

Lime Fixation in Clayey Soils

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Previous work in stabilization of clayey soils with lime has shown that small amounts of lime considerably improve workability but contribute little to strength, whereas larger amounts of lime also improve the strength and bearing capacities of these soils. This suggests the possibility that lime added to soil must first satisfy an affinity of the soil for lime, an affinity referred to as "lime fixation." In some clayey soils the addition of flyash with the lime caused an even more significant gain in strength.

The research described in this paper was undertaken to determine whether lime fixation does occur, and if so, to determine the mechanisms involved and the amount of lime utilized.

Samples of six natural clayey soils were mixed with varying amounts of lime (0 to 12 percent), cured two days at 100 percent humidity and 70 F temperature, and subjected to Atterberg limits tests. Similar mixes were compacted at optimum moisture content to standard Proctor density and tested in unconfined compression after 7 and 28 days moist curing.

Curves of lime content vs. Atterberg limits and lime content vs. unconfined compressive strength indicate that when the plastic limit increases, with small amounts of lime, the strength remains relatively constant, whereas with larger amounts of lime the plastic limit remains constant and strength increases. Thus, the plastic limit is indicative of the amount of lime fixation in clayey soils.

Further correlations show that the amount of fixation is proportional to the type and amount of 2-micron clay present and is independent of the adsorbed cation present.

As a result of the unconfined compressive strengths, kaolinitic and montmorillonitic clayey soils were found to be well stabilized with lime alone, whereas illitic-chloritic clayey soils require additions of flyash to obtain significant gains in strength.

●THE USE OF lime and lime-flyash additives to improve the engineering properties of clayey soils is growing. Desirable results obtained from lime treatments include better workability, increased immersed and dry strengths, increased resistance to freeze-thaw cycles, and better volume change characteristics.

Previous research has indicated that the addition of a very small percentage of lime improved the workability of heavy clay soils many-fold but added little to strength. Additional lime improved the strength and bearing capacities of these soils, and the addition of flyash caused an even more significant strength gain in some clayey soils.

That lime added to soil must first satisfy an affinity of the soil for lime was suggested by previous research. If this is true then it would be suspected that lime would not be available for the pozzolanic reactions with the soil constituents or flyash needed to pro-

duce strength gains until the affinity of soil for lime is satisfied. Because this lime is "fixed" in the soil and is not available for other reactions, the process by which the lime becomes fixed may be termed lime fixation. The percentage amount of calcium hydroxide by oven dry weight of the soil which can be fixed by a given soil may be identified as the lime fixation capacity of the soil.

If there is lime fixation in a clayey soil, the strength of compacted and cured specimens of the soil should not increase with small additions of lime. To confirm this, unconfined compressive strength tests were used, because unconfined compression is a reliable indication of cohesive and cementing strength. This strength test can be performed relatively rapidly on a large number of specimens.

Inasmuch as the liquid and plastic limits of a soil are affected by cohesiveness, one or both of these tests were investigated to determine if they also can be used as parameters of lime fixation capacity.

REVIEW OF LITERATURE

Much has been written of the desirable effects of adding lime to a soil rich in clay. The National Lime Association (14) reports that the addition of lime to over-wet clayey soils appears to dry them out and materially improve their workability. Fuller and Dabney (8) report that in highly plastic soils in Texas the ease of pulverizing clay balls after addition of lime and water exceeded expectations and that during final mixing and placing with motor patrols the material was friable and had many characteristics of a non-plastic mix. Reductions in the plasticity index with additions of less than three percent lime were noted in both of the foregoing references.

Increases in strength with the addition of lime have been observed by a great many researchers. The Iowa State University Engineering Experiment Station Soil Research Laboratory since 1953 has been carrying out research projects on the treatment of soils with lime and lime-flyash. Publications on the research show favorable results of increasing strength of soils with the addition of lime and lime-flyash (12).

Some of the basic mechanism involved have been explained by Davidson and Handy (7). First, calcium ions cause a reduction in plasticity of cohesive soils so they become more friable and more easily worked. The mechanism is either a cation exchange or a crowding of additional cations onto the clay. Both processes change the electrical charge density around the clay particles. Clay particles then become electrically attracted to one another, causing flocculation or aggregation. The clay particles, now acting as aggregates, behave as a silt which has a low plasticity or cohesion. A second chemical reaction is carbonation of lime by carbon dioxide of the air, producing calcium carbonate, a weak cement which is deleterious to over-all strength gains. A third class of reactions, termed pozzolanic reactions, results in a slower, long-term cementation of compacted mixtures of lime and soil. Pozzolanic reactions apparently involve interactions between hydrated lime and minerals in the soil.

Lime contents of 1 percent and less in a clayey soil are reported to produce a metastable state; but when lime contents greater than that are used, the flocculation of the clay particles is of a more permanent and progressive nature (5). Calcium silicate and aluminate formed by chemical breakdown of the clay lattice material contribute to flocculation by bonding adjacent soil particles. Ionic flocculation and silicate bonding commence at the same time, the former being an immediate effect while the latter takes a considerable time to complete. Nearly all of the clays used in their investigation were already saturated with adsorbed calcium; changes in properties as a result of additions of calcium hydroxide could not involve a cation exchange relationship.

An addition of 8 percent calcium hydroxide to clayey soils resulted in the complete conversion of $\text{Ca}(\text{OH})_2$ to other forms after one month (10, 13). Reactions other than ion exchange probably accounted for the conversion. However, in other research calcium hydroxide was found to be still present after 12 months curing of specimens (5).

Changes in the engineering properties of clayey soils with addition of lime depend appreciably on the cation originally adsorbed on the clay surfaces, and on the type of clay (11). The nature of the exchangeable cation does not make much difference in kaolinitic soils, but it makes a tremendous difference in montmorillonitic soils.

Expanding clays containing montmorillonite react readily with lime immediately losing plasticity, and after compaction slowly gain pozzolanic strength. Clays containing mainly illite, chlorite, vermiculite, or kaolinite are less effective users of lime (7).

Laboratory tests on two soils of high clay content indicate that no appreciable pozzolanic reactions can take place between lime and flyash until lime is present in excess of the requirements of the soil (6).

SPECIMEN PREPARATION AND TESTING

Materials

Soils.—Seven soils were used in the investigation. The choice of these soils was based on the type and amount of the principal clay minerals present. Three soils containing montmorillonite, two containing illite-chlorite mixtures, and two of the kaolinite group (one containing kaolinite, and the other halloysite) were selected. Each of the soils is identified by a letter designating the principal clay minerals present, and a number indicating the percentage content of the soil less than two microns in diameter. For example, the designation, M-75, indicates a soil containing montmorillonite as the principal clay mineral, with 75 percent of this soil less than 2μ in effective diameter. The locations from which the soil samples were taken and other pertinent information appear in Table 1. Table 2 gives the physical and chemical properties of the seven soils.

Lime.—Reagent grade calcitic hydrated lime, $\text{Ca}(\text{OH})_2$, was used to minimize compositional variables. Individual 1 lb bottles of lime were kept sealed until immediately before use to prevent carbonation of the lime.

Flyash.—Flyash is "the finely divided residue that results from the combustion of ground or powdered coal and is transported from the boiler by flue grass" (4). The flyash used was collected at the St. Clair Power Plant of the Detroit Edison Company, Detroit, Mich. (2). This flyash had a loss-on-ignition 3.6 percent, and 88.7 percent of the ash was finer than the No. 325 sieve.

MIXTURE AND SPECIMEN PREPARATION

Soil Preparation

The soil to be used was selected from the appropriate bin and was pulverized repeatedly until all soil aggregations were reduced to particle size or were fine enough to sieve through either the No. 10 or the No. 40 mesh sieve, depending on whether the soil was to be used for strength tests or for liquid and plastic limits tests. The soil passing the appropriate mesh sieve was then put through a sample splitter, placed in covered cardboard containers, and stored until needed.

Mixing

A predetermined amount of air dry soil was weighed on a balance sensitive to 0.1 gram and then placed in a mixing bowl. Additives, if used, were weighed and mixed in at low speed with a mechanical mixer. After mixing the soil and additives together dry for 30 sec, distilled water was added in appropriate amounts, and mixing was continued for another 4 min.

Unconfined Compression Test Specimen Preparation

Strength test specimens were 2 in. in diameter by 2 in. high and were molded in an apparatus developed at the Iowa State University Engineering Experiment Station Soil Research Laboratory. The apparatus (Fig. 1) is a hand-operated drop hammer with which a predetermined amount of soil mixture in a 2-in. diameter mold is compacted to a density near standard Proctor density.

Approximately 200 grams of the mixture of soil, additives, and water is placed in the mold by means of a scoop and funnel. This mixture is then given five blows from the hammer, the mold is inverted, and another five blows are applied. The resulting soil cylinder is extruded from the mold with an hydraulic jack. The compacted speci-

men is weighed to the nearest 0.1 gram, and the height is measured to the nearest 0.001 in. Any specimen not measuring 2.000 in. \pm 0.050 in. is rejected. The soil specimen is then wrapped in waxed paper and sealed with cellulose tape to prevent carbonation of the lime by the carbon dioxide in the air. The wrapped specimens are placed in shelves in a curing room where the relative humidity is maintained at 95 \pm 5 percent and the temperature at 70 \pm 5 F.

TABLE 1

SOIL SITE CHARACTERISTICS

Sample	Location	Classification	Soil Series and Morizon	Sampling depth (in.)
M-67	Keokuk Co., Iowa	Kansan-age gumbotill	Mahaska, ^a fossil B horizon	91-101
M-51	Harris Co., Tex.	Coastal plane deposit, largely deltaic	Lake Charles, probably B horizon	39-144
M-33	Keokuk Co., Iowa	Plastic Wisconsin-age loess	Mahaska, C horizon	36-77
IC-44	Monroe Co., Mich.	Probably Wisconsin-age glacial till	Unknown, probably C horizon	Unknown
IC-41	Livingston Co., Ill.	Wisconsin-age glacial till	Clarence, C horizon	46-56
K-30	Durham Co., N.C.	Residual soil over medium grained biotite granite	Durham, B Horizon	24 in. below A horizon
K-29.5	Orange Co., Va.	Residual soil over diorite	Davidson, B horizon	Unknown

^aUnder soil M-33.

TABLE 2
PROPERTIES OF SOILS

Sample	M-67	M-51	M-35	IC-44	IC-41	K-30	K-29.5
I. E. S. designation	528-8	AR-3	528-4	AR-4	AR-8	AR-6	AR-5
Textural composition							
Gravel > 2mm	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sand (2.0-0.074mm)	16.0	3.0	0.2	7.0	10.0	45.2	21.0
Silt ($74-5\mu$)	15.5	36.0	60.8	36.0	38.0	18.3	37.0
Clay (5μ)	70.5	61.0	39.0	57.0	52.0	36.5	42.0
Clay (2μ)	87.0	51.0	33.0	44.0	41.0	30.0	29.5
Passing No. 10 sieve	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Passing No. 40 sieve	98.0	99.0	100.0	98.0	96.0	67.0	90.0
Physical properties							
Liquid limit, %	76.6	64.6	52.1	44.0	35.5	51.0	43.5
Plastic limit, %	25.6	17.6	20.0	21.1	17.5	25.5	27.0
Plasticity index	50.0	47.0	32.1	22.9	18.0	25.5	16.5
Chemical properties							
pH	7.1	8.2	5.6	8.4	-	5.7	5.9
C. E. C. (soil passing No. 10 sieve), m.c./100g	-	27.5	23.5	14.5	-	8.4	11.0
C. E. C. (soil passing No. 40 sieve), m.c./100g	41.0	33.1	26.8	13.4	-	13.5	12.4
Carbonates, %	0.8	16.6	0.0	7.2	-	0.1	0.7
Organic matter %	0.2	0.1	0.2	0.6	-	0.1	2.6
Predominant clay							
Mineral ^b classification	M	M	M	I & C	I & C	K	H & V
Textural ^c	Clay	Clay	Silty Clay	Clay	Clay	Clay	Clay
Unified	CH	CH	CH	CL	CL	CH-CL	CL-ML
BPR (AASHO)	A-7- 6(20)	A-7- 6(20)	A-7- 6(18)	A-6- 6(14)	A-6- (11)	A-7- 6(11)	A-7- 6(12)

^aTextural gradation tests were performed only on the soil fraction passing the No. 10 sieve. All soils used contained less than 5 percent gravel.

^bSymbols are M-montmorillonite, I-illite, C-chlorite, K-kaolinite, H-halloysite, and V-vermiculite. Determinations were made by X-ray diffraction.

^cU. S. Dept. of Ag. textural classification was used.

Testing

Liquid and Plastic Limits. —ASTM Methods D423-54T and D424-54T (1) were followed except that after the soil, lime, and distilled water were mixed together, the mix was scraped into a porcelain pan, covered, and stored in a near 100 percent humidity room for two days. This allowed the water to infiltrate the clay particles thoroughly and produce uniform wetting of the sample. Preliminary tests after different storage periods up to four days showed no perceptible daily change in the liquid and plastic limits after two days' storage.

After seasoning for two days the contents of the covered pan were removed from the humidity room, and enough of the mixture was placed in an evaporating dish for four liquid limit tests. This procedure was followed on the soil passing the No. 40 mesh sieve with additives of 0, 1, 2, 3, 7, and 12 percent lime by oven dry weight of soil (hereafter abbreviated dry weight of soil). Liquid limits were determined only for mixtures prepared with the montmorillonitic and the illitic-chloritic soils. Because of the wide variety of variables which enter into a liquid limit test, consistency and reproducibility of results were difficult to obtain. Because the plastic limit was found to produce reliable and consistent results correlating well with the data to be presented, liquid limit tests were discontinued.

A sample weighing about eight grams was taken from the mixture prepared for the liquid limit test. Four plastic limits were rolled for each soil-lime mixture studied (0, 1, 2, 3, 7, and 12 percent additions of lime by dry weight of soil). The plastic limit of the mix at each percentage additive was determined as the average of the moisture contents of the four threads rolled.

Strength Testing. —The testing apparatus was a model AP-170 Stability Testing Machine. Loads are indicated on a 10,000-lb capacity proving ring, which has a dial indicator reading to 0.0001-in. deflection. Strain is applied to the test specimens at a constant rate of 0.1 in. per minute.

Because the objective of the investigation was to study the process of lime fixation in clayey soils, it was important to obtain positive values of strength for all mixtures of soils and additives. Therefore, strength testing was done on specimens which had been moist cured but not subjected to immersion, inasmuch as immersion causes specimens of low lime content to slake.

To obtain the optimum moisture content for maximum strength for molding the 2-by 2-in. specimens, moisture-strength tests were conducted in series with four sets of three specimens each, molded for each soil mix at varying moisture contents. After seven days moist curing ($95 + 5\%$ R. H. 70 ± 5 F) these specimens were tested for unconfined compressive strength, and the strengths of the specimens at failure were recorded. Graphs of molding moisture content versus seven day strength were prepared for each mixture studied, and optimum moisture contents for maximum strengths were interpolated. This procedure was carried out for additives of 0, 6, and 12 percent lime for each soil and also for the same percentages of lime plus 20 percent flyash. The optimum moisture contents thus obtained were then plotted against lime contents for each soil. The resulting curves were used for interpolating moisture contents for mold-

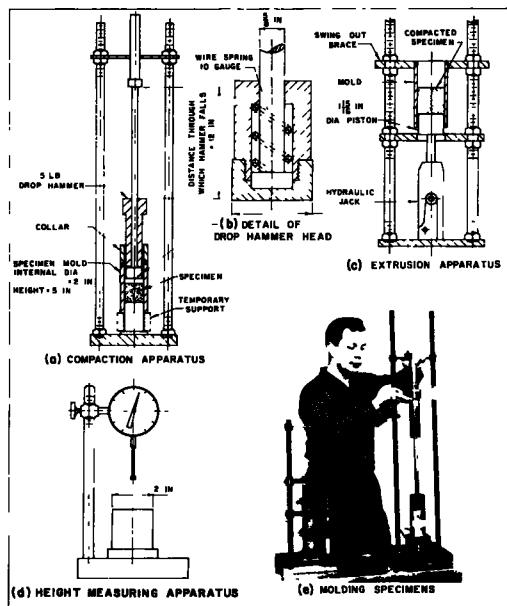


Figure 1. Molding apparatus.

each soil. The resulting curves were used for interpolating moisture contents for molding specimens of the various mixtures used in the final work.

Final Testing.—The soils with the highest percentage of each type of clay mineral (M-67, IC-44, and K-30) were selected for final testing. Additives to the soils fell into two groups: the first was lime and the second, lime and flyash. Lime alone was added to each of the soils in amounts of 0, 1, 2, 3, 4, 6, 8, and 12 percent by dry weight of soil. In the second group the same percentages of lime by dry weight of soil were used, but 20 percent flyash by dry weight of soil also was added to provide an excess of pozzolanic material.

Batches for molding nine specimens out of each were prepared to obtain uniformity of mixing. All batches of each group for a soil were molded on the same day to assure uniform curing conditions. Of the nine specimens molded, three were tested at the end of seven days curing in the humidity room, three at 28 days, and the final three after 27 days moist curing and one day immersion in distilled water.

RESULTS

Effect of Lime on the Plastic Limit

The plastic limits of all soils and mixtures tested showed that this limit was materially increased with small additions of lime (Fig. 2). The largest increases in the plastic limit (P. L.) due to lime treatment were obtained in the soils containing montmorillonite as the principal clay mineral; the greater the amount of clay-size material in these soils, the greater was the increase in the P. L. Increases in the P. L. of the illitic-chloritic clayey soils also were considerable, but not as great as in the montmorillonitic soils of comparable clay-size content. The smallest increases of the P. L. were observed in the kaolinitic rich soils.

Of particular interest is the "point" on each curve at which the rate of change of the slope approaches zero and at which the slope itself approaches zero. Because the curve approximates that of a right hyperbola, the change in slope never reaches zero but approaches this value in soils M-67, M-51, and M-33 at lime contents of 3.2 percent, 2.7 percent and 2.2 percent, respectively. A plot of these lime percentages against respective 2 micron clay contents (Table 2) of the soils revealed the following linear relationship:

$$\text{Optimum lime additive for maximum increase} = \frac{\% \text{ of } 2 \mu \text{ clay}}{35} + 1.25 \quad (1)$$

in plastic limit

Inasmuch as only two illitic-chloritic soils and two kaolinitic soils were tested, it is not known whether or not the optimum lime additive for these two soils is directly proportional to 2 micron clay content.

To determine the factors responsible for the observed change in P. L. with the addition of lime, the definition of the plastic limit must be stated in terms of the events occurring in the laboratory test. The definition of P. L. (1) as the boundary between the plastic and semi-solid states must be modified to a definition that reflects laboratory procedure. Thus a more descriptive definition of the P. L. as determined by the laboratory soil test is the lowest moisture content at which the bonds between soil particles or aggregates can be constantly renewed.

The nature of these bonds has been described as being due to cation exchange and to a crowding of additional cations onto the surfaces of the clay (7). However, one of the soils tested, M-51, already had an excess of carbonates present (16.6 percent). Certainly, then, this soil is already saturated with calcium, yet the P. L. of the soil was increased from 18 to 40 with the addition of less than 3 percent lime. Thus the crowding of additional calcium onto the clay must be the more important of the two mechanisms.

One other mechanism not previously mentioned enters into the bonding of clay particles and affects the plastic limit. The surface tension of water in minute pores such as those in clayey soils exerts a bonding force between clay size particles. Because

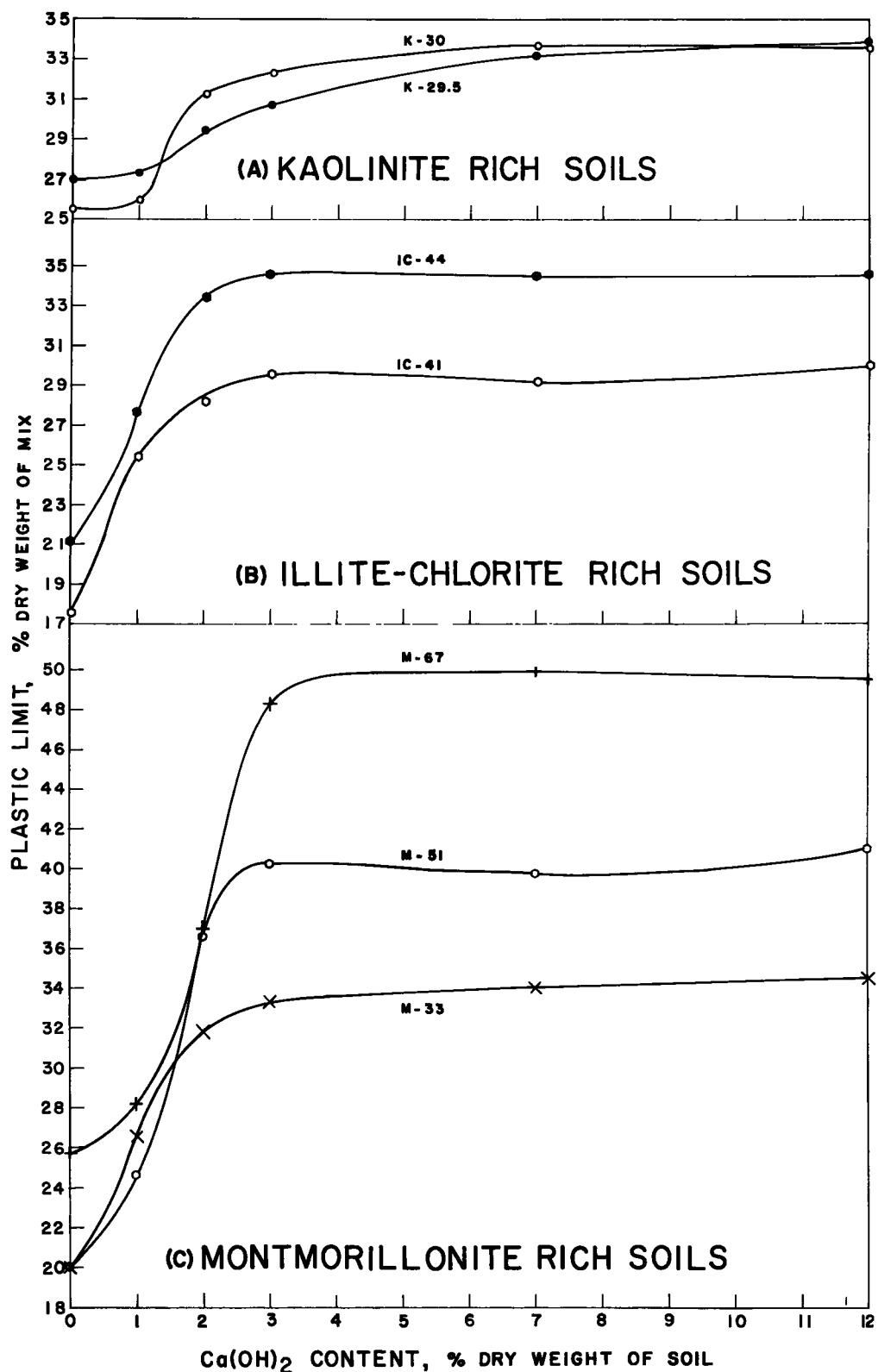


Figure 2. Plastic limits of seven clayey soils at varying lime contents.

capillary pressure is inversely proportional to the radius of curvature of the meniscus and directly proportional to surface tension, changes in either of these will be reflected in the amount of water necessary to renew the bonds continually between soil particles while a plastic limit is being rolled.

When the plastic limits of the soils tested are increased by lime additives, actually more water must be added to the soil-lime mixture to make the bonds between the soil particles capable of being renewed as rapidly as they are broken (Fig. 2). The addition of lime causes the clay particles to become electrically attracted, causing flocculation or aggregation. The clay then behaves more like a silt with each floc of clay particles acting like a silt grain. Though bonding between the particles within a floc has been increased, bonding between flocs is relatively weak. When a plastic limit is rolled, the bonds between individual clay particles within the floc remain relatively unaffected, but the bonds between the flocs are being constantly broken and reformed until the moisture content is reduced to the point where the bonds can no longer be reformed as fast as they are being broken, and the thread crumbles.

At some percentage of lime additive all of the calcium that can crowd onto the clay particles is present and further increases in lime result only in supplying to the soil an excess of calcium which is not effective in flocculation or other mechanisms which contribute to the increase in the plastic limit.

If the calcium which increases the plastic limit is so fixed in the soil that it cannot react with the natural pozzolans of the soil, then the percentage of lime present at the point where the plastic limit reaches its maximum will reliably indicate the percentage of lime fixation in the soil.

Effect of Lime and Lime-Flyash on Strength

Unconfined Compressive Strengths.—The three soils with the greatest amount of each clay mineral, M-67, IC-44, and K-30, were selected for determining the effect of lime and lime-flyash treatments on the unconfined compressive strengths of clayey soils (Figs. 3, 4, and 5).

The addition of lime increased the unconfined compressive strength of montmorillonitic soil M-67 the largest amount. The strength of kaolinitic soil K-30 also was greatly improved by lime treatment but the strength of illitic-chloritic soil IC-44 was only slightly increased.

The addition of 20 percent flyash to the soil plus lime had little effect on soils M-67 and K-30, but produced marked gains in unconfined compressive strength in soil IC-44. A comparison of the maximum unconfined compressive strengths of soil IC-44 plus lime after 28 days moist curing with and without flyash additive shows that the addition of 20 percent flyash has increased the strength of this soil by 28 percent.

From this data it appears that both montmorillonite and kaolinite are natural pozzolans; and they, or elements within their crystal lattices, react with lime to produce cementing materials. Because soil M-67 contains much more minus two micron material than soil K-30, it can be expected that lime mixed with soil M-67 will produce more cementing materials than will lime and soil K-30 even if both clays are equally reactive.

However, because the addition of lime to soil IC-44 produces only relatively small increases in unconfined compressive strengths, one can conclude that either illite or chlorite or both are not effective natural pozzolans. Thus it is necessary to add a pozzolanic material such as flyash to obtain significant increases in strength in stabilization with lime.

The initial and generally flat portion of the unconfined compressive strength curves is of particular interest. In this region small additions of lime do not produce corresponding increases in strength. This shows graphically that a certain amount of lime must be added to a clayey soil before cementing products which will increase the strength of the soil can be formed. Because lime fixation was defined as the process by which lime is held by the soil and is not available for pozzolanic reactions, this initial flat portion of the curves proves that lime fixation does occur in clayey soils.

The region of lime fixation may be defined as that portion of the unconfined compressive strength versus lime content curves in which strength does not perceptibly increase as the percentage of lime additive increases. Similarly, the lime fixation capa-

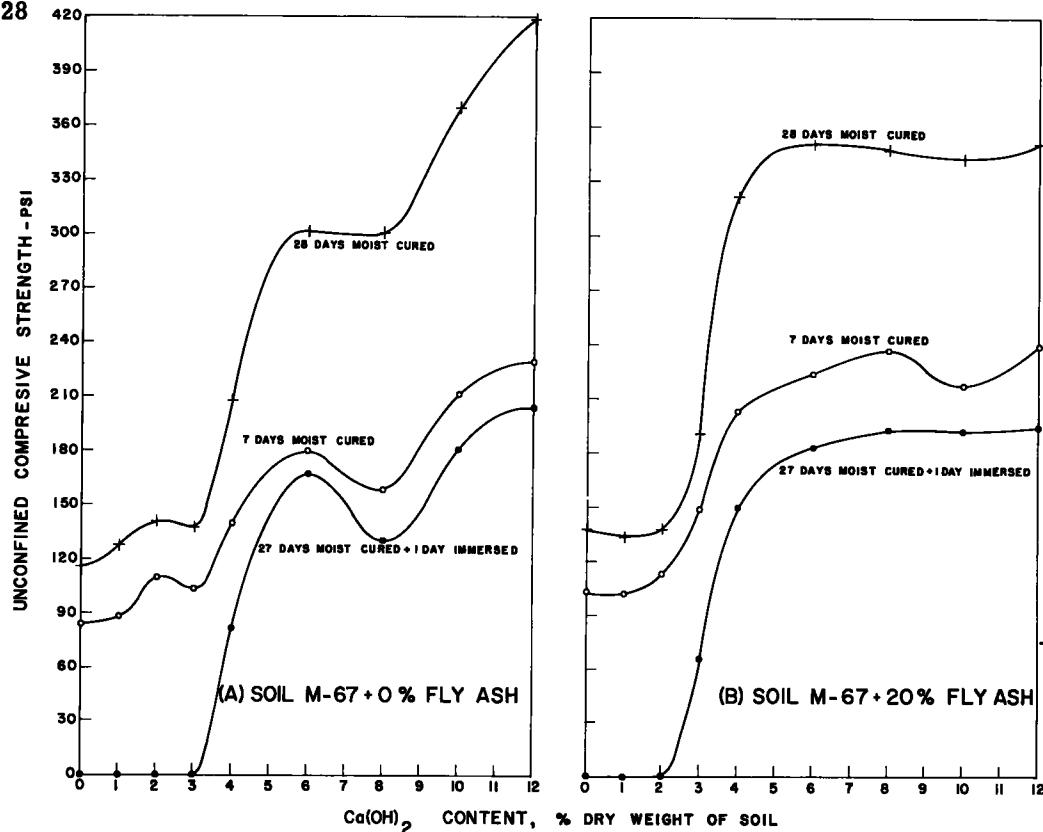


Figure 3. Unconfined compressive strengths of soil M-67 at varying lime and lime-flyash contents.

city of a soil is the percentage of lime additive at which strength just begins to increase.

Comparison of Plastic Limits and Strengths

Object of Comparison.—By comparing the optimum lime additive for maximum increase in the plastic limit (Fig. 2 and Eq. 1) with the maximum percentage of lime fixation which can occur in a particular soil (Figs. 3, 4, and 5) it can be shown that these two percentages are the same, and thus this optimum on the plastic limit curves is also a quantitative parameter of the lime fixation capacity of a particular soil.

Method of Comparison.—If the unconfined compressive strengths of the soils tested remain constant as the plastic limits increase with increasing percentages of lime additive, and if the plastic limit then remains constant with further additions of lime as the unconfined compressive strengths increase, then the optimum lime additive for maximum increase in the plastic limit will be a quantitative parameter of lime fixation (Fig. 6).

Because previous research (15) has shown that lime does not react with the coarse portion of the soil and that P. L. tests utilized the portion of the soil passing the No. 40 sieve whereas unconfined compressive strength testing was performed on cylinders molded from the soil passing the No. 10 sieve, a correction must be made. This correction is based on relating the percentage of lime additive to the amount of clay present in the soil passing the No. 10 sieve. Thus the equivalent percentage of lime in the plastic limit test is

$$\frac{L_E}{L_0} = \frac{Q_{40}}{Q_{10}} \quad (2)$$

in which

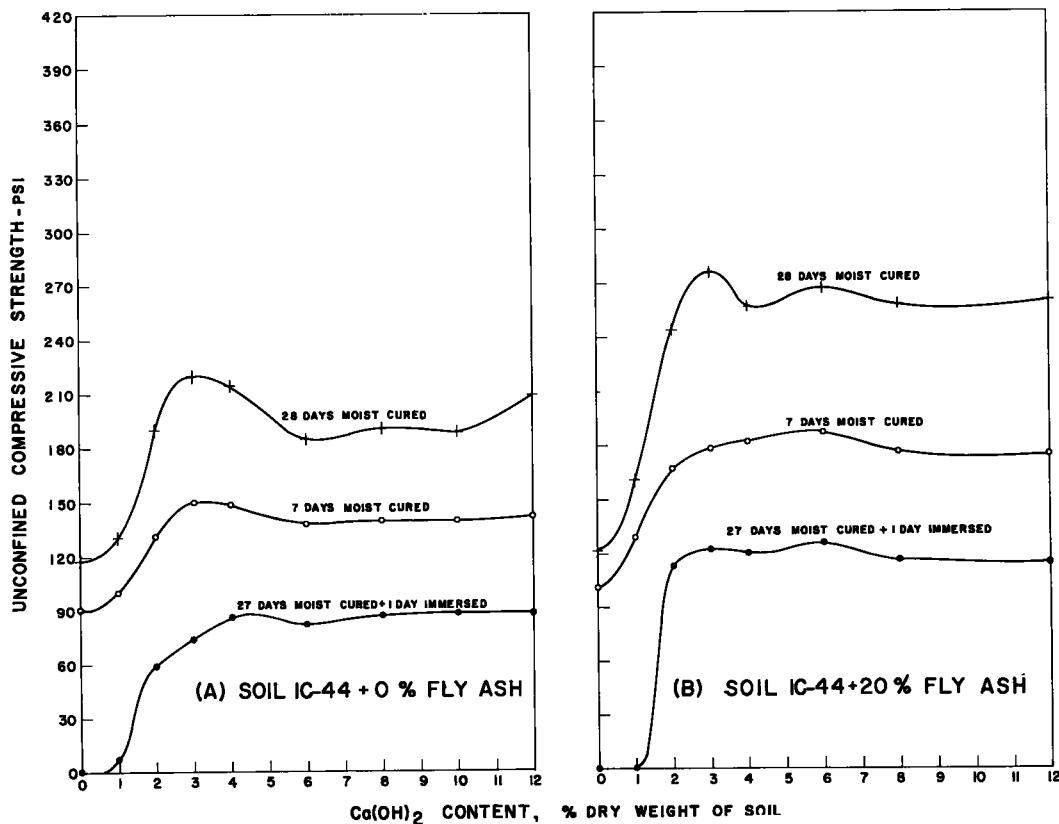


Figure 4. Unconfined compressive strengths of soil I-44 at varying lime and lime-flyash ratios.

L_E = equivalent lime content (%)

L_O = original lime added (%)

Q_{40} = amount of soil passing the No. 40 sieve (%)

Q_{10} = amount of soil passing the No. 10 sieve (%)

Results and Discussion. —The curves (Fig. 6) show that the compressive strengths of soil M-67 and K-30 remain constant as the plastic limits increase, and the plastic limits remain constant as the strengths increase.

However, in soil IC-44, which contains illite and chlorite as the principal clay minerals, the strength is increasing while the plastic limit is still increasing. A possible explanation for this is that if one of the two clay mineral constituents of the soil has a lower lime fixation capacity than the other, then, at a percent additive of lime at which one is still engaged in the process of lime fixation, the other may have completed this process and begun to engage in the production of cementing materials through pozzolanic reactions.

Conclusions from Comparison. —Based on the graphical results of this comparison, the optimum lime additive for maximum increase in the plastic limit is a reliable quantitative indicator of the lime fixation capacity of the montmorillonitic and kaolinitic soils tested. However, it does not reliably indicate the lime fixation capacity of clayey soils containing a mixture of illite and chlorite, though it may be a valid indicator in soils containing one or the other of these minerals.

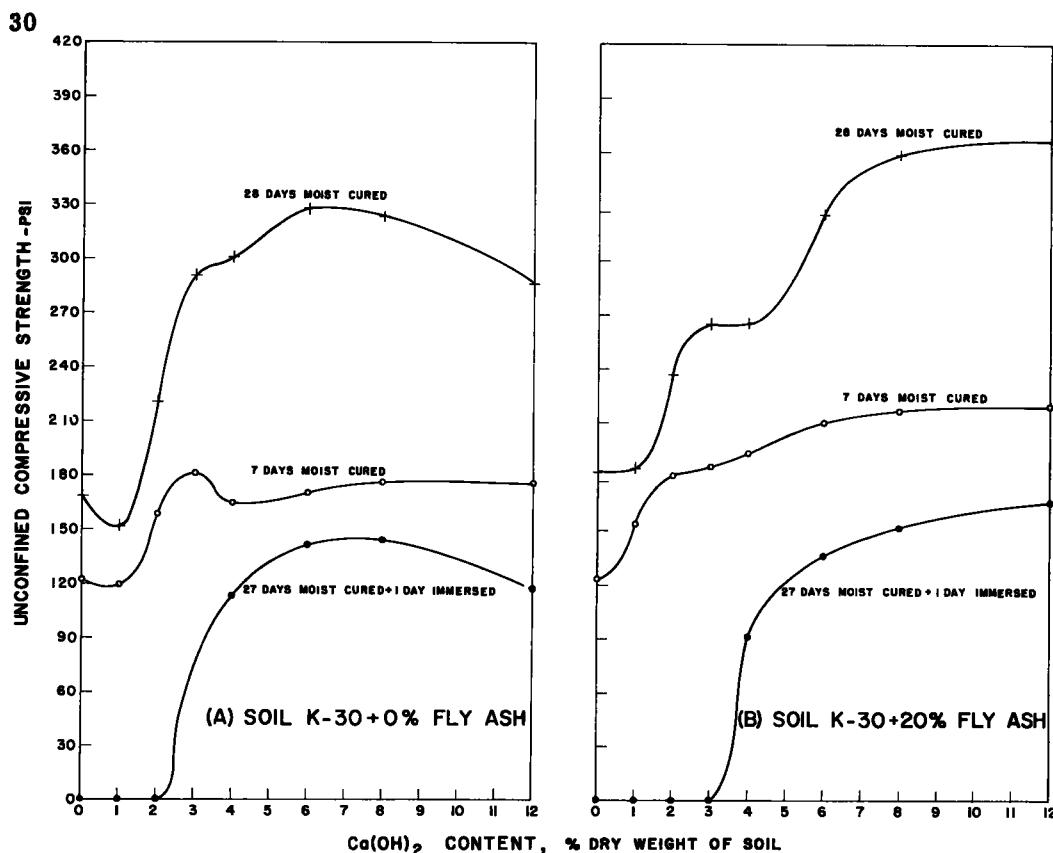


Figure 5. Unconfined compressive strengths of soil K-30 at varying lime and lime-flyash ratios.

CONCLUSIONS

1. Large increases in the plastic limits of clayey soils can be obtained by adding small quantities of lime, $\text{Ca}(\text{OH})_2$. The largest increases are in soils containing montmorillonite; illitic-chloritic clayey soils are affected somewhat less, and the plastic limits of kaolinitic clayey soils are the least changed.
2. A descriptive definition of the plastic limit as determined by the standard laboratory method is the lowest moisture content at which the bonds between soil particles or aggregations can be constantly renewed.
3. Both montmorillonite and kaolinite are effective pozzolanic reagents. They or elements within their crystal structure will react with lime to produce a cementing material equal to or greater in strength producing qualities than the cementing agents produced in the reaction of lime with flyash. It is not necessary to add flyash to soil containing large amounts of montmorillonite or kaolinite when treating with lime. Such additions may even be detrimental.
4. The percentage amount by oven dry weight of the soil of calcium hydroxide which can be fixed by a given soil is the lime fixation capacity of that soil. This lime contributes to the improvement of soil workability but not to increases in strength. Amounts of lime added above the lime fixation capacity cause the formation of cementing materials within clayey soils.
5. Lime fixation in clayey soils does take place. The lime fixation capacity of a montmorillonitic or kaolinitic clayey soil is the same as the optimum lime additive for maximum increase in the plastic limit of the soil.

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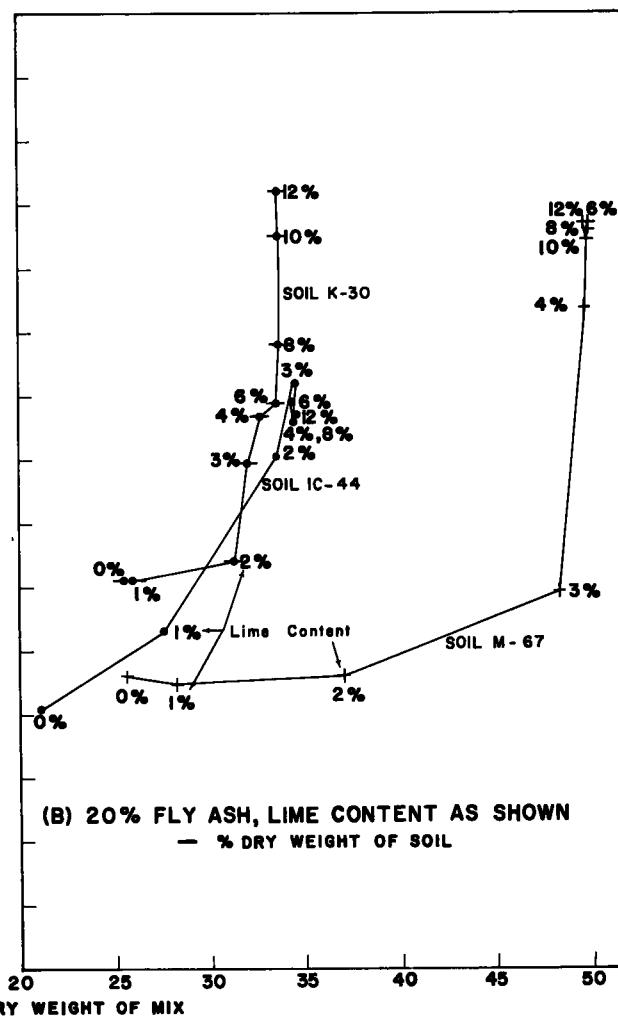
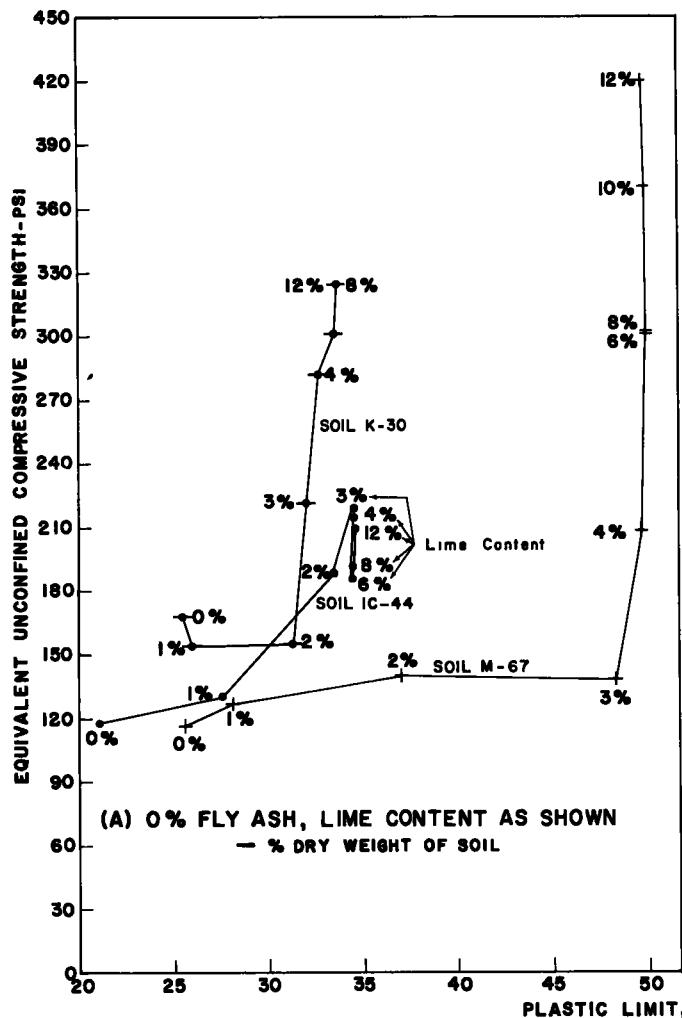


Figure 6. Comparison of plastic limits and unconfined compressive strengths for three lime-treated clayey soils.

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