# Effect of Lime on Cement Stabilization of Montmorillonitic Soils

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Although lime as a secondary additive to soil-cement mixtures has been investigated before, the effectiveness of the addition has not been thoroughly explained. The present research is an attempt to fill this gap.

Five soils were studied. Though all contained montmorillonite as the dominant clay mineral, they varied texturally from friable loess to high-clay gumbotil. Various amounts of lime and cement were used, and the compressive strengths of compacted specimens were determined after 7, 28 and 84 days humid room curing and 1 day immersion in distilled water. The results obtained indicate that there is an optimum amount of lime which gives the maximum strength for a fixed amount of cement.

The increase of strength with addition of lime was higher for soils with high clay content and much higher when noncalcareous soils of similar gradation were used.

The effect of elapsed time between mixing and compacting was studied. The results showed a decrease of density and strength with the time elapsed between mixing and compacting when the molding moisture content was below or near the optimum moisture content. Use of lime minimized both the density and strength reductions due to this time lag. However, with molding moistures above the optimum moisture content an increase in strength was obtained when an interval of 2 hr was allowed between mixing and compacting.

Unimmersed unconfined compressive strengths within a period of 24 hr after mixing and sedimentation tests were performed on soil-lime-cement mixtures for tracing exchange reactions and sedimentation.

• PORTLAND CEMENT is the chemical most successfully used in soil stabilization for road construction. Almost all soils respond to treatment with cement; however, chemical conditions of some soils (by interfering in the hydration of cement) and high plasticity of others (by preventing an intimate mixture) have limited the use of portland cement. Another chemical widely used in soil stabilization is lime, which has been shown to improve greatly the workability of the soil and to increase the strength of the mixture.

Previous studies have pointed out beneficial results of a simultaneous use of lime and cement under certain conditions, both in field construction (7, 11) and in laboratory (4, 10). The purpose of the present investigation was to evaluate quantitatively and economically this treatment as a function of some soil characteristics and to attempt an explanation for some of the reactions involved.

## MATERIALS

Five soils were used in the study (Table 1). In all five, montmorillonite was the dominant clay mineral, but the soils varied texturally from friable loess to high-clay gumbotil. The friable loess was sampled from the deep loess bordering the Missouri River. The unleached Kansan till was obtained in north western Iowa. The plastic loess, the gumbotil, and the leached Kansan till were sampled at different depths from the same site in southeastern Iowa.

As for the stabilizing agents, the properties of the type I portland cement, the main agent, are given in Table 2; and those of the hydrated lime, which was the secondary additive, are given in Table 3.

TABLE 1

PROPERTIES OF SOILS

| Property | Friable Loess | Plastic Loess | Leached Kansan Till | Unleached Kansan Till | Gumbotil |
|---|---|---|---|---|---|
| I. E. E. S. sample designation | 20-2 | 528-4 | 528-10 | 411 | 528-8 |
| Sampling location (Iowa) | Harrison Co. | Keokuk Co. | Keokuk Co. | Page Co. | Keokuk Co. |
| Soil series | Hamburg | Mahaska | --- | Shelby | --- |
| Horizon | C | C | $C_p$ | C | $B_p$ |
| Sampling depth (in.) | 467-480 | 36-77 | >110 | 216-240 | 91-107 |
| Textural composition[a]: | | | | | |
| Gravel (above 2 mm) | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Sand (2 - 0.074 mm) | 0.6 | 5.5 | 37.0 | 23.9 | 22.2 |
| Silt (0.074 - 0.005 mm) | 81.4 | 53.3 | 22.3 | 28.3 | 15.0 |
| Clay (below 0.005 mm) | 18.0 | 41.2 | 40.7 | 47.8 | 62.8 |
| Clay (below 0.002 mm) | 13.0 | 33.5 | 36.2 | 39.7 | 59.6 |
| Physical (%): | | | | | |
| Liquid limit | 33 | 52 | 44 | 45 | 76 |
| Plastic limit | 28 | 20 | 17 | 15 | 26 |
| Plasticity index | 5 | 32 | 27 | 30 | 50 |
| Chemical: | | | | | |
| pH[b] | 8.4 | 6.3 | 7.0 | 7.7 | 6.9 |
| C.E.C.[c] (meq/100 g) | 15.58 | 23.64 | 23.6 | 19.84 | 37.54 |
| Carbonates[d] (%) | 10.91 | 1.87 | 2.27 | 12.05 | 2.45 |
| Organic matter[e] (%) | 0.50 | 0.44 | 0.13 | 0.10 | 0.16 |
| Predominant clay mineral | M[f] | M | M | M | M |
| Classification: | | | | | |
| Textural[g] | Silt loam | Silty clay loam | Clay loam | Clay loam | Clay |
| Unified | ML | CH | CL | CL | CH |
| BPR (AASHO) | A-4 (8) | A-7-6 (18) | A-7-6 (16) | A-7-6 (17) | A-7-6 (20) |

[a] Textural gradation tests performed only on soil fraction passing No. 10 sieve All soils contained less than 5 percent gravel.

[b] Glass electrode method using suspension of 15 g soil in 30 cc distilled water.

[c] Ammonium acetate (pH = 7) method on soil fraction below 2 mm.

[d] Versenate method for total calcium.

[e] Potassium bichromate method

[f] M standing for montmorillonite

[g] USDA textural classification

TABLE 2

PROPERTIES OF PORTLAND CEMENT USED

| Property | Value |
|---|---|
| Chemical analysis (%): | |
| Silicon dioxide, $SiO_2$ | 21.62 |
| Aluminum oxide, $Al_2O_3$ | 5.05 |
| Ferric oxide, $Fe_2O_3$ | 2.97 |
| Calcium oxide, CaO | 64.05 |
| Magnesium oxide, MgO | 2.90 |
| Sulfuric trioxide, $SO_3$ | 2.26 |
| Insoluble residue | 0.16 |
| Loss on ignition | 0.58 |
| Specific surface (sq cm/g) | |
| Turbidimeter (Wagner) | 1,855 |
| Air permeability (Blaine) | 3,395 |

TABLE 3

PROPERTIES OF HYDRATED LIME USED

| Property | Value |
|---|---|
| Chemical analysis (%): | |
| Silicon dioxide, $SiO_3$ | 0.3 |
| Aluminum and ferric oxide, $Al_2O_3$ $+Fe_2O_3$ | 0.6 |
| Calcium oxide, CaO | 73.8 |
| Magnesium oxide, MgO | 0.6 |
| Sulfuric trioxide, $SO_3$ | 0.3 |
| Loss on ignition | 24.1 |
| Percent passing No. 325 sieve | 95.5 |

## METHODS OF INVESTIGATION

The samples of soil were air dried and ground repeatedly until all soil aggregations were reduced to individual particle size or were fine enough to pass through the No. 10 mesh sieve.

### Unconfined Compressive Strength

The unconfined compressive strengths of the soils treated with various amounts of lime and cement were determined to evaluate the effectiveness of the additives on the hardening of the mixtures.

Test specimens were prepared from batches mixed in a Hobart C-100 kitchen mixer at the lower speed. The required amount of air-dry soil and additives were first machine mixed for 1 min. Then water in the amount required to bring the mixture to a moisture content close to the optimum moisture content determined by the standard Proctor test was added and machine mixed for 1 min. Next, the sides of the bowl were scraped, and the materials were mixed again for 1 min.

From each batch, nine specimens were molded 2 in. in diameter by 2 in. high. The specimens were compacted in an apparatus developed in the laboratory (9). In this method the desired amount of mixture is placed in a 2-in. diameter mold and receives five blows on each end from a hand-operated 5-lb drop hammer falling 12 in. This procedure was found to give a density near standard Proctor density.

The specimens were weighed to the nearest 0.1 g, and the height was determined to the nearest 0.001 in. All specimens tested were 2 ± 0.050 in. high. Then to prevent loss of moisture the specimens were wrapped in waxed paper, sealed with cellulose tape, and stored in a curing room where the relative humidity was maintained at 95 ± 5 percent and the temperature was kept at 70 ± 5 F. At the end of a predetermined curing period, the specimens were immersed in distilled water for 24 hr and then were immediately tested for unconfined compressive strength. Three different curing periods were used. At the end of each period three specimens were tested.

### Prolonged Mixing Studies

The reduction of density with the time elapsed between mixing and compaction of the specimens and the minimizing effect of lime on this reduction were noticed during performance of the unconfined compression tests. Because density changes are known to introduce strength variations, and inasmuch as in field practice there is a time lag between mixing and compacting, a laboratory study of the effect of prolonged mixing was undertaken.

The study was conducted on two soils, the friable loess and the plastic loess, using two mixtures for each: with friable loess one was 10 percent cement, and the other was 10 percent cement plus 2 percent lime; with the plastic loess one was 10 percent cement, the other was 8 percent cement plus 2 percent lime. These amounts were chosen because they were expected to give approximately the same 7-day strengths.

The procedure of test was programed, taking into consideration results of earlier research (6) which brought out that the effect of time is more pronounced when the mixture is left undisturbed than when it is intermittently mixed. Intermittent mixing, which is more representative of the field condition, was adopted.

It has also been verified that the optimum moisture content varies when a certain time elapses between mixing and compacting (6). To take this effect into account, various amounts of water were used in the investigation.

For each mixture, the following procedure was used: the desired amounts of soil, additives, and water were mixed as for the unconfined compression tests. Immediately after mixing a set of three 2- by 2-in. specimens were molded, their densities were determined, and they were wrapped and stored in the curing room. The remaining mixture was kept in the bowl and covered with a cloth, which was kept damp throughout the process. Every 20 min the mixture was hand mixed for about 1 min. Two hours after the addition of water, a second set of three specimens was molded and processed. The intermittent mixing proceeded and after 2 more hours the procedure was repeated for a third set of three specimens. During the molding of each 3 specimen set, a sample of the mixture was collected for determination of the moisture content.

## Flocculation Studies

The effect of lime and cement on flocculation of soils was studied qualitatively by sedimentation tests. Preliminary tests showed that when a flocculated soil dispersed in water settles down, a sharp line of demarcation is observed between the supernatant water and the suspension. The rate of sedimentation is practically constant from the beginning of the process until the piling up of particles on the bottom changes the density and the viscosity of the suspension and decreases the settling velocity. This result leads to the deduction that the process in this case is analogous to that observed in sedimentation of suspensions of uniform spheres (2). Although particles larger than the flocs are present in the soil, they settle faster, so that the over-all settling process resembles closely that of uniform flocs.

The initial rate of sedimentation is a function of the following factors (2):

1. Size of the flocs.
2. Shape of the flocs.
3. Concentration of the suspension or its density.
4. Specific gravity of the soil plus additive mixture.
5. Density of the fluid.
6. Viscosity of the fluid.
7. Temperature.
8. Shape of the glass in which the sedimentation takes place.

With the shape of the flocs corrected by a factor and the effect of the concentration of the suspension determined, the size of the flocs or their relative diameter could be determined by Stokes' law. However, no attempt was made with this purpose in the present investigation; only qualitative results were looked for. The last five of the factors indicated were kept constant or considered to be nearly constant; therefore, their relative effect was disregarded.

The concentration of the suspension was varied for each of the three soils studied. The amounts of mixture to be dispersed in 1,000 ml of water were selected from preliminary tests so that approximately the same rate of settling would be obtained when 8 percent of lime was added to each soil, 8 percent being considered the amount of lime above which no further flocculation would take place. The preliminary tests suggested the use of 155 g of mixture for the friable loess, 85 g for the leached Kansan till, and 65 g for the gumbotil. Such amounts would give approximately the same density of slurry if the suspension was made up only of particles smaller than 0.012 mm.

The procedure for running the sedimentation test was as follows: the desired amounts of air-dry soil and lime or cement were placed in a 1,000-ml hydrometer jar and mixed for 1 min. Then about 150 ml of distilled water was added, and the mixture was stirred thoroughly with a glass tube. More water was added to make a slurry of approximately 250 ml. Next the mixture was dispersed by the air-jet apparatus (3) for 10 min at a pressure of 15 psi. The hydrometer jar with a rubber stopper in the open end was then successively turned upside down and back for a period of 1 min to make the suspension uniform, and finally the jar was set on a horizontal surface.

The time was recorded when the suspension reached a 2.5-cm mark ($T_1$) and again when it reached a 12.5-cm mark ($T_2$) below the 1,000-ml line of the hydrometer jar. These data were used to calculate the average rate of sedimentation by

$$V = \frac{10\ (\text{cm})}{T_2 - T_1\ (\text{sec})} \qquad (1)$$

## Initial Hardening Studies

The results of the prolonged mixing studies showed that lime plays an important part in the initial hardening of soil cement. This effect was studied by means of unimmersed unconfined compressive strengths determined within a period of 24 hr after mixing.

Two-inch diameter by 2-in. high specimens were prepared, cured, and tested by the same procedure used for immersed unconfined compression tests. However, the study required that only one specimen be molded from each batch. Small amounts were used for each mixture and hand mixing had to be used instead of machine mixing.

The unimmersed unconfined compressive strengths were determined 5, 15, and 30 min, and also 1, 2, 4, 8, 16, and 24 hr after the addition of water to the mixture. Preparation of the specimens took approximately 3 min. All specimens were tested at their molding moisture content, which was close to the optimum moisture content for maximum density.

## RESULTS

## Unconfined Compressive Strength

The general pattern of the results of unconfined compressive strength tests (Figs. 1, 2, 3, 4, and 5) indicates that the beneficial effect of lime does not depend on the cement

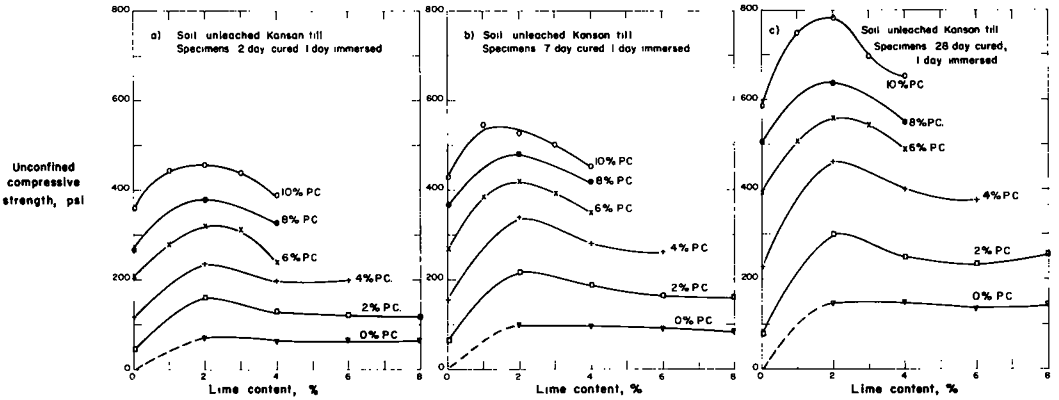

Figure 1. Unconfined compressive strengths of unleached Kansan till with varying lime and cement contents, after various curing periods.

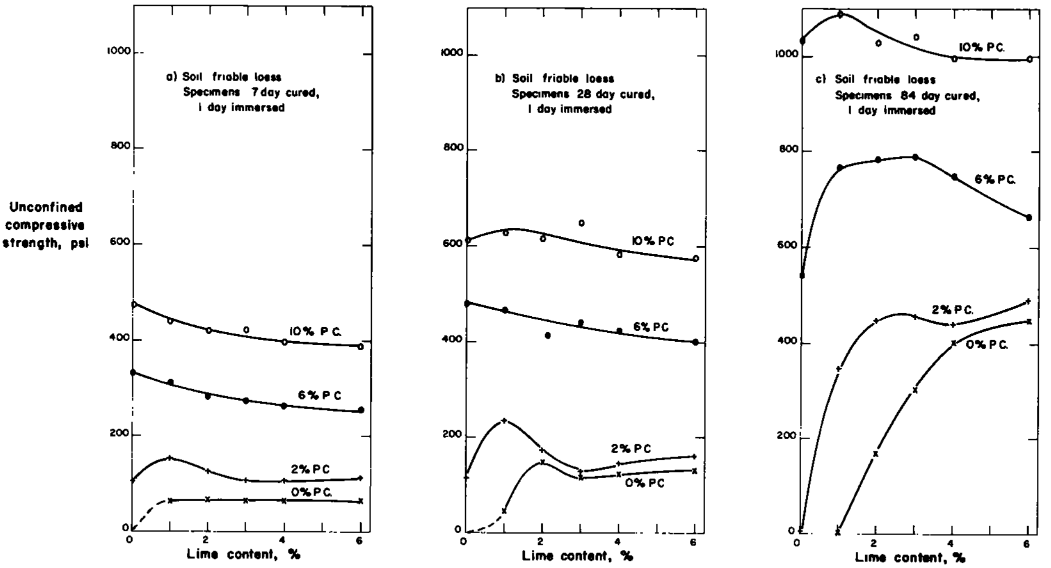

Figure 2. Unconfined compressive strengths of friable loess with varying lime and cement contents, after various curing periods.

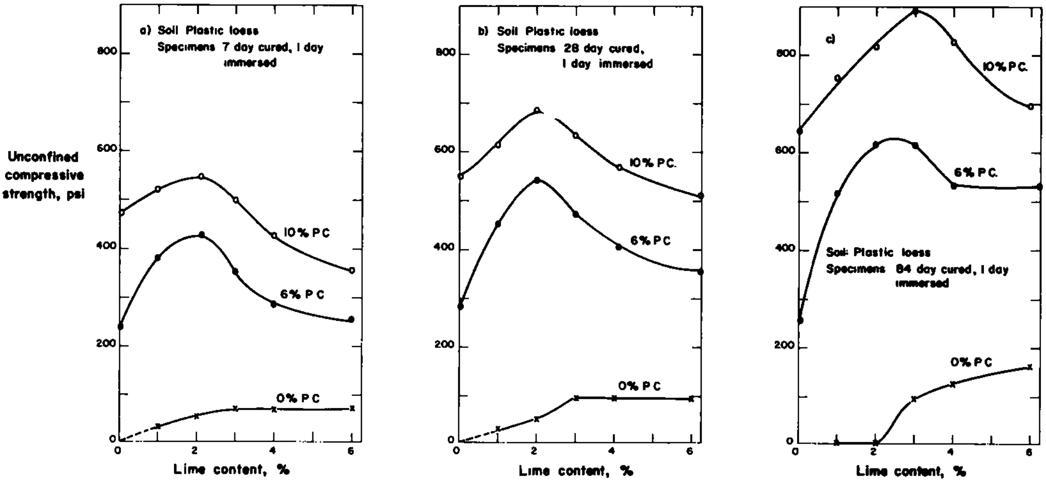

Figure 3. Unconfined compressive strengths of plastic loess with varying lime and cement contents, after various curing periods.

content in soil-lime-cement mixtures. In tests where lime proved beneficial, and this happened with four of the five soils studied, the compressive strength increased with addition of lime; however, above a certain amount of lime, further addition caused reduction of strength. The amount of lime for which a maximum strength occurred will be hereafter referred to as the "optimum amount of lime."

For the unleached Kansan till the optimum amount of lime was found to be 2 percent and remained constant for all cement contents and for all the curing periods—2, 7, and 28 days. These results suggested a modified program of testing for the other soils: concentration of work on only two cement contents and adoption of the 84-day curing instead of the 2-day.

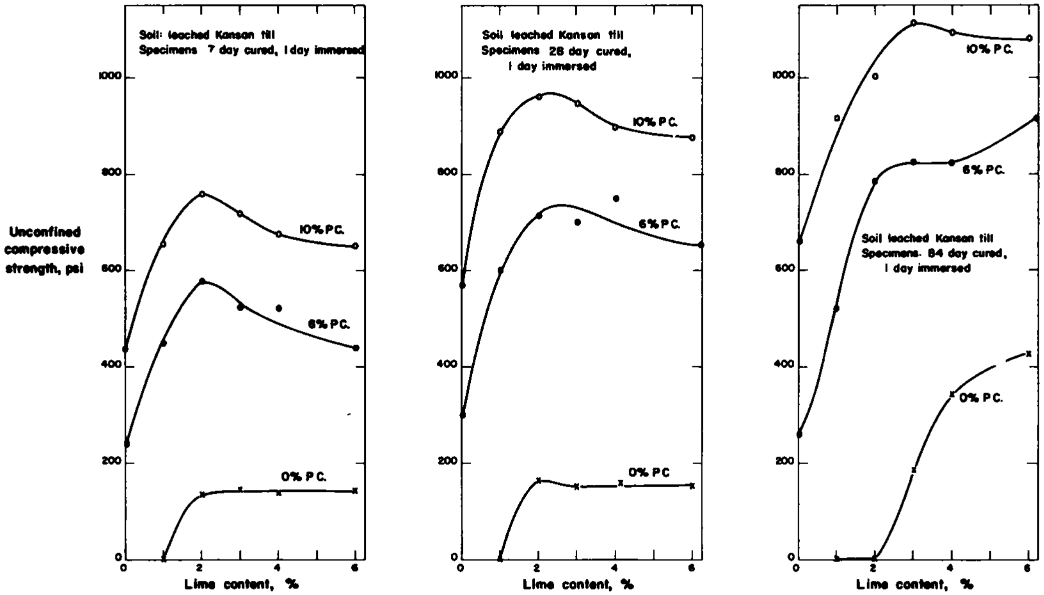

Figure 4. Unconfined compressive strengths of leached Kansan till with varying till and cement contents, after various curing periods.

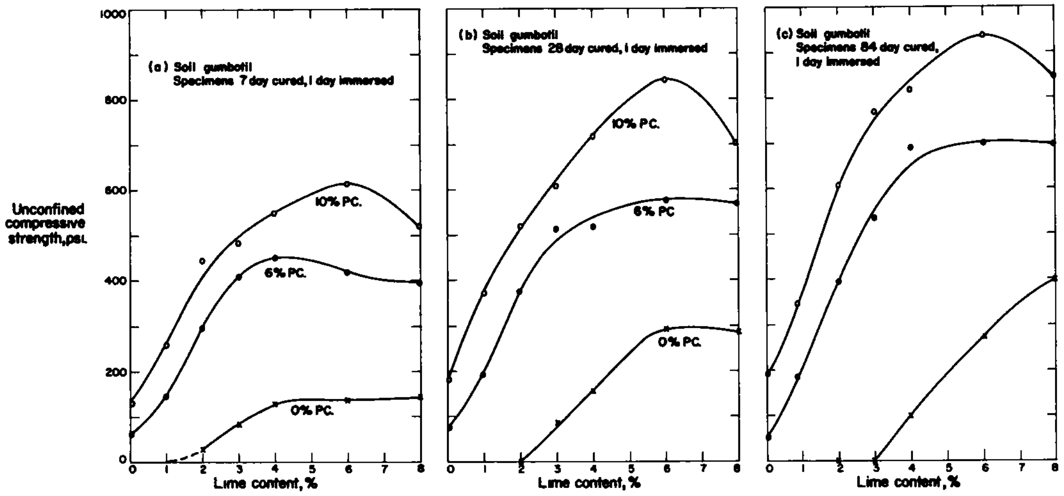

Figure 5. Unconfined compressive strengths of gumbotil with varying lime and cement contents, after various curing periods.

For the friable loess, addition of lime to mixtures with 6 and 10 percent cement did not have any beneficial effect within the 28-day curing period; in fact, it caused a gradual but small reduction of strength. In mixtures with 2 percent cement, however, addition of lime caused an increase of strength. When only lime was added to the soil, the strength of 7-day cured specimens was practically constant for all amounts of lime. At the end of the 28-day curing period, the 1 percent lime mixture showed a decrease of strength. The strength of mixtures containing larger amounts of lime, although higher than at 7 days, did not vary with the lime content. The 84-day strength indicated an interesting change of pattern in that the specimens with 1 percent lime failed completely when immersed in water, though the other mixtures gave relatively high strengths, which increased with lime content and reached 400 psi for 4 percent lime. No explanation was found for the decrease of strength for low amounts of lime in the mixtures. However, the results suggest that, in a second reaction of the system, the initially formed gel is destroyed; when lime is present in larger amounts the second reaction produces a stronger cementation, but for low amounts this cementation is not strong enough to withstand immersion in water. The same phenomenon occurred with admixtures of small amounts of lime and other soils.

The notable increase of strength after 28 days for mixtures with 2 or more percent lime indicates the effect of pozzolanic reactions occurring between 28 and 84 days. These reactions are reflected, although on a reduced scale, in the 84-day strength of friable loess-lime-cement mixtures.

Results of unconfined compressive strength tests for the plastic loess mixtures show a displacement of the optimum amount of lime from 2 percent at 7- and 28-day curing periods to 2.5 or 3 percent for 84-day cured specimens. The pozzolanic reactions, which occur mainly when the lime content is increased from 2 percent to 3 percent, may explain the displacement of the optimum amount of lime.

The test results for the leached Kansan till, indicate an optimum amount of lime of 2 percent for 7-day curing, 2.5 percent for 28-day curing, and 3 percent for 84-day curing. Exception to this is the 84-day strength of the 6 percent cement plus 6 percent lime mixture, which was higher than the strength of the 6 percent cement plus 3 percent lime mixture.

The results for the gumbotil suggest an optimum amount of lime of 6 percent, with only one exception: the maximum 7-day strength for the 6 percent cement occurred with 4 percent lime. Results of mixtures with lime only suggest that pozzolanic reactions did take place but did not change the position of the optimum amount of lime for different curing periods.

The increasing of strength with addition of lime indicates that while the increase of strength for the plastic loess and the leached Kansan till is higher for 6 percent than for 10 percent cement, for the gumbotil it is higher for 10 percent cement than for 6 percent (Table 4). Strength increase for unleached Kansan till evidently does not depend on cement content. In terms of percentage, however, the increase of strength with addition of lime always decreases for higher amounts of cement (Table 5).

## TABLE 4

### INCREASE OF THE UNCONFINED COMPRESSIVE STRENGTH WITH ADDITION OF OPTIMUM AMOUNT OF LIME, FOR VARIOUS CURING TIMES

| Soil | Opt. Amt. of Lime (%) | Cement Content (%) | Diff. Betw. Strengths of Soil-Opt. Amt. of Lime-Cement Mix. and Soil-Cement Mix. (psi) | | | |
|---|---|---|---|---|---|---|
| | | | 2-Day Cured[a] | 7-Day Cured[a] | 28-Day Cured[a] | 84-Day Cured[a] |
| Unleached Kansan till | 2 | 2 | 112 | 145 | 220 | |
| | | 4 | 120 | 186 | 234 | |
| | | 6 | 113 | 150 | 168 | |
| | | 8 | 113 | 115 | 235 | |
| | | 10 | 95 | 101 | 295 | |
| Plastic loess | 2 | 6 | | 178 | 263 | 358 |
| | | 10 | | 75 | 135 | 175 |
| Leached Kansan till | 2 | 6 | | 337 | 420 | 527 |
| | | 10 | | 225 | 395 | 340 |
| Gumbotil | 2 | 6 | | 390 | 475 | 651 |
| | | 10 | | 485 | 662 | 747 |

[a] Plus 1-day immersed.

## TABLE 5

## PERCENTAGE INCREASE OF UNCONFINED COMPRESSIVE STRENGTH WITH ADDITION OF OPTIMUM AMOUNT OF LIME, FOR VARIOUS CURING TIMES

| Soil | Opt. Amt of Lime (%) | Cement Content (%) | Ratio of Diff. Betw. Strs. of Soil-Opt. Amt. of Lime-Cement Mix and Soil-Cement Mix. to Soil-Cement Str. (%) | | | |
|---|---|---|---|---|---|---|
| | | | 2-Day Cured[a] | 7-Day Cured[a] | 28-Day Cured[a] | 84-Day Cured[a] |
| Unleached Kansan till | 2 | 2 | 255 | 230 | 275 | |
| | | 4 | 104 | 122 | 99 | |
| | | 6 | 55 | 56 | 43 | |
| | | 8 | 42 | 32 | 58 | |
| | | 10 | 26 | 24 | 61 | |
| Plastic loess | 2 | 6 | | 74 | 94 | 139 |
| | | 10 | | 16 | 25 | 27 |
| Leached Kansan till | 2 | 6 | | 140 | 140 | 204 |
| | | 10 | | 52 | 69 | 54 |
| Gumbotil | 6 | 6 | | 650 | 633 | 1,300 |
| | | 10 | | 374 | 368 | 388 |

[a] Plus 1-day immersed

Another point of interest in the results is the increase of strength with time. The compressive strengths for mixtures without lime and for those with the optimum amount of lime at different curing times are compared with those of 7-day cured specimens (Table 6). For the glacial till soils no significant difference in the rate of strength increase is obtained with the addition of lime. However, the addition of lime to the loessial soils caused a more pronounced gain of strength after the first 7 days of cure.

Also, the mixtures of plastic loess, leached Kansan till, and gumbotil with 6 percent of cement showed a reduction of strength after 28 days of curing. Although it is questionable that these mixtures would satisfy the durability criteria based on soil-cement losses during 12 cycles of either the wet-dry test or freeze-thaw test, they certainly do not satisfy the strength criteria which stipulates that compressive strength should increase both with age and cement content (12).

The maximum strengths attained by the five soils with 6 and 10 percent cement, and the optimum amounts of lime show that all the soils studied can be successfully stabilized with lime and cement on an economical basis (Table 7).

### Prolonged Mixing Studies

Results from the study of the effects of prolonged mixing (i. e., the time elapsed between addition of water and compaction) on strength and density are shown in Figures 6 and 7.

The dry density of the mixtures decreased with prolonged mixing for both the plastic loess and the friable loess, whether any lime was in the mixture or not. The moisture-density curves of aged mixtures with friable loess show an increase of optimum moisture content with a decrease of maximum density. However, aged mixtures with plastic loess gave irregular moisture-density curves, resembling the result of a compaction test with sand.

The difference between the densities of specimens molded right after mixing and those molded after a definite interval of time, as outlined in the methods of investigation, was practically constant for all moisture contents below optimum moisture content. This difference, which was less beyond the optimum moisture content, tended to disappear as the densities approached the saturation line.

## TABLE 6

## UNCONFINED COMPRESSIVE STRENGTHS AT VARIOUS AGES OF MIXTURES WITHOUT AND WITH 7-DAY OPTIMUM AMOUNT OF LIME, EXPRESSED AS PERCENTAGE OF 7-DAY UNCONFINED COMPRESSIVE STRENGTH

| Soil | Opt. Amt. of Lime (%) | Cement Content (%) | Ratio of Unconfined Compress. Str. to 7-Day Str. (%) | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | 7-Day Cured[a] | | 28-Day Cured[a] | | 84-Day Cured[a] | |
| | | | Without Lime | With Opt. Amt. Lime | Without Lime | With Opt. Amt. Lime | Without Lime | With Opt. Amt. Lime |
| Unleached Kansan till | 2 | 2 | 100 | 100 | 127 | 138 | | |
| | | 4 | 100 | 100 | 149 | 136 | | |
| | | 6 | 100 | 100 | 145 | 133 | | |
| | | 8 | 100 | 100 | 111 | 133 | | |
| | | 10 | 100 | 100 | 114 | 148 | | |
| Friable loess | 1 | 2 | 100 | 100 | 110 | 136 | 0 | 356 |
| | | 6 | 100 | 100 | 145 | 149 | 164 | 245 |
| | | 10 | 100 | 100 | 126 | 143 | 217 | 247 |
| Plastic loess | 2 | 6 | 100 | 100 | 117 | 127 | 107 | 144 |
| | | 10 | 100 | 100 | 117 | 125 | 137 | 150 |
| Leached Kansan till | 2 | 6 | 100 | 100 | 125 | 125 | 108 | 136 |
| | | 10 | 100 | 100 | 131 | 146 | 152 | 152 |
| Gumbotil | 6 | 6 | 100 | 100 | 125 | 122 | 83 | 155 |
| | | 10 | 100 | 100 | 138 | 137 | 148 | 153 |

[a] Plus 1-day immersed.

The beneficial effect of lime occurred during the first 2 hr. The lime in the mixture lessened the decrease of density due to prolonged mixing (Figs. 8a-c and 9a-c). The unconfined compressive strengths of specimens compacted right after the initial mixing showed a dependence on density, with the maximum strength occurring at the optimum moisture content for maximum density. Noticeable, however, is the decrease of strength when the moisture content was near to or higher than 2 percent above the optimum moisture content.

## TABLE 7

## MAXIMUM UNCONFINED COMPRESSIVE STRENGTHS OF MIXTURES WITH 6 AND 10 PERCENT CEMENT PLUS LIME AFTER 7, 28, AND 84 DAYS OF CURING

| Soil | Maximum Unconfined Compressive Strength (psi) | | | | | |
|---|---|---|---|---|---|---|
| | 7-Day Cured[a] | | 28-Day Cured[a] | | 84-Day Cured[a] | |
| | 6% Cement | 10% Cement | 6% Cement | 10% Cement | 6% Cement | 10% Cement |
| Friable loess | 330 | 475 | 479 | 649 | 789 | 1,089 |
| Unleached Kansan till | 419 | 527 | 559 | 782 | | |
| Plastic loess | 427 | 546 | 543 | 685 | 617 | 892 |
| Gumbotil | 451 | 615 | 569 | 843 | 697 | 940 |
| Leached Kansan till | 578 | 760 | 717 | 961 | 828 | 1,116 |

[a] Plus 1-day immersed.

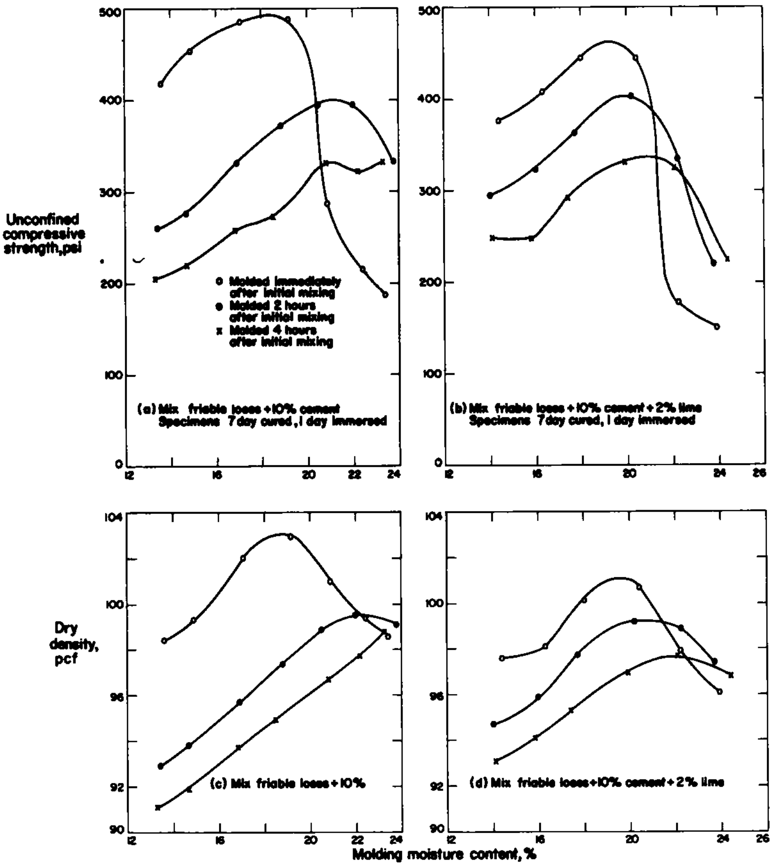

Figure 6. Unconfined compressive strengths and dry densities of friable loess with 10 percent cement, and with 10 percent cement plus 2 percent lime, at varying molding moisture contents; specimens being molded immediately after initial mixing, and after 2 and 4 hr of prolonged mixing.

The compressive strength of specimens molded after 2 hr of intermittent mixing did not show the same pattern for all mixtures. Though the compressive strength for the plastic loess-cement was continuously increasing with moisture content, the moisture-strength curve for the plastic loess-lime-cement and for the two mixtures with friable loess was similar to the density-moisture curve. However, with high moisture contents in all, this strength became greater than that of specimens molded right after mixing.

The compressive strengths of specimens molded after 4 hr of intermittent mixing, although lower in value, followed the same pattern as those molded after 2 hr mixing.

As it was with density, the compressive strength decreased whether lime was in the mixture or not, but here again, lime minimized the reduction. Figures 8d-f and 9d-f show that when compaction was done 2 hr after the initial mixing, the decrease in strength of soil-lime-cement mixtures was about one-half that with soil-cement mixtures. Similarly, when an increase of strength was observed, the increase was more pronounced for mixtures containing lime. The differences between the strengths of specimens molded after 4 hr of mixing was still the same, indicating that the effect of lime took place during the first 2-hr period.

In an attempt to explain the increase of strength with mixing time, for high moisture contents, X-ray diffraction patterns of mixtures were determined immediately after

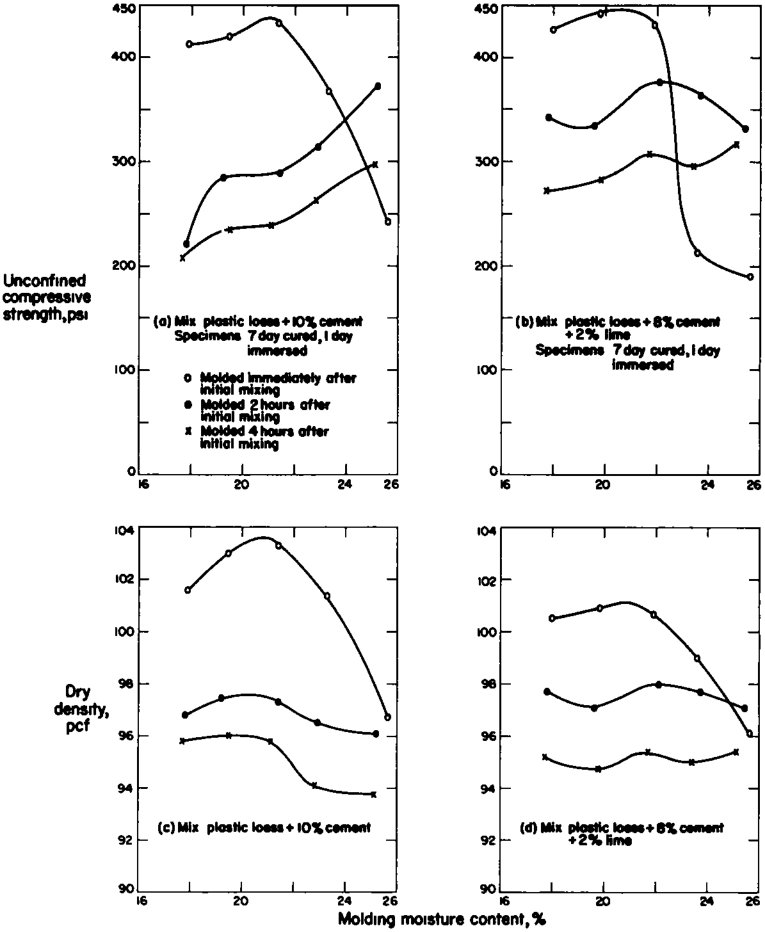

Figure 7. Unconfined compressive strengths and dry densities of plastic loess with 10 percent cement and with 8 percent cement plus 2 percent lime, at varying molding moisture contents; specimens being molded immediately after initial mixing, and after 2 and 4 hr of prolonged mixing.

mixing and then after several intervals of time within a 2-hr period. These patterns showed that the basal distance d of the clay remained constant during this period, being approximately 19.5 Å. This observation eliminates the hypothesis of the adsorption of additional water by the clay mineral with time; therefore, it cannot be said that the water-cement ratio decreases with attendant increase in strength.

Following are some visual observations during the performance of the tests and their explanations relative to the increase of strength.

When mixtures with moisture contents above the optimum were compacted immediately after mixing, horizontal cracks appeared in the specimens as a result of the high compactive energy for that particular moisture condition. Molding of specimens in transparent plastic molds showed that these cracks occur during compaction and not during the removal of the specimens from the mold. These local shear failures could be responsible for the low strengths of these specimens. After 2 hr of intermittent mixing, the reactions of the soil-lime-cement-water system caused an apparent drying out of the mixture; and crack-free specimens were obtained, although the moisture content did not change. This explanation seems satisfactory for both mixtures of the friable loess and also for the plastic loess-lime-cement mixture,

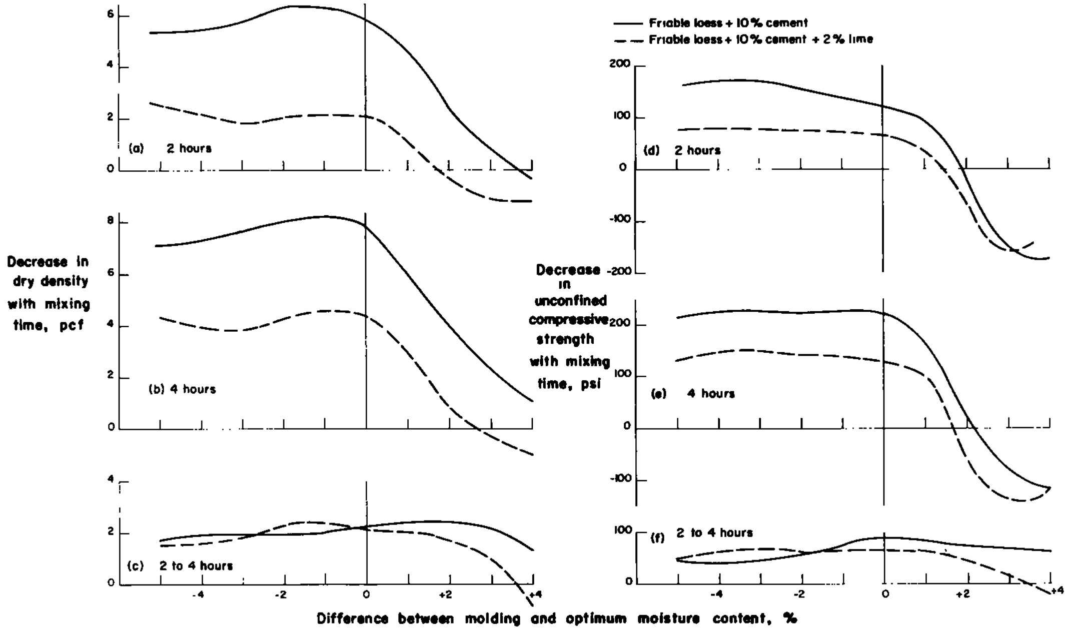

Figure 8. Decrease of unconfined compressive strength and dry density of specimens of friable loess with 10 percent cement and with 10 percent cement plus 2 percent lime, at varying molding moisture contents, during first 2 hr and first 4 hr of intermittent mixing, and during the period from 2 to 4 hr after initial mixing.

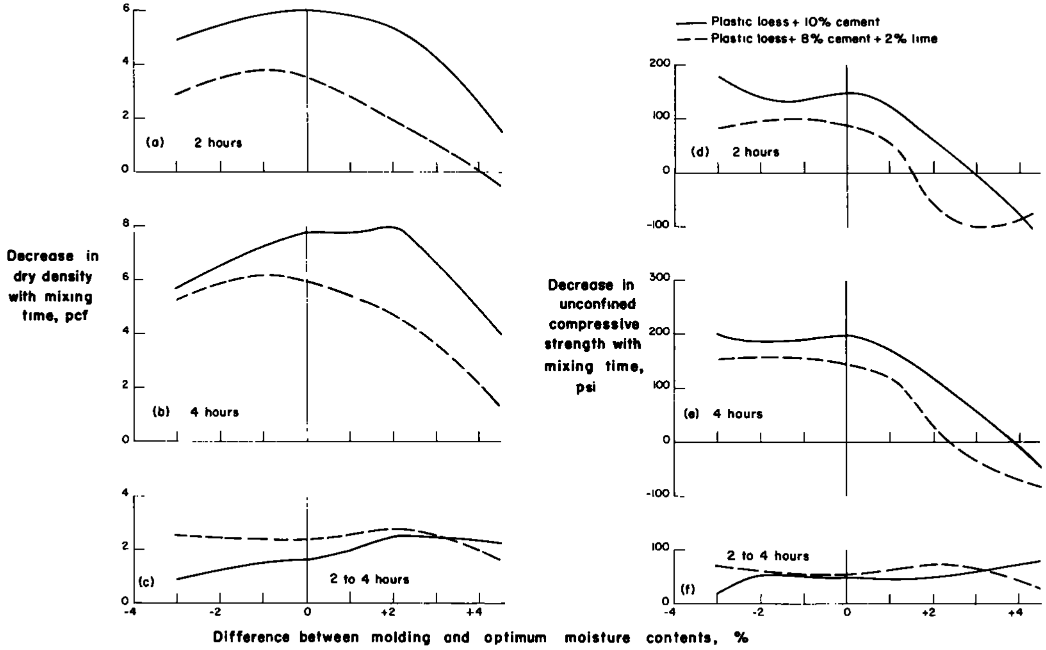

Figure 9. Decrease of unconfined compressive strength and dry density of specimens of plastic loess with 10 percent cement and with 8 percent cement plus 2 percent lime at varying molding moisture contents, during first 2 hr and first 4 hr of intermittent mixing, and during period from 2 to 4 hr after initial mixing.

because the compressive strengths for all of these mixtures after 2 and 4 hr of mixing were approximately proportional to the densities.

Further, in the plastic loess-cement it was observed during the intermittent mixing that small aggregates were formed and became hard after a time. Compaction of this mixture did not completely deform these aggregates, and small air voids in the specimens were visible. Strong aggregation did not take place in all mixtures of friable loess or when lime was added to the plastic loess, but formation of aggregates was observed in all clayey soils with cement. The hardness of the aggregates decreased with increase of moisture content; thus, for high moisture contents the aggregates were deformed much more during compaction and therefore a larger area of contact was attained, giving rise to higher strengths.

## Flocculation Studies

When the square root of the rate of sedimentation, which is proportional to the floc diameter, is plotted vs the amount of lime or cement additive (Fig. 10), the rate of sedimentation shows an increase with increase in lime content for all soils, but tends to flatten out above a certain lime content. The leveling of the curves is gradual; therefore, the optimum point is not very distinct. However, this lime content can be roughly estimated to be 1 percent for the friable loess, 2 percent for the leached Kansan till, and 3.5 percent for the gumbotil.

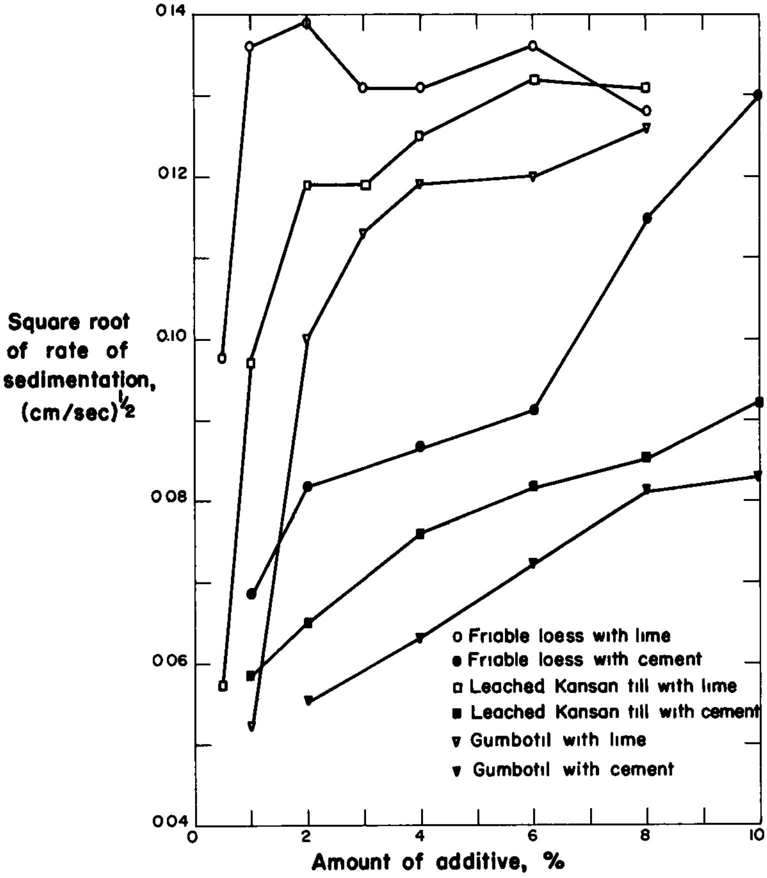

Figure 10. Square root of rate of sedimentation of friable loess, leached Kansan till, and gumbotil flocculated by addition of lime or cement, at varying additive contents.

The effect of lime is similar for both the sedimentation tests and the plastic limit tests. In both, the addition of lime produces a gradual change in results until an optimum lime content is reached beyond which further addition of lime does not seem to produce a further influence. The results of sedimentation tests agree both qualitatively and quantitatively with some recent studies on the plastic limit (9). If the rate of sedimentation is a measure of the degree of flocculation of clays, the increase of plastic limit with addition of lime is due, in fact, to the flocculation of the clay.

Flocculation of soil by lime has been stated as being due either to a replacement of the calcium ions for the cations naturally adsorbed on the soil clay or to a crowding of additional cations onto the clay (5). The relative importance of the second mechanism can be brought out by the following calculations:

The gumbotil has a cation exchange capacity of 37. 54 meq per 100 g of oven-dry soil. This means that 100 g of gumbotil can adsorb $37.54 \times \frac{40.08}{2 \times 1,000} = 0.75$ g of $Ca^{++}$.

In this equation 40. 08 is the atomic weight of $Ca^{++}$ and 2 its valence.

On the other hand, the amount of $Ca^{++}$ in 100 g of $Ca(OH)_2$ is $\frac{40.08}{74.10} = 54.1$ g, in which 74. 10 is the molecular weight of $Ca(OH)_2$.

Assuming that no $Ca^{++}$ is adsorbed on the clay in the natural gumbotil, the amount of $Ca(OH)_2$ for a complete replacement of adsorbed ions, per 100 g of the soil, would be $\frac{0.75 \times 100}{54.1} = 1.38$ g.

Because the commercial lime used in this investigation had 97. 5 percent of $Ca(OH)_2$ as calculated from its chemical analysis considering the molecular weights, it is calculated that $\frac{1.38 \times 100}{97.5} = 1.4$ percent would be the required amount of lime for a complete saturation of the gumbotil with adsorbed $Ca^{++}$ cations. Actually this value must be even smaller, because some $Ca^{++}$ is probably present among the adsorbed cations of the soil. However, this soil shows a complete flocculation, determined by the sedimentation test, or a constant increase of plastic limit (9) only for amounts of lime in excess of 3. 5 percent. This indicates that of the two mechanisms suggested, the crowding of additional calcium cations onto the clay requires a larger amount of lime than the amount required by the exchange reactions. The latter, however, probably takes place before the former does.

Cement and lime cause a similar flocculation of soil; the $Ca^{++}$ cations are furnished mainly by the $Ca(OH)_2$ resulting from the hydrolysis of the tricalcium aluminate. However, as the percent of cement added is increased, it produces a much slower increase of the rate of sedimentation for the friable loess equivalent to that achieved with 1 percent of lime (Fig. 10). A similar difference in the effectiveness of lime and cement on the plastic limit has been reported (13).

## Initial Hardening Studies

Results of unimmersed unconfined compressive strength determinations within the interval of 24 hr after the addition of water to the mixture are presented as a function of curing time (Fig. 11 a-c). Results for different mixtures should not be quantitatively compared because the test specimens of each mixture were tested at their molding moisture contents which were near the optimum moisture content, and the strength of unimmersed specimens is highly dependent on moisture content.

The most interesting aspect of this study was the results obtained within the first two hr, as shown in Figure 11 d-f. The effect of lime in delaying the hardening of the mixture was noticeable in all soils. This effect took place mainly during the first 30 min, after which, mixtures with the optimum amount of lime showed a more pronounced gain of strength than those without lime or with an excess of lime.

## Final Remarks

The effect of lime on the flocculation of clays has been demonstrated by the sedimentation tests. Flocculation resulted in easier workability of the mixtures containing

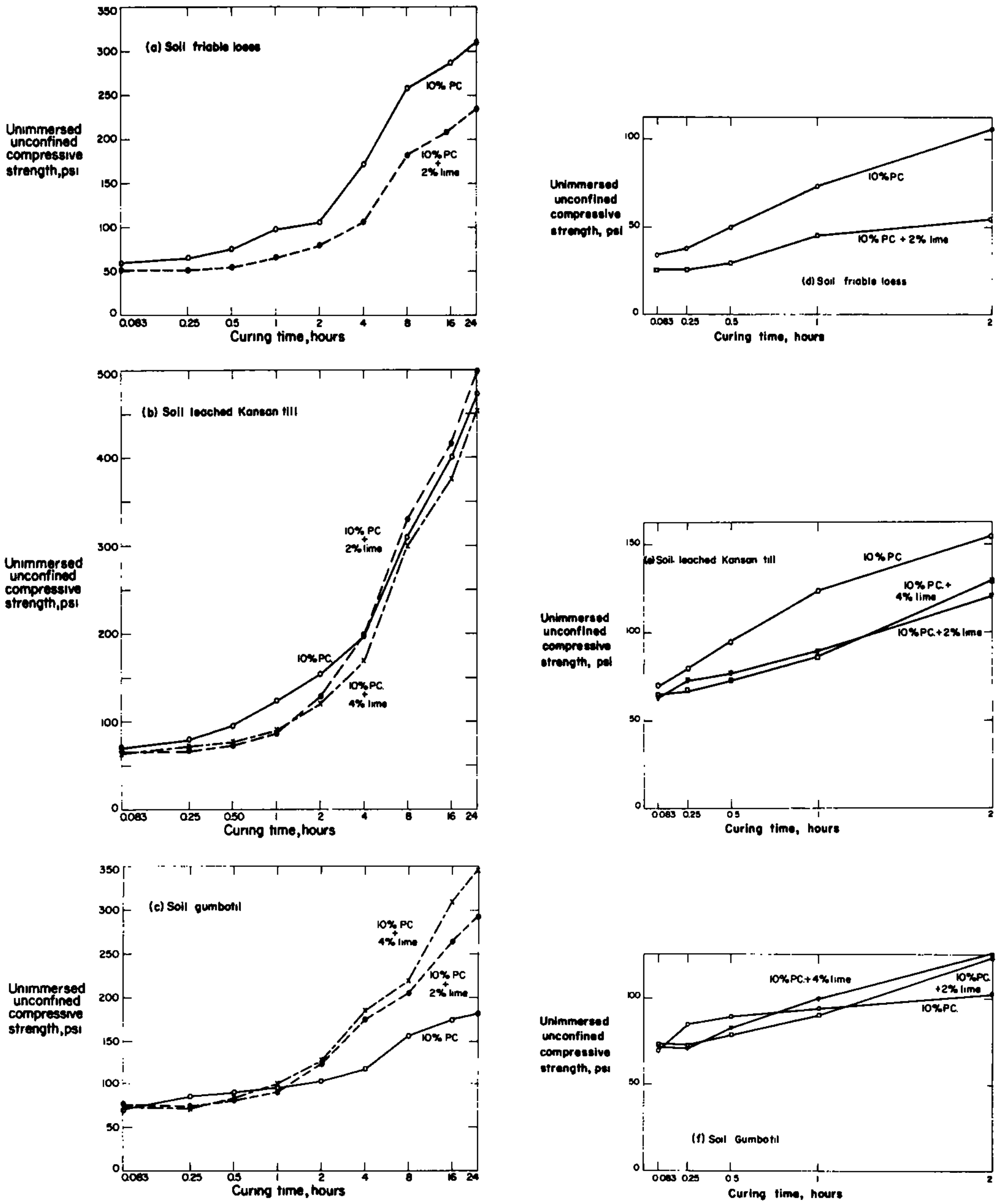

Figure 11. Unimmersed unconfined compressive strengths of friable loess, leached Kansan till, and gumbotil with cement and with cement plus lime, after varying periods of moist cure.

lime, which could be observed during the preparation of specimens from plastic soils mixtures. Though mixtures with lime had a rather "soft" texture, mixtures with only cement formed aggregates and tended to stick to the mixing apparatus. This was even more pronounced for mixtures tested at moisture contents above the optimum moisture content for maximum density.

The effect of lime in facilitating mixing should be even more noticeable in field construction of soil-cement than in the laboratory, where a uniform distribution of the cement within the already pulverized soil is obtained by the initial dry mixing. In the field, addition of lime before the cement should facilitate the achievement of the specified degree of pulverization, often one of the most difficult and costly phases of construction.

The amount of lime required for complete flocculation varies with the amount of clay in the soil and probably with other soil characteristics, such as the amount of carbonates present. Results of the sedimentation tests indicate that complete flocculation of montmorillonitic clay soils is achieved with the addition of approximately 0.6 percent of lime for each 10 percent of clay content below 0.002 mm in size. Observations during the preparation of laboratory specimens, however, indicated that equally workable mixtures are obtained with amounts of lime less than those indicated by this relationship; soils that were completely flocculated with 2 percent lime showed practically the same ease of mixing when either 1 or 2 percent of lime had been added.

The optimum amount of lime for maximum strength is well correlated with the clay content—the higher the clay content, the higher the optimum amount of lime. However, the optimum amount of lime for strength in mixtures of soil-lime-cement is equal neither to the required amount of lime for complete flocculation nor to the lime fixation capacity to which the amount of lime required for flocculation is very close. Although lime was not beneficial for the friable loess, which flocculates with 1 percent of lime, the optimum amount of lime for strength for the gumbotil, which completely flocculates with 3.5 percent of lime, was found to be 6 percent. Soils containing 30 to 40 percent of clay finer than 0.002 mm have an optimum amount of lime that is about equal to the amount causing complete flocculation, both amounts being close to 2 percent.

The reactions of either portland cement or lime with moist soils are complex and not yet completely understood; the simultaneous addition of lime and cement to soils makes the problem even more complex. However, an attempt is made to clarify some phases of the reactions on the basis of the results of this investigation and known hydration reactions of portland cement.

When portland cement comes in contact with water, the cement components undergo a hydrolysis reactions: a supersaturated solution is formed from which the excess solids precipitate as a complex combination of gels and crystalline hydrates. The major hydration products are hydrated basic calcium silicate, calcium aluminate, and calcium hydroxide, the first two being responsible for most of the strength-gaining properties of the portland cement. The calcium hydroxide, which has a low solubility, provides the saturated solution required for the formation of alumina, and of silicate gels with high Ca:Si ratios. Excess of lime is deposited as a separate crystalline solid phase (1).

In the cementation that takes place in a soil-cement mixture, the minerals are not only mechanically bonded to the cement but also react chemically with it (8). The finer the soil is, the more surface area that is available, and the more extensive the chemical reaction may become.

One of the reactions of soils with the cement compounds is an adsorption of ions to satisfy bonding energies unshielded by either polarization of surface ions or a deeper structural screening (8). The bonds developed between the mineral surface and the gel reduce the unbalance of forces at the mineral surface, with a resultant improvement of the chemical bonding. Although hydroxyl ions for this reaction are available since the beginning of the process, the increase of strength is gradual over a period of time. It has been suggested that some silicates, such as quartz and feldspars, mainly the first, respond to this chemisorption more effectively than clay minerals which are flakes too thin to present satisfactory structural screening. However, the clay minerals, by their affinity for adsorbing cations, influence the hydroxyl concentration of the solution during cement hydrolysis, and this influence is felt almost immediately. The sedimentation tests in this investigation were performed approximately 15 min after the addition of cement. Flocculation of the clay had occurred during this interval, as a result of the exchange of adsorbed cations and the concentration of $Ca^{++}$ in the clay micelle.

The attraction of $Ca^{++}$ cations by the clay minerals present in soil-cement mixtures causes a modification of the normal process of hydrolysis of portland cement in water, a modification probably similar to that caused by organic matter. One of the consequences may be that the solution is no longer saturated with $Ca(OH)_2$, a condition under which the precipitation of the calcium aluminates and silicates normally takes place. The chemical interference of clay in the hydration of cement may account, at least partially, for the low strength attained by high-clay soils when mixed with portland cement in amounts commonly used in soil-cement.

Small amounts of lime flocculate clay more effectively than cement. In a calcium-satisfied clay, the hydration of the cement can proceed normally. This is shown by the beneficial effect of adding small amounts of lime to clayey soil-cement, and it is helpful in explaining the increase of the optimum amount of lime with clay content. Results of the initial hardening studies evidence the effect of lime on the hydrolysis of the cement.

An excess of lime is known to be harmful to the hydration of concrete. The results obtained show the same to be true for soil-cement mixtures, although to a lesser degree. The particles of soil can not be completely surrounded by particles of cement, and there will always be an independent field of action for lime, with the pozzolanic reactions of the lime and soil particles mainly responsible for an increase of strength. The optimum amounts of lime for strength and flocculation do not coincide because of this additional gain of strength. Also, the increase of the optimum amount of lime with time is due to the slow rate of the pozzolanic reactions taking place.

The lack of improvement of friable soil-cement, the friable loess as an example, with even a small addition of lime may be because the amount of $Ca^{++}$ required by the clay mineral is very small and can be supplied by the cement without much interference of hydration.

Another point to be considered in the use of friable loess is the presence of calcium carbonate, a potential source of calcium for the reactions. Although calcite is not soluble enough to supply calcium for the flocculation of the clay, it must have an overall beneficial influence on the reactions, as is indicated by the results obtained with the two Kansan tills. Both had approximately the same gradation and optimum amount of lime. However, the addition of this amount of lime increased the strength of the leached Kansan till-cement mixtures about twice as much as it did the unleached Kansan till-cement mixtures.

The effect of lime in retarding the hydration of the cement, or perhaps better stated, in opposing the accelerated hydration caused by the clay, may explain the results obtained in the study of prolonged mixing. The strength decreased with mixing time, primarily because of the reduction in density, due to the hardening of the aggregates. The addition of lime, by reducing the formation of aggregates and retarding their hardening, decreased the reduction of strength.

## Economics of Lime-Cement Treatment

The addition of lime to soil-cement mixtures presents one possible disadvantage and three advantages. The disadvantage is the possible increase of operational cost of incorporating two additives instead of one.

The first advantage is the improved workability of the mixture, with the reduced depreciation of equipment and time required to achieve the specified degree of pulverization.

The second advantage stems from the effect of lime on the mixing period. The strength of the mixture compacted after the field mixing, during which some time is always taken up, is what determines the quality of a base course. Because lime minimizes the loss of strength during this period, either a reduction in the amounts of additives or a prolongation of the mixing time can be allowed when lime is added.

The third advantage concerns the cost of the additives. Because the cost of lime and of cement are practically equal, the total cost of the additives is in proportion to the total amount of additives. Although the mix designs are often based on results of wet-dry and freeze-thaw tests, the following comparisons are made in terms of the compressive strengths on the assumption that strength denotes quality:

1. Addition of lime to friable loess is uneconomical.
2. The plastic loess showed a 7-day strength of 420 psi with either 9 percent cement or 2 percent lime plus 6 percent cement. For the same strength the soil-lime-cement mixture gives a saving of 1 percent of additive material.
3. A strength of 360 psi for the unleached Kansan till after 7-day curing was obtained with 8 percent cement or with 2 percent lime plus 5 percent cement. Again, 1 percent of additive material is saved by the soil-lime-cement mixture.
4. A 7-day strength of 435 psi for the leached Kansan till obtained with 10 percent cement was also obtained with 2 percent lime plus 5 percent cement. Thus, for the same strength a saving of 3 percent additive material is given by the soil-lime-cement mixture.
5. The economic advantage of the simultaneous use of lime and cement for the gumbotil is paramount. Although 10 percent of cement gave a 7-day strength of 130 psi, and 8 percent lime produced a 7-day strength of 140 psi, an admixture of 4 percent lime plus 6 percent cement raised the 7-day strength to a value of 450 psi. These results leave no doubt that the gumbotil, which does not respond to stabilization easily, can be stabilized economically with a well-designed mixture of lime and cement.

## CONCLUSIONS

The results of this investigation show that beneficial effects are obtained by the addition of small amounts of lime to soil-cement mixtures, and lead to the following conclusions:

1. Addition of lime increases the compressive strength of soil-cement mixtures containing montmorillonitic clay soils.
2. For each soil-cement mixture there is an optimum amount of lime which gives a maximum compressive strength.
3. The optimum amount of lime is independent of the cement content of the mixture, and increases with increase of clay content in the soil.
4. The increase of strength with addition of lime is, in terms of percentage, higher for soils with high clay content and for soil-cement mixtures with lower cement content.
5. Addition of lime produces a higher increase of strength for noncalcareous soils than for calcareous soils.
6. The pozzolanic reactions, noticeable in some soils, cause an increase in the lime requirements for optimum conditions and a higher gain of strength with prolonged curing periods.
7. Addition of lime minimizes the decrease of both density and compressive strength with the time elapsed between addition of water to the mixture and compaction.
8. Addition of small amounts of lime to clayey soils causes flocculation of the clay and facilitates mixing of cement with such soils.
9. Sedimentation tests show that there is for each soil an amount of lime above which further increase of lime does not cause corresponding increase of flocculation. This amount is nearly the same as the lime fixation capacity of the soil.
10. Soil-cement mixtures harden much faster during the first 30 min after compaction than soil-lime-cement mixtures.

## ACKNOWLEDGMENTS

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