion of the unconfined compression tests, samples were broken up partly for water content determination and partly for pH value measurements. The pH value of a soil sample was measured with 5 parts of CO_2-free distilled water, and 1 part of the soil mixture. Figures 7 and 8 show the variations of pH values for various C/S mixtures with curing time. The untreated mixtures had much lower pH values (Table 4).

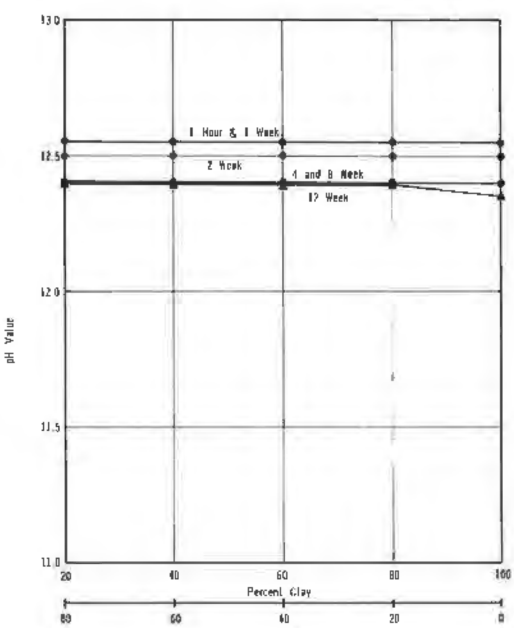

Figure 7. pH values of kaolinite-sand mixtures with 5 percent lime.

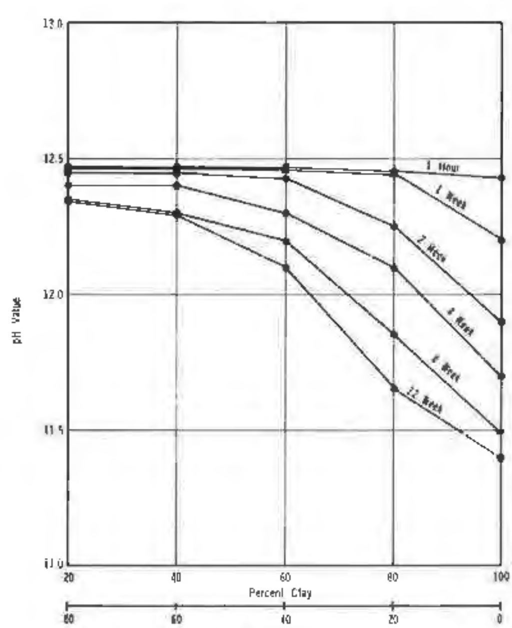

Figure 8. pH values of illite-sand mixtures with 5 percent lime.

TABLE 4

pH VALUES

Specimen	Untreated	5 Percent Lime					
		1H	1W	2W	4W	6W	12W
K 20	5.2	12.55	12.55	12.50	12.40	12.40	12.40
K 40	4.9	12.55	12.55	12.50	12.40	12.40	12.40
K 60	4.9	12.55	12.55	12.50	12.40	12.40	12.40
K 80	4.9	12.55	12.55	12.50	12.40	12.40	12.40
K 100	4.9	12.55	12.55	12.50	12.40	12.40	12.35
I 20	3.5	21.47	12.20	11.90	11.70	11.50	12.35
I 40	3.2	12.47	12.45	12.25	21.10	11.65	12.30
I 60	3.0	12.47	12.47	12.43	12.30	12.20	12.10
I 80	3.0	12.45	12.47	12.45	12.40	12.30	11.65
I 100	2.9	12.43	12.47	12.45	12.40	12.35	11.40

The addition of 5 percent lime to the soil mixture immediately elevated the pH values to approximately 12.5 for all mixtures. The pH value decreased as curing time was prolonged. However, the amount of decrease in pH with time depends on the C/S ratio and the clay mineral of the mixture. The relatively rapid drop in pH in I-S mixtures reflects the higher strength-gaining capacity of the mixtures.

Lime-Treatment Level

A limited number of samples of I-S mixtures were prepared with 3 and 7 percent lime. These samples were cured for 4 weeks prior to testing. These tests were designed to investigate the effect of lime-treatment level on the strength of samples having various C/S ratios. The results of these tests are shown in Figure 9. pH values were also determined after the completion of strength tests and are shown in Figure 10.

DISCUSSION OF RESULTS

Compressive Strength

K-S Mixtures—For samples with a fine-grain fraction greater than 40 percent as shown in Figure 3, the strengths of untreated samples range from 3.5 to 4.5 kg/cm^2. For samples with a fine-grain fraction of less than 40 percent, the untreated strength decreases drastically

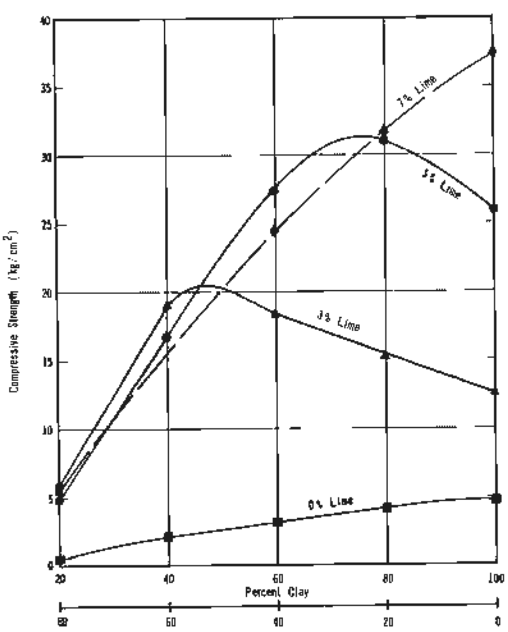

Figure 9. Illite-sand mixture with 4-week curing strength.

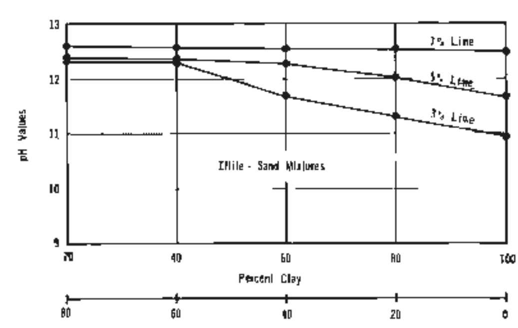

Figure 10. pH variations with lime-treatment level after 4-week curing.

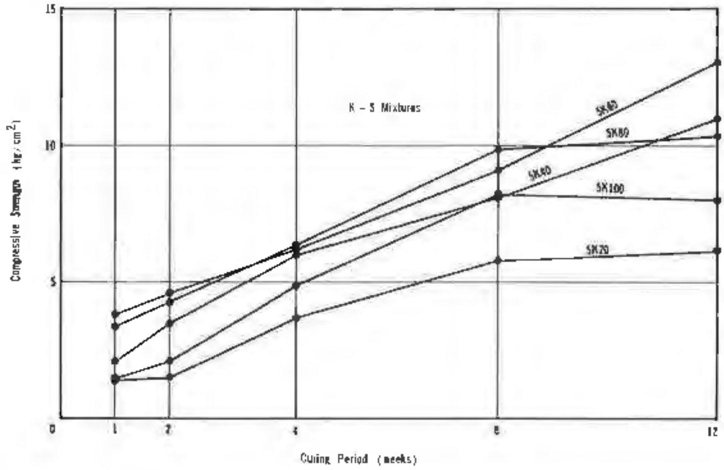

Figure 11. The increase in compressive strength with curing period of K-S mixtures with 5 percent lime.

because of lack of cohesion. The addition of 5 percent lime increases the strengths of all samples; in general, the longer the curing period is, the stronger the sample. The percentage of strength increase is the greatest in the low fine-grain fraction range. This results from the fact that the untreated strengths of those samples are extremely low. The rate of strength gain due to pozzolanic reaction, however, is not the same for samples of different fine-grain fractions. For high strength gain the most effective range is between 40 and 80 percent depending on the curing period (1 to 12 weeks). Figure 11 shows the strength increase with time for different C/S ratios, indicating that the rate of strength increase varies with both the curing period and the fine-grain fraction content.

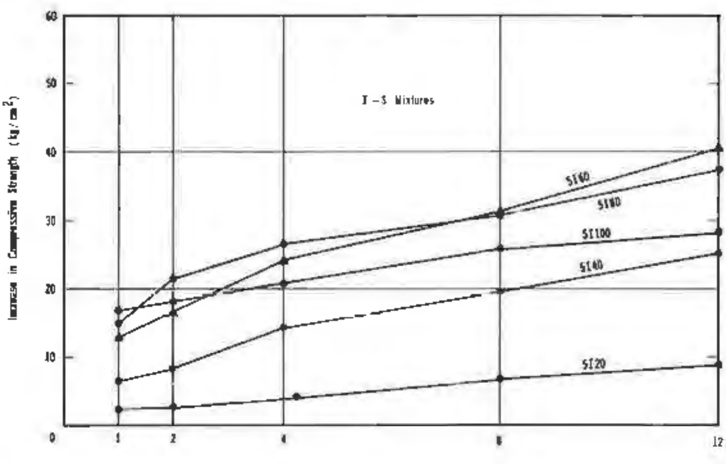

Figure 12. The increase in compressive strength with curing period of I-S mixtures with 5 percent lime.

TABLE 5

FINE-GRAIN FRACTION/LIME RATIO OF CLAY-SAND MIXTURES

Specimen	3 Percent Lime	5 Percent Lime	7 Percent Lime
I 20	6.4	3.8	2.7
I 40	12.7	7.6	5.4
I 60	19.0	11.4	8.2
I 80	25.4	15.2	10.9
I 100	31.7	19.0	13.6
K 20		4.0	
K 40		8.0	
K 60		12.0	
K 80		16.0	
K 100		20.0	

I-S Mixtures—The same tendency of strength variation can also be seen in I-S mixtures as shown in Figures 4 and 12. However, the rate and magnitude of strength gain are much more significant, indicating the high lime reactive nature of the fine-grained soil. The most effective range for high strength gain in this case is between 60 and 100 percent and, like the K-S mixtures, the maximum strengths move from samples of high to low fine-grain fraction content as the curing time is prolonged. Data presented by McDowell (8) have shown that the optimum lime content for maximum strength is not a constant but rather it varies with curing time for any given soil.

Fine-Grain Fraction/Lime Ratio

The bulk of this test program was based on samples treated with 5 percent lime by weight of the total soil mixture. Because of the various C/S ratios of the samples, the fine-grain fraction/lime ratios of these samples were different and are given in Table 5.

The gain of strength of lime-stabilized soils is regarded primarily as a result of pozzolanic reaction between soil silica and/or alumina and lime to form various types of cementing agents. The possible sources of silica and alumina in soils are clay minerals, quartz, feldspars, micas, and other similar very fine silicate or aluminosilicate minerals (1). The clay fraction of a soil is generally considered as the major source of silica or alumina, or both, for the lime-soil pozzolanic reaction; however, minerals of the silt fraction may also serve as a source for pozzolanic reaction. Thompson (1) has reported that the clay content of a soil is not indicative of its lime reactivity, and soils having low clay content can be adequately stabilized with 3 to 7 percent lime. It appears proper, then, to use fine-grain fraction/lime ratio to define the effectiveness of lime-soil stabilization.

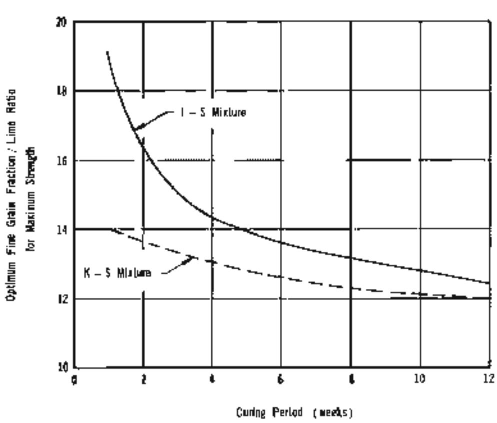

Figure 13. The variation of optimum fine-grain fraction/lime with curing period for mixtures with 5 percent lime.

The optimum FGF/L ratios for maximum strength of various curing periods are shown in Figure 13 for both K-S and I-S mixtures. The optimum ratios for K-S mixtures vary within a rather narrow range (14 to 12), whereas for I-S mixtures this ratio decreases rapidly from 1 week to 4 weeks curing (19 to 14.3); however, the change of optimum FGF/L ratio from 4 to 12 weeks is gradual and slow (14.3 to 12.4). It is generally recognized that the effectiveness of lime stabilization is measured by the 4-week or longer curing strength; therefore, it is reasonable to conclude that the optimum FGF/L ratios for both mixtures studied are similar, ranging from 14 to 12 depending on the curing period. It appears then that the optimum amount of lime needed for any soil mixture can be determined by the gradation curve of the mixture and the proper range of FGF/L ratio. This ratio according to the present study ranges from approximately 12 to 14. The conventional method of determining optimum lime content for any soil mixture can thus be simplified.

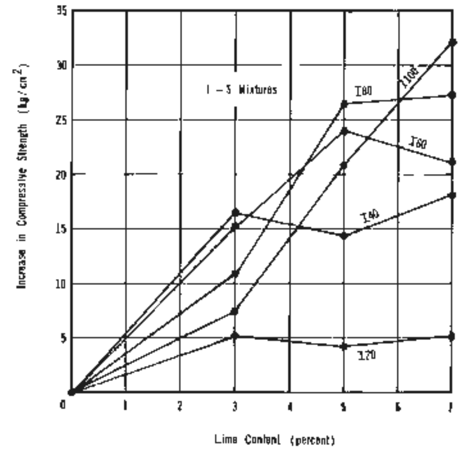

Figure 14. The increase in compressive strength with various lime content and 4-week curing period.

Lime-Treatment Level

The 3 and 7 percent lime-treated I-S samples were compared with those with 5 percent lime treatment of the same curing age. Figure 14 shows that the rate of strength gain is affected by the lime-treatment level. After 4 weeks of curing, the maximum strength of the 7 percent lime samples was 7I100 (optimum FGF/L = 13.6), that of 5 percent lime samples was between 5I60 and 5I80 (≃ 14.5), and that of 3 percent lime samples was between 3I40 and 3I60 (≃ 15). It is important to note that the optimum FGF/L ratios are very close even though the compositions and lime contents of these samples are quite different. This indicates that the optimum FGF/L is probably unaffected by the lime-treatment level.

Coarse Grain Fraction Content

The strengths of samples having the same FGF/L ratios are affected by the amount of coarse-grained soil contained in the samples. Figure 15 shows the 4-week curing strengths of I-S mixtures with 3, 5, and 7 percent lime; generally speaking, the lower the coarse-grained soil content is, the higher the strength for a given FGF/L ratio. This difference in strength is due to the different amount of available silica, alumina, and lime in the mixture for lime-soil pozzolanic reaction. Although the optimum FGF/L is probably unaffected by the lime-treatment level for the 2 types of minerals used in this study, the magnitudes of maximum strength for any given FGF/L ratio do vary with the coarse-grained soil content of a sample.

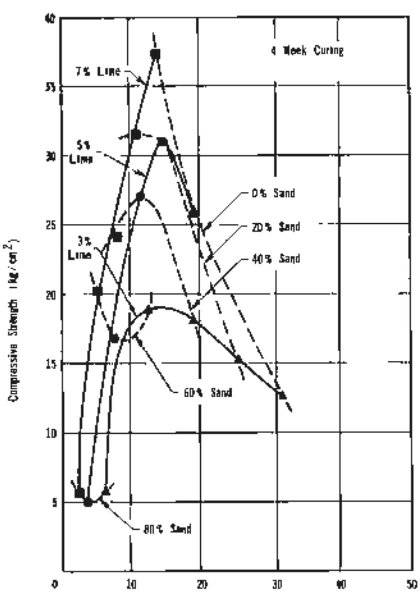

Figure 15. Relationships of compressive strength, fine-grain fraction/lime ratio, and percentage of sand content.

CONCLUSIONS

This study was conducted in the laboratory on lime-stabilized samples of various clay-sand mixtures. These samples were compacted to the same densities as the corresponding untreated samples. Conclusions from this study may be summarized as follows:

1. Comparison of untreated and 12-week curing samples indicates that the addition of 5 percent lime to various K-S and I-S mixtures causes an increase in compressive strength from 4 to 7 times for K-S mixtures and 6 to 16 times for I-S mixtures.

2. The pH value of the lime-soil mixtures decreases with longer curing period and larger fine-grain fraction content of a sample. However, no significant correlation between strength gain and pH variation can be established.

3. The Grundite soil that contains primarily illitic clay mineral and a large amount of silt-size particles reacts better with lime than the Hydrite-UF soil of very fine pure kaolin particles.

4. The effectiveness of lime-soil stabilization appears to be related to the FGF/L ratio of a soil mixture. For the 2 types of clay-sand mixtures studied, the optimum FGF/L ratios for maximum strength range from 14 to 12 depending on curing period.

5. The FGF/L ratio is a more indicative parameter for dealing with lime-soil stabilization than the lime percentage specified on the basis of either total weight or total volume of the whole soil mixture.

6. The rate of strength gain is affected by the lime-treatment level; however, the optimum FGF/L ratios for maximum compressive strengths is only slightly affected.

7. The magnitudes of maximum strength for a given FGF/L ratio vary with the coarse-grained soil content in a mixture; the lower the coarse-grained soil content is, the higher the strength.

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