# Compaction Characteristics of Soil-Lime-Fly Ash Mixtures

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Field compaction is one of the most important steps to success in the stabilization of soils. There are several factors that influence compaction, including water content, amount of compaction, temperature of mix materials, and effect of delay in compaction after mixing. A laboratory investigation was made to study these factors using four soils, three fly ashes, and one lime. Specimens were molded near standard and modified AASHO compactive effort and moist cured up to 90 days.

The results indicate that the best compacting moisture for maximum strength is to the dry side of the optimum moisture for maximum density in the sandy soil and on the wet side in the two clayey soils. The temperature of the materials does not have a marked influence on the strength. Of paramount importance is the minimizing of the delay between wet mixing and compaction of the soil-lime-fly ash mixtures when the soil contains clay particles that can react with lime, lowering the density and strength for the same compactive effort. The modified compactive effort gave strengths from 50 to 160 percent higher than the standard.

•FIELD COMPACTION is one of the most important steps in the stabilization of soils. Several factors affect compaction; among them water content, amount and type of compaction, temperature of mix materials, and effect of delay in compaction after mixing. These also affect other kinds of soil stabilization using cementitious compounds (1, 2, 3).

In laboratory investigation, some of the factors that affect the compaction of soil, lime, and fly ash mixtures were studied. The results of this investigation are presented in this paper.

## MATERIALS

Dune sand, friable loess, alluvial clay, and gumbotil, all from Iowa, were used. An analysis of the soils and other materials used is given elsewhere (4, 5). The sand was Wisconsin-stage eolian sand, fine grained, oxidized, and leached. The friable loess was a Wisconsin-stage silt, friable, oxidized, and calcareous. The alluvial clay was a recent alluvial fill, plastic, slightly calcareous, with 72 percent 5-$\mu$ clay and 1.6 percent organic matter. The gumbotil was a Kansan-stage highly weathered till, plastic, noncalcareous, with 66 percent 5-$\mu$ clay. The predominant clay mineral in these soils is montmorillonite.

Three representative fly ashes were selected. Based on the pozzolanic reactivity with lime, fly ash No. 1 is of a medium to good quality, fly ash No. 2 is of a poor quality, and fly ash No. 3 of a very good quality (6).

A commercial grade calcitic (high-calcium) hydrated lime, $Ca(OH)_2$ was used.

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## METHODS

The mix proportions used were 76.5 percent soil, 6 percent lime, and 17.5 percent fly ash, on a dry weight basis. Only the soil fraction passing a No. 10 (2-mm) sieve was used.

Molding was started immediately after a batch was mixed, except in the studies on delay of compaction. Test specimens 2 in. in diameter by 2 in. high were molded in the Iowa State compaction apparatus. Five blows on each side with a 5-lb hammer dropping 12 in. were given to approximate standard Proctor compaction (ASTM Designation D698-58T; AASHO Designation T99-57) (7). Ten blows on each side with a 10-lb hammer dropping 12 in. were given to approximate modified Proctor compaction (ASTM Designation D1557-58T and AASHO Designation T180-57) (8).

After being molded, specimens were moist cured at 70 ± 4 F at a relative humidity of over 90 percent. The specimens wrapped in waxed paper and sealed with cellophane tape were placed in the humid room.

After each curing period, specimens were removed from the curing chamber and immersed for one day in distilled water. They were then tested for unconfined compressive strength using a load travel rate of 0.1 in. per min. Tests were run in triplicate; the average strengths are reported.

## INVESTIGATION

### Moisture-Density and Moisture-Strength Relationships

The most common practice in soil stabilization is to compact specimens at a moisture content as near to the optimum for maximum dry density as possible. Previous tests made at the Engineering Experiment Station of Iowa State University with mixtures of soil, lime, and fly ash showed some differences between the optimum moisture for maximum dry density and that for maximum 7-day strength of a silty soil (7).

Inasmuch as little is known of the effects of molding moisture on the strength of lime-fly ash-stabilized soils, an investigation was conducted to find if there is any correlation between the moisture for maximum strength. Specimens were molded with different moisture contents and were cured for periods of 7, 28, and 90 days.

Two compactive efforts were used—one approximating the standard Proctor and the other approximating the modified Proctor. The soils used were the dune sand, friable loess, alluvial clay, and gumbotil; lime was commercial calcitic hydrated and the fly ashes were No. 3 with all the soils and Nos. 1 and 2 also with dune sand and gumbotil (Figs. 1 to 8).

Dune Sand. —The moisture for maximum dry density and the moisture for maximum 7- or 28-day strength in any of the six sets of mixtures show no correlation (Figs. 1 to 3). The moistures for maximum strength are far to the dry side of the optimum moisture for maximum density. Both moistures of the specimens cured 90 days are closer, but there is a difference of about 2.0 percent for the mixtures compacted at the standard Proctor and 1.0 percent or less for the modified Proctor; the moisture for maximum strength is on the dry side of the optimum moisture for maximum density. The strength curves for 7- and 28-day curing are rather flat, but for 90 days there is a very sharp peak for the maximum strength.

Gumbotil. —The moisture contents for maximum strength for gumbotil contrasted with that for sand are to the wet side of the moisture for maximum density (Figs. 4 to 6). Some of the density and strength curves are rather flat, making it difficult to define the maxima.

Friable Loess. —The moistures for maximum dry density and maximum strength for standard Proctor compaction of friable loess practically coincide (Fig. 7). That is not so for modified Proctor compaction, in which 7- and 28-day curing strength curves, although rather flat, show a maximum strength at moisture contents less than the optimum for maximum density, and a maximum is well defined at a moisture content greater than the optimum for maximum density for 90-day curing.

Alluvial Clay. —The moisture-density curves for alluvial clay do not show a peak for maximum dry density, and the density increases as the moisture content decreases

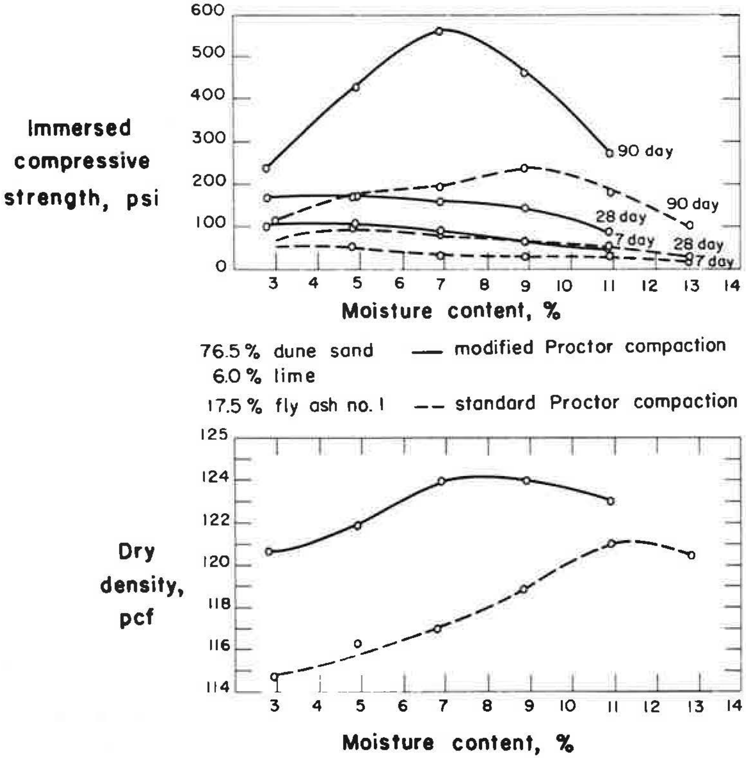

Figure 1. Moisture-density and moisture-strength relationships of 76.5:6:17.5 mixture of dune sand, calcitic hydrated lime, and fly ash No. 1 for standard and modified Proctor compactive efforts.

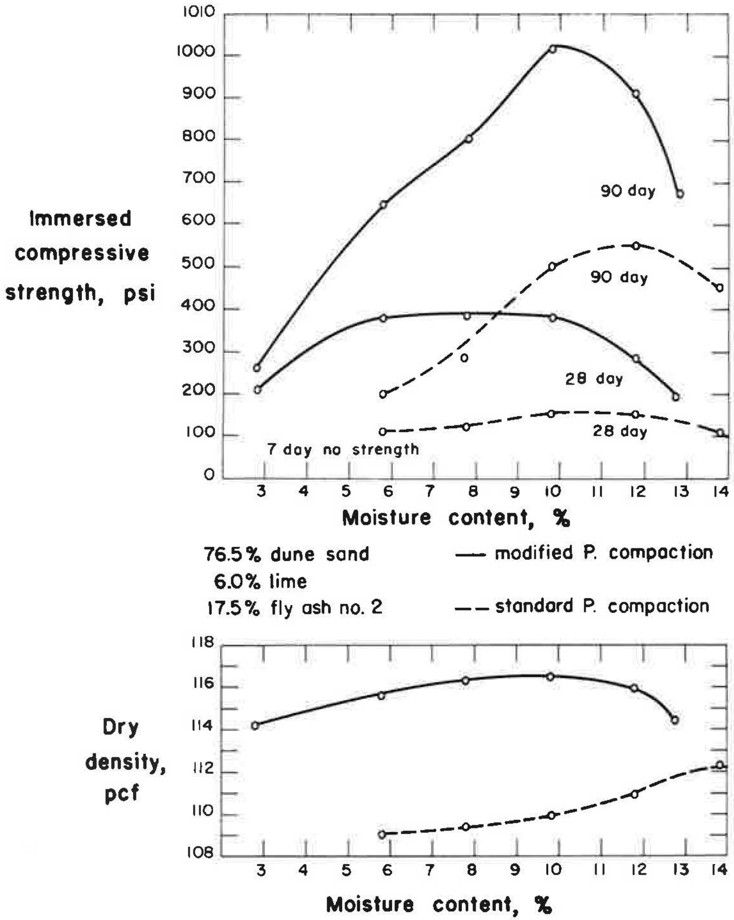

Figure 2. Moisture-density and moisture-strength relationships of 76.5:6:17.5 mixture of dune sand, calcitic hydrated lime, and fly ash No. 2 for standard and modified Proctor compactive efforts.

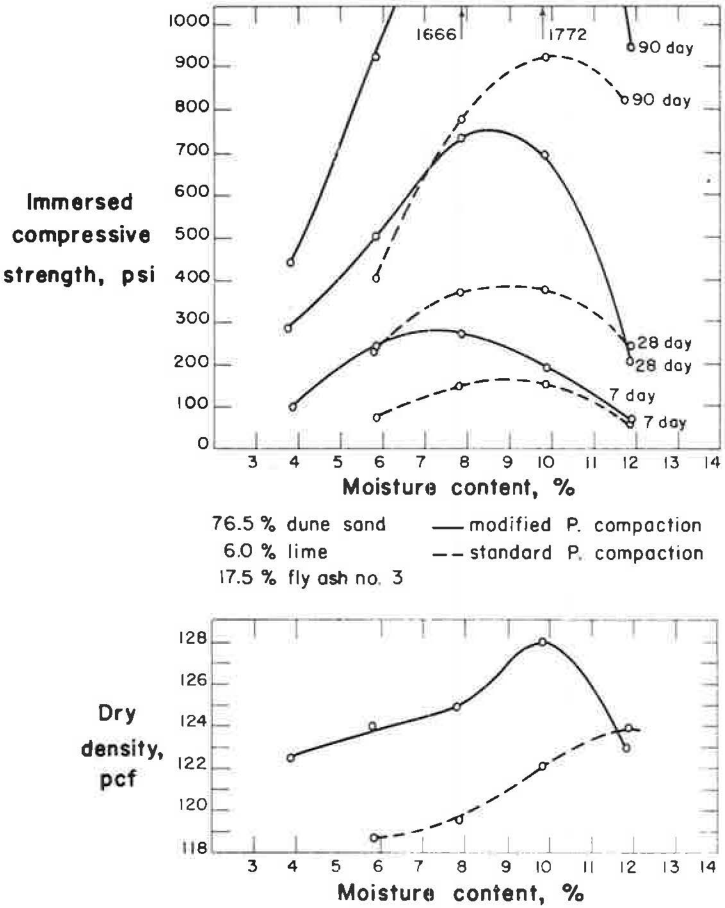

Figure 3. Moisture-density and moisture-strength relationships of 76.5:6:17.5 mixture of dune sand, calcitic hydrated lime, and fly ash No. 3 for standard and modified Proctor compactive efforts.

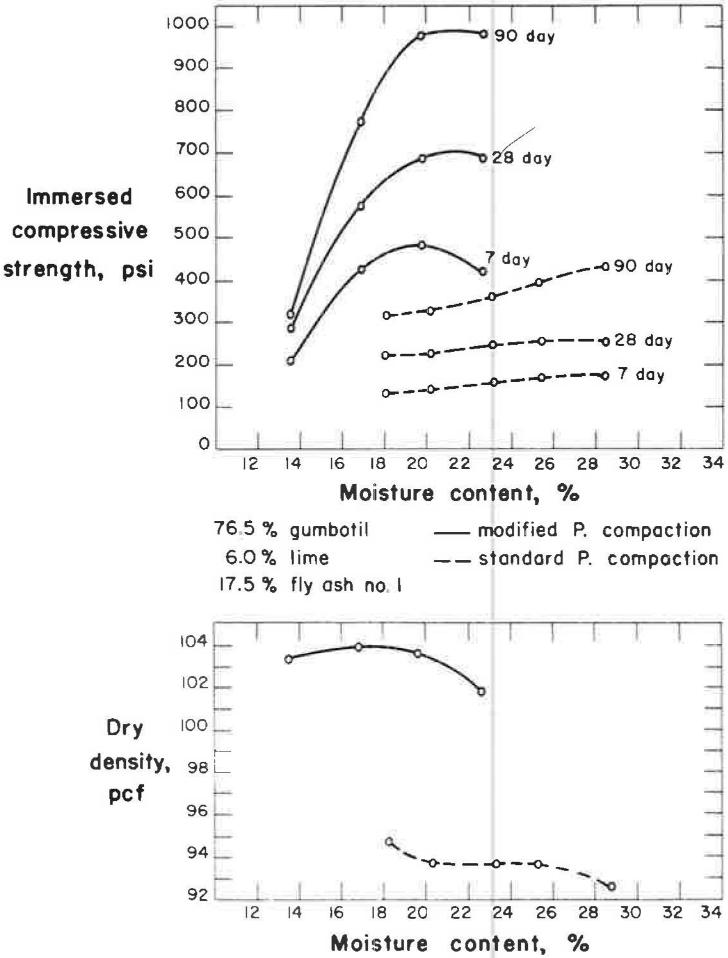

Figure 4. Moisture-density and moisture-strength relationships of 76.5:6:17.5 mixture of gumbotil clay, calcitic hydrated lime, and fly ash No. 1 for standard and modified Proctor compactive efforts.

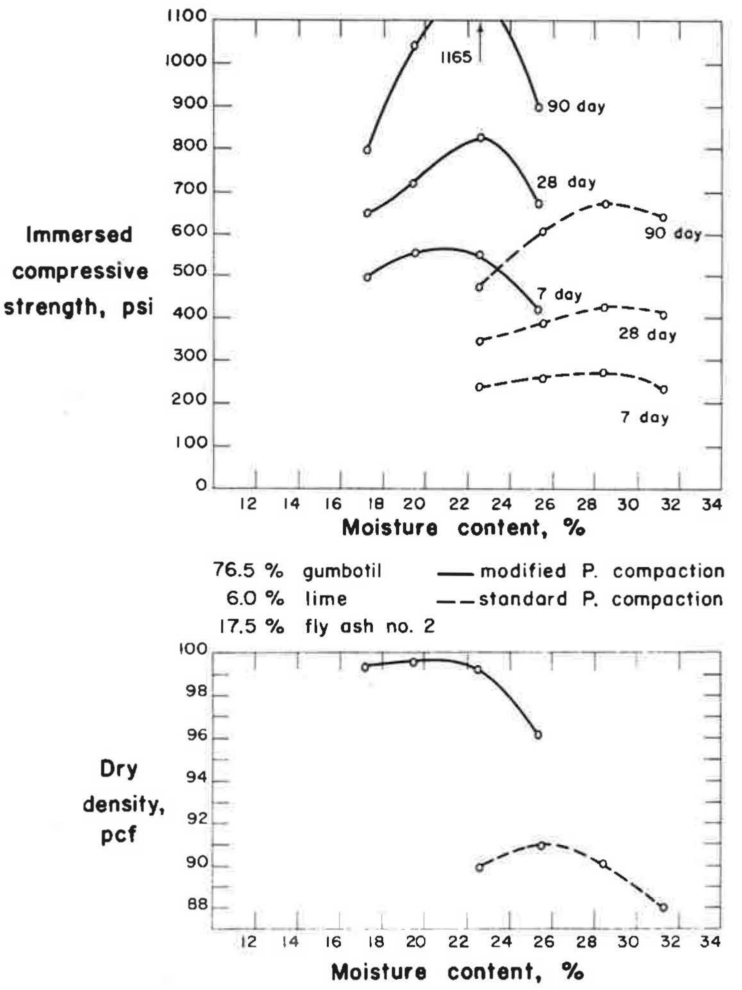

Figure 5. Moisture-density and moisture-strength relationships of 76.5:6:17.5 mixture of gumbotil clay, calcitic hydrated lime, and fly ash No. 2 for standard and modified Proctor compactive efforts.

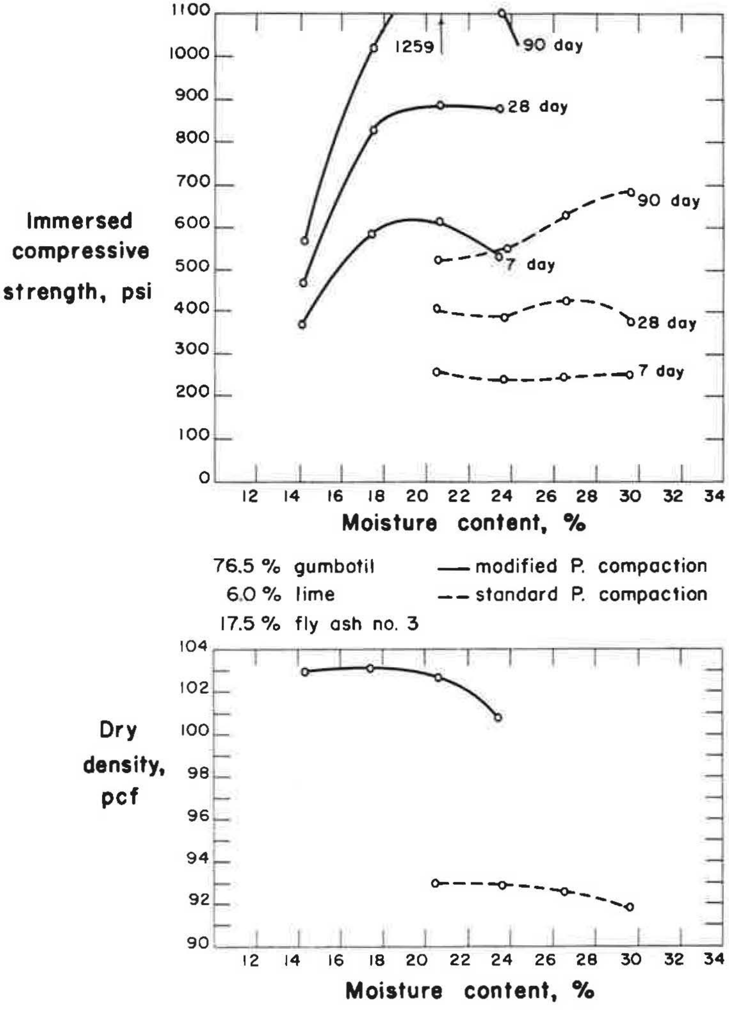

Figure 6. Moisture-density and moisture-strength relationships of 76.5:6:17.5 mixture of gumbotil clay, calcitic hydrated lime, and fly ash No. 3 for standard and modified Proctor compactive efforts.

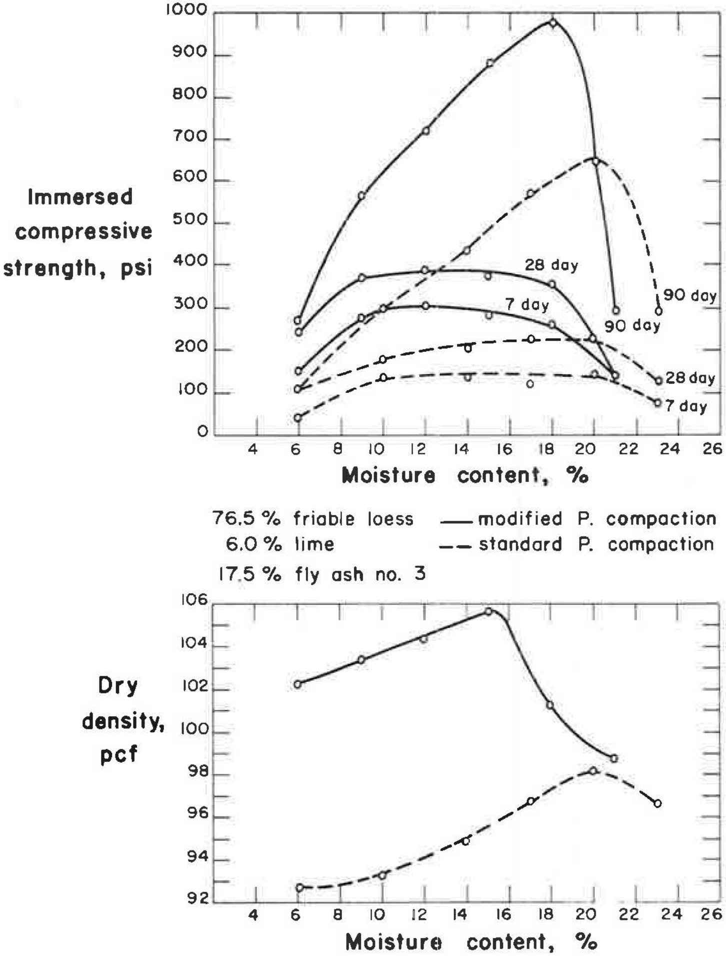

Figure 7. Moisture-density and moisture-strength relationships of 76.5:6:17.5 mixture of friable loess, calcitic hydrated lime, and fly ash No. 3 for standard and modified Proctor compactive efforts.

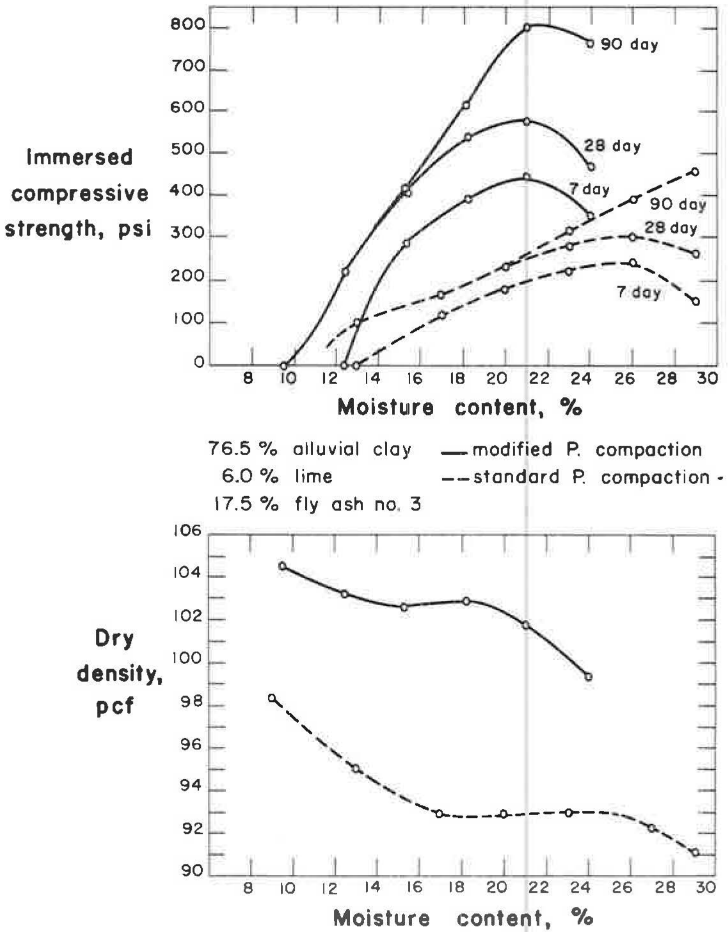

Figure 8. Moisture-density and moisture-strength relationships of 76.5:6:17.5 mixture of alluvial clay, calcitic hydrated lime, and fly ash No. 3 for standard and modified Proctor compactive efforts.

(Fig. 8). The strength curves show, however, a definite optimum moisture that changes conspicuously with curing time for standard compaction and slightly for modified.

Analysis. —The results obtained present new facts on the relations between maximum density and maximum strength in soil-lime-fly ash stabilization. The common practice has been to compact the stabilized soil as the optimum moisture for maximum density. It has been assumed that a maximum density should give a greater strength through a more dense packing of the soil and stabilizer particles, thus putting into contact more surface area for the development of the chemical reactions that lead to the formation of cementitious compounds. But in processes developing cementitious compounds by hydration, as that of the lime-fly ash reaction, the role of the water is of paramount importance.

Analyzing the results, the following have in general been observed:

1. The optimum moisture for maximum strength increased with the increase in curing time.
2. The optimum moisture for maximum strength was to the dry side of the optimum moisture for maximum dry density with the dune sand soil.

With both clayey soils (the gumbotil and the alluvial clay), it was on the wet side. With the friable loess both optimums coincide rather well.

The results indicate that a supply of water is needed for the hydration processes to continue. With dune sand, an amount of moisture two percentages below the optimum for maximum density will develop a maximum, or close to the maximum strength over a long curing period.

The moisture content is critical with friable loess. Reasonably good strengths were obtained at the optimum moisture content for maximum density, but an excess of water brought about a sharp decrease in strength; and amounts of water below the optimum reduced the strength. The optimum moisture for maximum density represents an amount of water sufficient for the chemical process of hydration which, therefore, should be the recommended moisture to stabilize the friable loess. The moisture should be on the dry side of the optimum.

The clayey soils showed great avidity for water. This is because complex reactions take place between the lime and soil particles apart from the lime-fly ash reaction. A rearrangement of the structure of the clay or colloidal particles may take place due to the excess of Ca ions in the stabilized soil. These Ca cations use up H and O ions and $H_20$ molecules. Based on long-term strengths, amounts of water much greater than the optimum for maximum density are advisable with clayey soils containing high percentages of montmorillonitic clay. It is observed that the shape of the moisture-density curves for both clayey soils is rather flat. In some instances the maximum density is not sharply shown, being undefined. The same happened when lime alone was used. This peculiarity has already been discussed (5).

## Effect of Compactive Effort

The trend in compaction of earth embankments, subgrades, and stabilized soils is towards compactive efforts greater than the standard Proctor. The Corps of Engineers and other agencies specify the required density in airfield construction as a percentage of the modified maximum density. Although some work has been done in comparing the strengths obtained at different compactive efforts (8, 9) only one fly ash was used, and the specimens were cured only up to 28 days.

In this work three fly ashes were used with the sand and gumbotil, and one fly ash was used with the alluvial clay and loess. Curing periods were carried up to 90 days. The results for different moisture contents and the maximum strengths vs time are plotted (Figs. 1 to 12).

The modified compaction gave strengths considerably greater than the standard compaction in all eight comparative studies. In all curing periods, the increase ranges from a minimum of 50 percent to a maximum of 160 percent without any correlation.

The rate of strength increase for 7-, 28-, and 90-day curing is almost a straight-line relationship, except for those mixes made with the gumbotil. Greater rate of in-

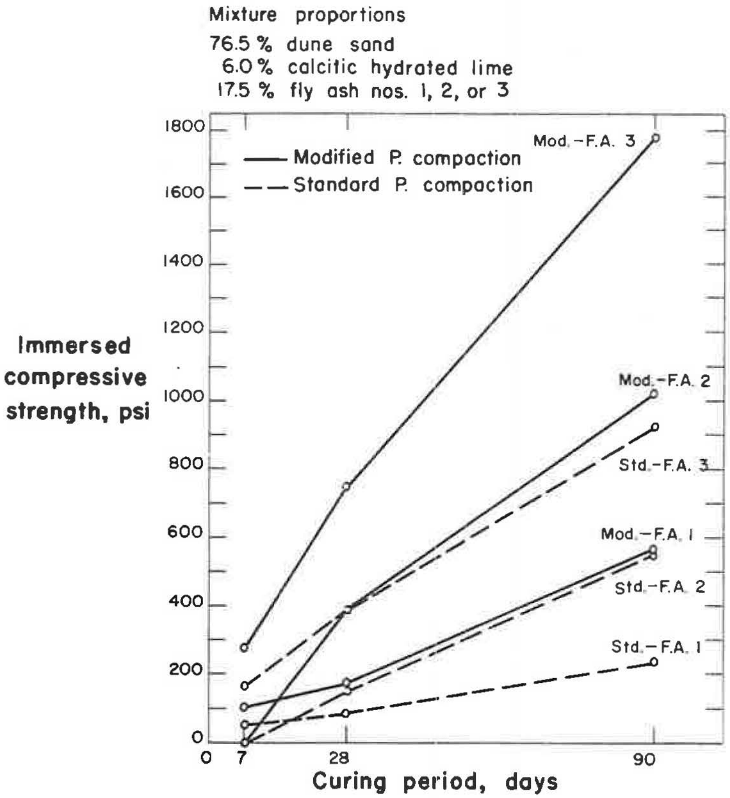

Figure 9. Effect of compactive effort on strength of 76.5:6:17.5 mixture of dune sand, calcitic hydrated lime, and fly ash.

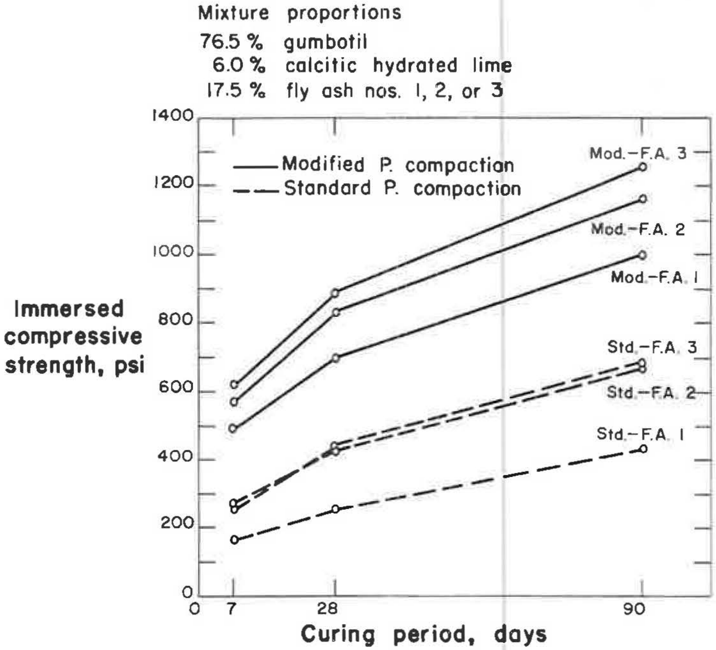

Figure 10. Effect of compactive effort on strength of 75.5:6:17.5 mixture cf gumbotil clay, calcitic hydrated lime, and fly ash.

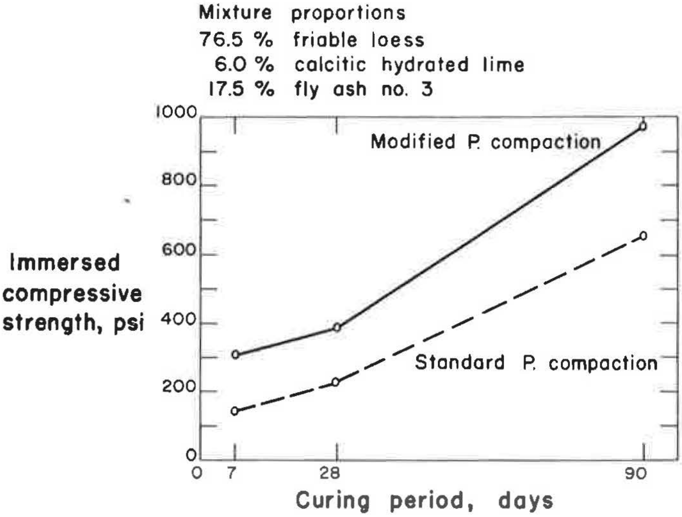

Figure 11. Effect of compactive effort on strength of 76.5:6:17.5 mixture of friable loess, calcitic hydrated lime, and fly ash No. 3.

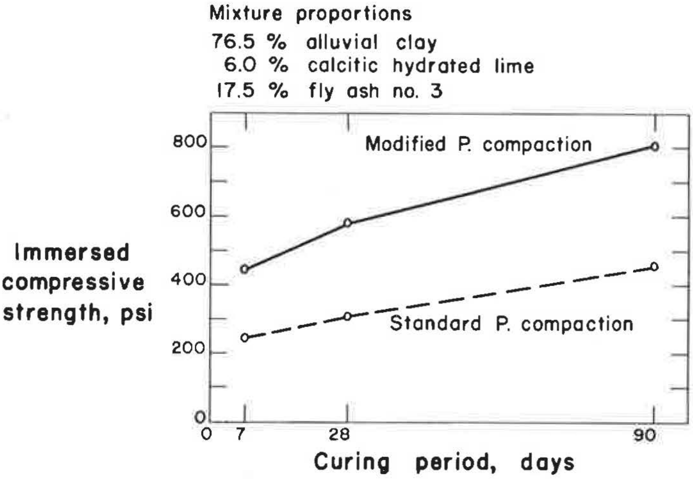

Figure 12. Effect of compactive effort on strength of 76.5:6:17.5 mixture of alluvial clay, calcitic hydrated lime, and fly ash No. 3.

crease with time is found in the friable soils (dune sand and friable loess), in which there is not a break in the rate of increase up to the longest curing period used. After 90-day curing, all the mixtures show that the strength increase also takes place at longer curing periods.

The convenience of compacting the mixtures of soil, lime, and fly ash to the highest possible degree is obvious. By a closer contact of particles at the proper moisture, the surface reactions have more opportunity to develop. This results in the higher strength obtained with the modified compaction.

When lime and fly ash are used to stabilize soils, the steady increase in strength with time has to be accounted for (Figs. 9 to 12). Early strengths may be low, but the continuous gain in strength over long periods of time increases the quality of the pavement made with lime-fly ash stabilized courses. This is desirable when the volume of traffic is expected to increase with time.

## Influence of Temperature of Materials at Time of Compaction

So far as known, the influence of temperature of the materials at the time of compaction on soil, lime, and fly ash mixtures has not been studied. The ambient mean temperature between two consecutive days may be as much as 40 F, and that between a cool day in the early working season and another day in the hot part of the summer may be more than 60 F. This work was undertaken to determine the influence of extremes in ambient temperature during the working season on the strength of soil, lime, and fly ash mixtures.

The soils used were dune sand and gumbotil. The very reactive fly ash No. 3 was used because it should accentuate the findings. A series of batches at different moisture contents was mixed and compacted with the soil, lime, fly ash, and water in a cooled state (about 54 F), and another series in a heated one (about 104 F). The soil-lime-fly ash mixtures, molded at several water contents, were stored in the moist room at 70 ± 3 F. The maximum immersed unconfined compressive strength and density values were obtained from the tests of these specimens (Table 1).

Although the data do not show a marked trend, mixing and compacting with hot materials may be detrimental in clayey soils stabilized with lime and fly ash. The density and strength were somewhat reduced.

The results show that the basic reaction between lime and fly ash with sand is not influenced by the temperature, in the range of 54 to 104 F of the materials at the time of mixing. The slight decrease in strength and density in the hot batches made with the clayey soil (gumbotil) is caused by the reaction between the lime and the highly active surface of clay particles before compaction.

Further tests were made in which the materials were mixed at the same temperatures with different water moisture contents and then stored at the same temperatures of mixing for 4 hr before compaction (Table 2). The compacted test specimens were cured in the moist room. Dune sand was the only soil used.

The results obtained further prove that the reaction between lime and fly ash in itself is not affected by the temperature of the materials, (between 54 and 104 F) at the time of mixing. Nevertheless, lime when used in clayey soils reacts in several ways with the clay particles, and some of these reactions may be activated by temperature. These reactions subtract or make inactive part of the lime for the pozzolanic reaction with fly ash and soil particles, causing a decrease in compacted density and in subsequent strength.

## Effect of Delay of Compaction After Wet Mixing

When interruptions in road construction occur after lime and fly ash are mixed with

TABLE 1

INFLUENCE OF MIXING TEMPERATURE OF MATERIALS ON STRENGTH OF 76.5:6:17.5 MIXTURE OF SOIL, CALCITIC HYDRATED LIME, AND FLY ASH NO. 3, WITH COMPACTION AFTER MIXING

| Soil | Temp. (°F) | Max. Immersed Unconf. Compress. Strength (psi) 7-Day | 28-Day | 90-Day | Max. Dry Density (pcf) | Optimum M. C. for Max. Density (%) |
|---|---|---|---|---|---|---|
| Dune sand | 54 | 154 | 422 | 1,004 | 123.8 | 12 |
| Dune sand | 70 | 165 | 390 | 930 | 124.2 | 12 |
| Dune sand | 104 | 158 | 382 | 1,010 | 124.2 | 12 |
| Gumbotil | 54 | 302 | 455 | 620 | 94.1 | 25 |
| Gumbotil | 70 | 255 | 445 | 685 | 93.0 | 25 |
| Gumbotil | 104 | 238 | 350 | 492 | 92.5 | 25 |

TABLE 2

INFLUENCE OF MIXING TEMPERATURE OF MATERIALS ON STRENGTH OF 76.5:6:17.5 MIXTURE OF DUNE SAND, CALCITIC HYDRATED LIME, AND FLY ASH NO. 3 IN WHICH COMPACTION WAS DELAYED 4 HR AFTER MIXING

| Temperature (°F) | Max. Immersed Unconf. Compress. Strength (psi) 7-Day | 28-Day | 90-Day | Max. Dry Density (pcf) | Optimum M. C. for Max. Density (%) |
|---|---|---|---|---|---|
| 54 | 140 | 369 | 960 | 124.0 | 12 |
| 70 | 141 | 348 | 935 | 122.7 | 12 |
| 104 | 148 | 342 | 973 | 122.0 | 12 |

soil and water and compaction is delayed, the strength of the stabilized soil may be affected. A few tests were made to establish a criterion on the maximum permissible length of time to be allowed soil, lime, and fly ash mixtures between wet mixing and compaction.

Selected mixes using dune sand or gumbotil were made. The mixtures were prepared with different amounts of water to obtain maximum values for strength and density. After mixing the soil, lime, fly ash, and water, one set of mixtures was immediately compacted into specimens; another set was stored for 4 hr in the moist room at 70 F, and then specimens were compacted; another set was stored for 24 hr in the same moist room before compaction of specimens. The maximum values for strength and density are givein in Tables 3 and 4. It was found that the longer the compaction was delayed, the higher the moisture content required to obtain a maximum strength.

Dune Sand.--Strength and density of the mixture with dune sand decrease slightly as the time between wet mixing and compaction increases. The greatest decrease in strength is found in mixtures made with fly ash No. 3. For 7-day curing it dropped from 165 psi for no delay in molding to 118 psi for a 24-hr delay; for 28-day curing the drop is from 390 to 243 psi; for 90-day curing there is no difference between the

TABLE 3

RESULTS OBTAINED WITH 76.5:6:17.5 MIXTURES OF DUNE SAND, CALCITIC HYDRATED LIME, AND FLY ASH COMPACTED AFTER DIFFERENT LAPSES OF TIME FOLLOWING WET MIXING

| Fly Ash No. | Setting Time[1] | Max. Dry Density (pcf) | Max. Immersed Unconf. Compress. Strength (psi) 7-Day | 28-Day | 90-Day |
|---|---|---|---|---|---|
| 1 | 0 | 121.2 | 55 | 90 | 240 |
| | 4 | 120.3 | 45 | 81 | 219 |
| | 24 | 118.6 | 41 | 60 | 210 |
| 2 | 0 | 112.3 | 0 | 150 | 560 |
| | 4 | 112.5 | 0 | 159 | 532 |
| | 24 | 110.8 | 0 | 141 | 417 |
| 3 | 0 | 124.1 | 165 | 390 | 930 |
| | 4 | 122.6 | 141 | 348 | 935 |
| | 24 | 122.6 | 118 | 243 | 945 |

[1] No. of hours elapsed between mixing and molding.

## TABLE 4

## RESULTS OBTAINED WITH 76.5:6:17.5 MIXTURES OF GUMBOTIL, CALCITIC HYDRATED LIME, AND FLY ASH COMPACTED AFTER DIFFERENT LAPSES OF TIME FOLLOWING WET MIXING

| Fly Ash No. | Setting Time[1] | Max. Dry Density (pcf) | Max. Immersed Unconf. Compress. Strength (psi) | | |
|---|---|---|---|---|---|
| | | | 7-Day | 28-Day | 90-Day |
| 1 | 0 | Undefined | 170 | 260 | 440 |
| | 4 | Undefined | 151 | 260 | 431 |
| | 24 | Undefined | 136 | 279 | 327 |
| 3 | 0 | Undefined | 255 | 445 | 685 |
| | 4 | Undefined | 260 | 405 | 596 |
| | 24 | Undefined | 173 | 244 | 351 |

[1] No. of hours elapsed between mixing and molding.

strength of specimens molded after mixing and of those molded after a 24-hr delay. With fly ash No. 2 specimens after 90-day curing there is also a great difference between the strengths of mixtures with no delay in compaction and those with a 24-hr delay, the strength for these two cases being 560 and 417 psi, respectively. The decrease is not very significant with fly ash No. 1, although it is steady with time of delay.

In general, the decrease in strength is very slight in mixtures when compaction was performed 4 hr after wet mixing. The decrease is more accentuated for the mixtures stored 24 hr before compaction.

A delay in compaction after wet mixing also brings about a decrease in dry density of sand, lime, and fly ash mixtures. The decrease amounts to less than 2 percent after a 24-hr delay.

Gumbotil. —A great decrease in strength correlates with the time of delay in compaction after wet mixing of gumbotil, calcitic hydrated lime, and fly ash mixtures. With a 24-hr delay for fly ash No. 3 the strengths were reduced from 32 to 49 percent, depending on the curing period. The reduction in the fly ash No. 1 mixture is less important, showingup in 7- and 90-day strengths but not in those of 28 days.

The density diminished consistently as compaction time was delayed. Because the maximum dry density was undefined, the moisture-dry density relationships in mixtures with gumbotil are plotted for the range in moisture content in which the maximum strengths were obtained (Figs. 13 and 14). The compacted density is lowered to a great extent by a delay in compaction. The drop in dry density is about 2 pcf for a 4-hr delay and about 5 pcf for a 24-hr delay.

Analysis. —The results stress the importance of proceeding with compaction as soon as possible after wet mixing of soil, lime-fly ash mixtures. This is highly recommended with montmorillonitic clayey soils in which strengths may drop by about 40 percent and dry density but about 6 percent for the same compactive effort if compaction is delayed one day after wet mixing. With sandy soils the drop in strength and dry density is not very important, and compaction may proceed the following day after wet mixing without significantly impairing the strength or dry density.

The lowering of strength and density may be for one or more of the following reasons:

1. Formation of carbonates by chemical reaction between lime and the carbon dioxide of the atmosphere.
2. Pozzolanic reactions between lime and fly ash.
3. Reactions between lime and soil particles.

The first two are probable in sandy soils and all three in clayey soils.

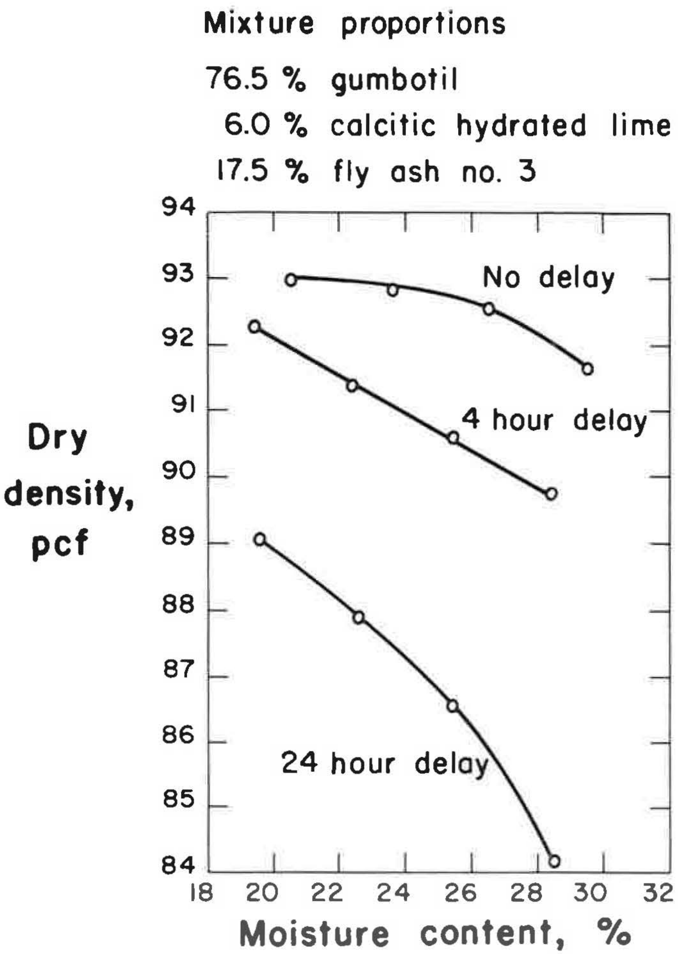

Figure 13. Moisture-density relationships of 76.5:6:17.5 mixture of gumbotil clay, calcitic hydrated lime, and fly ash No. 3,in which compaction was carried at different intervals of time after wet mixing.

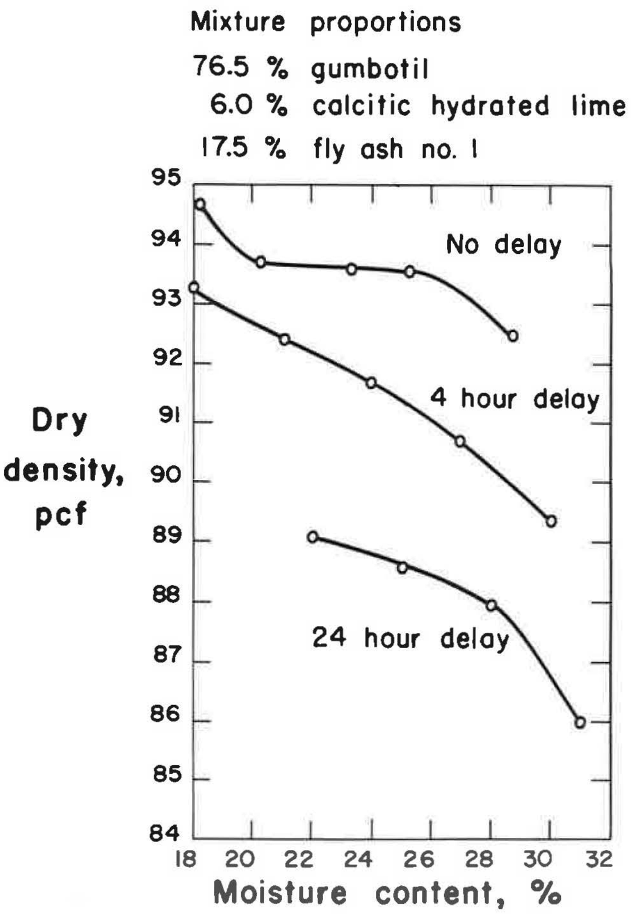

Figure 14. Moisture-density relationships of 76.5:6:17.5 mixture of gumbotil clay, calcitic hydrated lime, and fly ash No. 1, in which compaction was carried at different intervals of time after wet mixing.

A small reduction in strength and density in sandy soils indicates that the first two processes are not developed to a great extent. Because the carbonation of lime takes place at a rapid rate in a moist condition and because of the unlikeliness of quick pozzolanic reactions between lime and fly ash in a loose state, the first reaction is likely mainly responsible for the lowering of density and strength in sandy soils.

The reactions between lime and clay mineral particles are very important in montmorillonitic clay soils. The unbalanced electrical surface forces of the clay particles adsorb calcium cations of lime; calcium ions also produce a crowding action of clay particles; and lime reacts with the soil particles in a pozzolanic action. These reactions account for a great part of the reduction of strength and density when compaction does not soon follow wet mixing of clayey soil, lime, and fly ash mixtures.

## CONCLUSIONS

1. Maximum strength of soil, lime, and fly ash mixtures is produced by a compaction moisture content that is not necessarily the optimum moisture content for maximum density. The compaction moisture for maximum strength of specimens with sandy soils is to the dry side of the optimum moisture for maximum density. In soils having a high clay content, at least of the montmorillonite type, the compaction moisture is to the wet side. With such other soils as friable loess maximum strength and maximum density may occur at the same compaction moisture.
2. If no water is added during curing, the required compaction moisture content to produce maximum strength changes with the curing period–the longer the curing period, the greater the compaction moisture content needed for maximum strength.
3. Increasing the compactive effort from standard Proctor to modified increases the strength of soil, lime, and fly ash mixtures. The strength increase obtained varies from 50 to 160 percent.
4. If the materials are at high temperature at the time of mixing, the density and strength of clayey soil, lime, and fly ash mixtures are lowered, suggesting pre-compaction reactions. Sandy soils are not affected.
5. Compaction should proceed as soon as possible after wet mixing of soil, lime, and fly ash mixtures; otherwise density and strength may be substantially lowered. With clayey soils, compaction should be completed not later than 4 hr after wet mixing, whereas with sandy soils, compaction can be delayed until the day after wet mixing without appreciable loss of strength.

## ACKNOWLEDGMENTS

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