Improvement of Lime Stabilization Of Montmorillonitic Clay Soils With Chemical Additives

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Over the past decade, research has shown that lime produces beneficial results with clayey materials, although the unconfined compressive strengths of clayey soil-lime mixtures are relatively low. The investigation reported in this paper shows that lime in combination with small quantities of an inexpensive inorganic chemical may be the answer to an economical stabilization of clayey soils for highway usage.

Three Iowa soils ranging in clay content from 35 to 74 percent were studied in combination with varying amounts of both hydrated calcitic and hydrated dolomitic limes and three inorganic chemicals—sodium phosphate, sodium carbonate, and sodium hydroxide.

Additions of 1 to 3 percent of sodium hydroxide doubled the strength of soil-lime mixtures. Additions of sodium phosphate to soil-lime mixtures actually decreased the strength, and additions of sodium carbonate gave inconsistent results. It appears that sodium hydroxide can be successfully used in soil-lime.

A study of the effects of curing temperature and the freeze-and-thaw resistance of the soil-lime and soil-lime-chemical mixtures is also reported.

● RESEARCH AND FIELD experience have shown that lime treatments of clayey soils produce beneficial property changes, but that the strength gain of compacted mixtures may be too slow to meet base course requirements, particularly in the northern United States where desirably high curing temperatures cannot be counted on in late season construction, and where alternate cycles of freeze and thaw may cause failures of insufficiently hardened lime stabilized clayey soils. The results of recent work with chemical additives to improve the strength of soil-cement and soil-lime-flyash (1, 2, 3, 4, 5, 6) suggested that perhaps chemical additives could be used to improve the cement producing (pozzolanic) reactions in clayey soil-lime mixtures, giving rise to greater early strengths up to 28 days

Heat is another possible way to accelerate the hardening of lime treated soils (7). Although it may not be economical at present to cure a soil-lime base course with artificial heat, future cheap sources of heat may make this feasible. The effect of curing temperature on the rate of strength gain of compacted soil-lime mixtures is of practical interest in the natural temperature range attained under field conditions.

This paper presents the results of a laboratory investigation of the foregoing methods of improving the strength and durability of compacted clayey soil-lime mixtures.

Stability requirements for road bases in Iowa are used as the basis for evaluating the need for and the adequacy of the improvements.

MATERIALS

Properties of Soils

Three montmorillonitic clay soils were selected for the investigation. A description of each is given in Table 1, and physical and chemical properties are given in Table 2. The soils will be referred to as Kansan till, plastic loess and Kansan gumbotil.

They are typical of subgrade soils found in southern Iowa and parts of adjacent states, where, due to a lack of local deposits of granular road materials, stabilization methods for clayey soils are badly needed.

Kansan till and plastic loess contain approximately the same amount of montmorillonitic clay; but the non-clay size fraction of the two soils is considerably different. In Kansan till this fraction is about one-half silt sizes and one-half sand sizes; in plastic loess it is all silt sizes. Another difference is in carbonate content; Kansan till is calcareous, and plastic loess in noncalcareous or leached. The clay particles in a clacareous soil should be in a flocculated state with their appetite for calcium ions mostly satisfied, and nearly all added lime is available for pozzolanic reactions. In a leached soil, initial additions of lime furnish the calcium ions needed to flocculate the clay particles. Thus less lime should be required to stabilize Kansan till than plastic loess.

Kansan gumbotil is a unique soil type. Supposedly a fossil B-horizon developed from Kansan till, this highly weathered noncalcareous soil contains about 70 percent montmorillonitic clay, almost twice as much as the other two soils (Table 2). The non-clay fraction of Kansan gumbotil is about equal parts sand and silt-size material.

Properties of Limes

The properties of the two types of lime, dolomitic and calcitic, used are given in Table 3. Both were commercial grade hydrated limes produced by plants of the U.S. Gypsum Company, Chicago, Ill.

Properties of Chemicals

Three chemical additives were used, chosen as among the more promising for the improvement of pozzolanic reactions (6). The sodium carbonate (Na_2CO_3) was produced by the J. T. Baker Chemical Company, catalog no. 3602; the sodium phosphate ($Na_3PO_4 \cdot 12H_2O$) by the Mallinckrodt Chemical Works, catalog no. 7940; and the sodium hydroxide (NaOH) by the Mallinckrodt Chemical Works, catalog no. 7708. All three chemicals were analytical reagent grade.

TABLE 1

BRIEF DESCRIPTION OF SOILS

Soil	Kansan Till (409-12C)[a]	Plastic Loess (528-4)	Kansan Gumbotil (528-8)
Location	Ringgold Co., Iowa	Keokuk Co., Iowa	Keokuk Co., Iowa
Geological description	Kansan-age glacial till, plastic, calcareous, oxidized	Wisconsin-age loess, plastic, noncalcareous	Kansan-age gumbotil highly weathered, plastic, noncalcareous
Soil series	Shelby (Burchard)	Mahaska	Mahaska[b]
Horizon	C	C	Fossil B
Sampling depth	4½ - 10½ ft	3 - 6½ ft	7½ - 8½ ft

[a]Numbers in parentheses are those assigned by the Soil Research Laboratory of the Iowa Engineering Experiment Station.

[b]Underlies C horizon loess of Mahaska series.

TABLE 2

PROPERTIES OF SOILS

Soil	Kansan Till	Plastic Loess	Kansan Gumbotil
Textural composition[a] %			
Gravel (> 2mm)	0.0	0.0	0.0
Sand (2.0 - 0.074 mm)	31.5	0.2	16.0
Silt (0.074 - 0.005 mm)	30.0	60.8	13.5
Clay (< 0.005 mm)	38.5	39.0	70.5
Clay (< 0.002 mm)	31.0	33.0	67.0
Atterberg limits [b]			
Liquid limit, %	42.4	52.1	75.6
Plastic limit, %	20.5	20.0	25.6
Plasticity index, %	21.9	32.1	50.0
Classification			
Textural[c]	Clay	Silty Clay	Clay
Engineering (AASHO)[d]	A-7-6 (12)	A-7-6 (18)	A-7-6 (20)
Chemical			
Cat. Exch. Cap.,[e] m.e./100g	29.5	23.5	41.0
pH[h]	8.25	5.6	7.1
Carbonates,[g] %	4.9	0.0	0.8
Organic matter,[h] %	0.17	0.2	0.2
Predominant clay mineral[i]	Montmorillonite	Montmorillonite	Montmorillonite

[a]ASTM Method D 422-55T (8).
[b]ASTM Method D 423-54T and D 424-54T (8).
[c]Triangular chart developed by U.S. Bureau of Public Roads (9).
[d]AASHO Method M 145-49 (10).
[e]Ammonium acetate (pH = 7) method on soil fraction < 0.42 mm (No. 40 sieve).
[f]Glass electrode method using suspension of 15 g soil in 30 cc distilled water.
[g]Versenate method for total calcium.
[h]Potassium bichromate method.
[i]X-ray diffraction analysis.

METHODS

Preparation of Mixtures

Air dried soil passing the No. 10 sieve was dry mixed with the lime additive for 30 sec by a Hobart Model C-100 mixer. (The weight of lime or chemical additive used was expressed as a percentage of the oven-dry weight of the soil. The percentages of lime, sodium carbonate or sodium hydroxide refer to the as-received chemical; the percentages of sodium phosphate refer to anhydrous chemical.) Sufficient water was then added to bring the moisture to the desired optimum content and mixing was continued for 2 min. The mixture was next hand mixed a few times to loosen any of the soil stuck to the sides of the mixing bowl. It was then machine mixed for another 2 min. Chemical additives, when used, were dissolved in the mix water prior to adding to the soil-lime mixture. The crystal water of sodium phosphate was accounted for in calculating the amount of mix water required.

Molding Moisture Contents

The moisture-density, and moisture-7 day cured plus 1 day immersed strength relationships of the three soils treated with a 2 percent and 12 percent of each lime plus 0, 0.5 and 2 percent of sodium carbonate, and with 4, 6 and 8 percent of each lime plus

0, 0.5 and 2 percent of sodium hydroxide, were determined as described by Davidson and Bruns (11). The moisture-density and moisture-immersed strength curves showed that for each mixture the optimum molding moisture contents for maximum dry density and for maximum immersed strength were nearly the same. Hence it was decided to mold all test specimens at optimum moisture for maximum density.

Molding of Specimens

Each mixture was molded into cylindrical shaped specimens, 2 ± 0.05 in. high and 2 in. in diameter, having a density near 100 percent standard Proctor. The drop-hammer compaction apparatus and the molding method used have been described (11).

Curing of Specimens

Specimens made for evaluating the effect of chemical additives on the strength of soil-lime mixtures were cured for 7 and 28 days in a moist curing room maintained at a relative humidity of 90 percent or higher. The temperature in the moist curing room was within a few degrees of 70 F, except for the mixes with sodium hydroxide, which were cured at a temperature between 75 and 80 F (due to malfunctioning of the temperature control system). After being molded and prior to storing in the curing room, each specimen was sealed in wax paper to reduce the loss of moisture and to prevent carbon dioxide of the air from reacting with the lime in the specimens during curing.

The specimens for the variable temperature curing studies, after being molded, were sealed in wax paper. (Those treated with sodium hydroxide were further wrapped with Saran wrap and aluminum foil.) They were then placed in metal containers having tight fitting lids. A small can of water inside each container maintained the relative humidity near 100 percent. Little loss in weight by the specimens was observed, indicating little or no loss of moisture during curing. The specimens for curing temperature versus immersed strength tests were cured for 3, 7, 14, and 28 days at temperatures of 50, 70, 100 and 140 F. Additional sets of specimens were cured 7 days at each temperature in preparation for freeze-thaw testing.

TABLE 3

PROPERTIES OF LIMES

	Hydrated Limes	
	Dolomitic (Monohydrate, Type N)	Calcitic (Hi-calcium)
Chemical analyis, percent by weight:		
Silicon dioxide	0.4	0.28
Iron and aluminum oxide	0.3	0.6
Magnesium oxide	31.8	0.59
Sulfur trioxide	1.1	0.25
Carbon dioxide	1.0	ND[a]
Total calcium oxide	48.8	73.82
Available calcium oxide	47.1	70.3
Loss on ignition	17.0	24.1
Combined H_2O	18.0	ND[a]
Processing Location	Genoa, Ohio	New Braunfels, Texas
Trade Name	Kemidol Hydrated	Kemikal Hydrated

[a]Not determined.

Immersed Strength Testing

The cured specimens were immersed in distilled water for 24 hr and then tested for unconfined compressive strength. The rate of loading specimens in the testing machine was 0.1 in. per minute. The maximum load causing failure was taken as the immersed strength of the specimen. Strength values reported in psi are the average of three test specimens; the difference between the individual values and the average value rarely exceeded 10 percent of the average value.

Durability Testing

A modified British standard freeze-thaw test (B.S. 1924:1957) (11), was used to evaluate the durability of selected mixtures. Two identical 2- by 2-in. specimens from each mixture were cured 7 days at each of the previously mentioned temperatures, then immersed in distilled water at room temperature for 24 hr. One specimen, designated the control specimen, was left immersed for 14 more days; and the other specimen, designated the freeze-thaw specimen, was exposed alternately to temperatures of 23 ± 2 F (16 hr) and 77 ± 4 F (8 hr) for 14 cycles, each cycle lasting 24 hr. (A vacuum flask specimen container was used to cause freezing to occur from the top down and to supply unfrozen water to the bottom of the specimen throughout the test.) After these treatments, the unconfined compressive strength of the freeze-thaw specimen (p_f) and of the control specimen (p_c) were determined. These values were used to evaluate the durability of the stabilized soils. The index of the resistance to the effect of freezing (R_f) was calculated from the formula:

$$R_f = \frac{100\, p_f}{p_c} \qquad (\%)$$

TEST RESULTS AND INTERPRETATIONS

Effect of Lime on Immersed Strength

Dolomitic Hydrated Lime.—Specimens of Kansan till, plastic loess, and Kansan gumbotil treated with 2 percent to 12 or 14 percent dolomitic lime, in 2 percent increments, were tested for immersed strength (unconfined compressive strength after 24 hr immersion) after 7 and 28 days moist curing at approximately 70 F and 90 + % R.H. The test results are plotted in Figure 1. The general trend of the data is similar for each soil at each curing period, showing low immersed strengths at low lime contents, near maximum strengths at intermediate lime contents, and little or no further increase of strength at higher lime contents. Recommended base course mix designs for roads might be: Kansan till plus 4 percent lime, plastic loess plus 6 percent lime, Kansan gumbotil plus 8 percent lime, but there might be an advantage in using more lime with the latter soil. These mixtures gave 7 and 28 day cured immersed strengths of 163 and 276 psi (Kansan till), 77 and 228 psi (plastic loess), 141 and 203 psi (Kansan gumbotil). The use of higher lime contents with Kansan till and Kansan gumbotil gave 28 day strengths of about 300 psi.

Calcitic Hydrated Lime.—The results of comparable tests using calcitic lime instead of dolomitic lime are plotted in Figure 2. Immersed strengths reached a fairly well-defined maximum value at fairly low lime contents and showed no increase at the higher lime contents used. Mix designs probably would be: Kansan till plus 4 percent lime, plastic loess plus 4 percent lime, Kansan gumbotil plus 6 percent lime. Corresponding 7 and 28 day cured immersed strengths were: 133 and 209 psi (Kansan till), 54 and 153 psi (plastic loess), 69 and 151 psi (Kansan gumbotil).

Summary—Dolomitic Lime vs Calcitic Lime.—The immersed strengths obtainable with treatments of dolomitic monohydrate (Type N) lime indicate that the three clay soils could probably be satisfactorily stabilized for base courses of roads in Iowa, providing construction was completed early enough to take advantage of high summer temperatures. Mixtures of the soils with calcitic lime probably would not be satisfactory for base courses, but should be satisfactory for subbases or subgrade treatments.

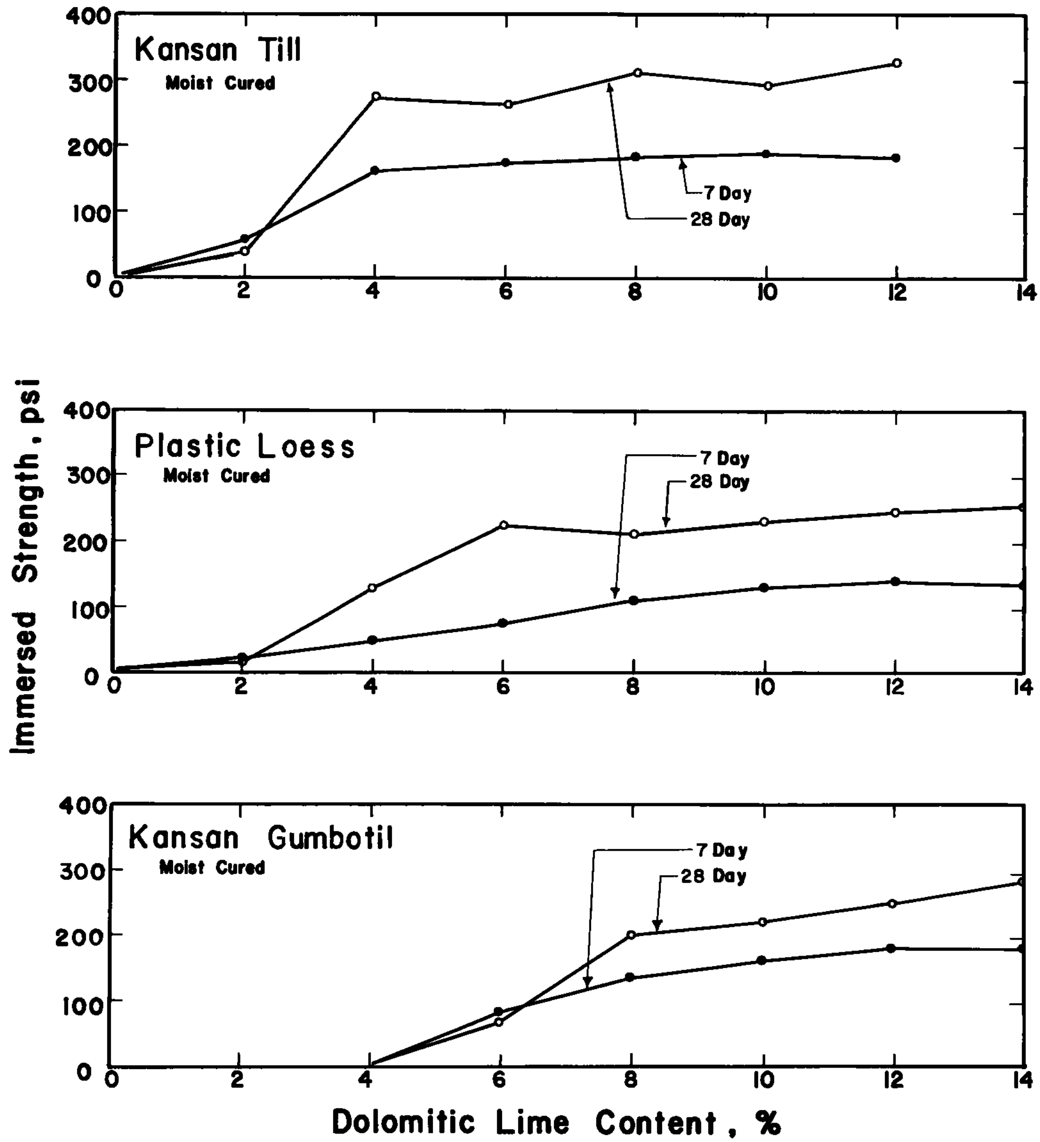

Figure 1. Immersed strength-dolomitic lime content relationships for Kansan till, plastic loess and Kansan gumbotil.

Effect of Lime Plus Chemical Additives on Immersed Strength

Dolomitic Hydrated Lime Plus Sodium Carbonate or Sodium Phosphate.—Specimens of Kansan till treated with 4, 6 and 8 percent of dolomitic lime plus 0, 0.25, 0.5, 1, 2 and 4 percent of each chemical were cured 7 and 28 days at approximately 70 F and 90 + R.H., immersed in distilled water for 24 hr, then tested for unconfined compressive strength. Test results indicated that the use of sodium carbonate or sodium phosphate in Kansan till-dolomitic lime mixtures caused a marked decrease in immersed strength. Therefore these chemicals were not evaluated with the other two soils.

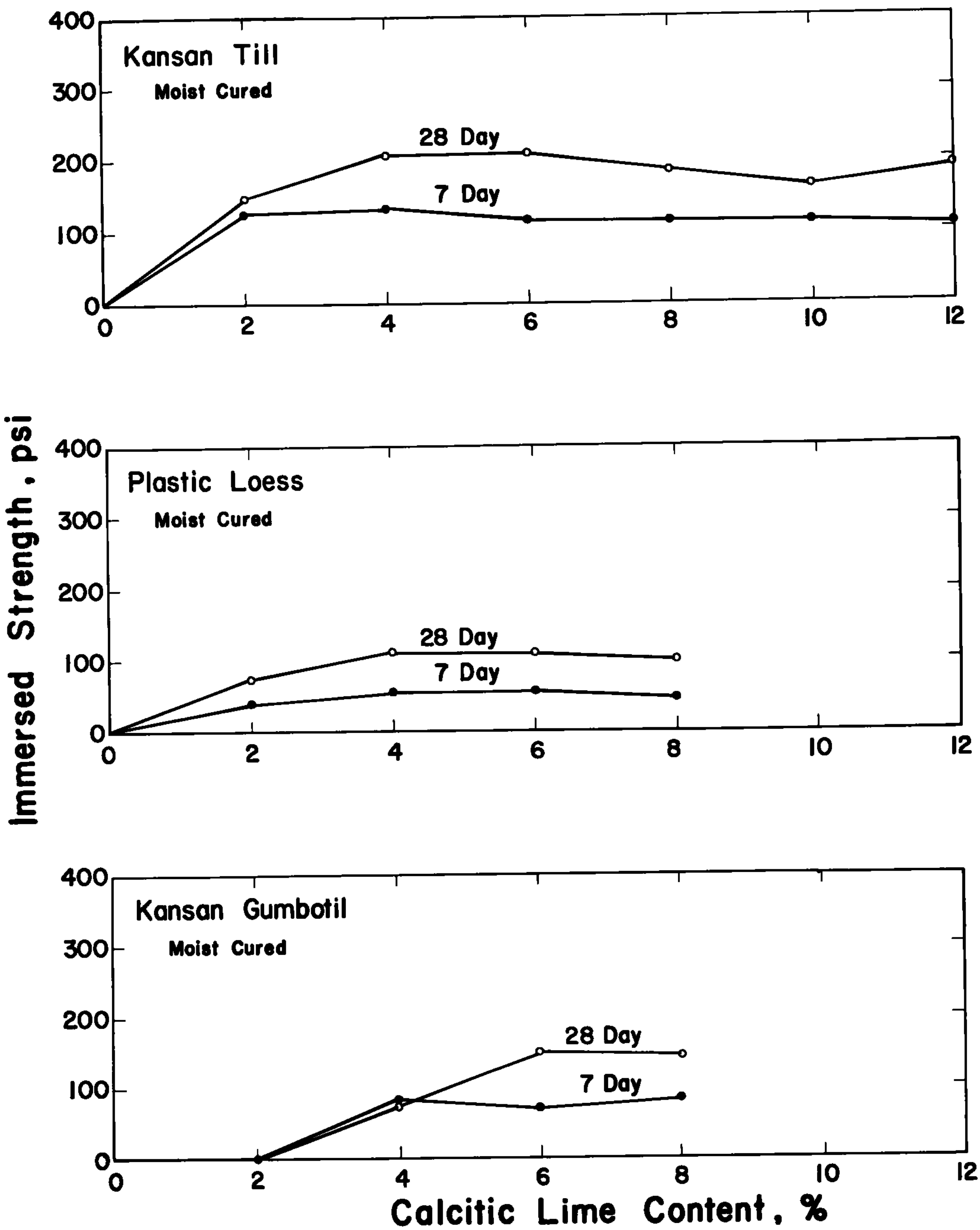

Figure 2. Immersed strength-calcitic lime content relationships for Kansan till, plastic loess and Kansan gumbotil.

Calcitic Hydrated Lime Plus Sodium Carbonate or Sodium Phosphate.—Specimens of Kansan till with combiantion treatments of calcitic lime and each chemical, proportioned the same as the combination dolomitic lime-chemical treatments, gave the immersed strength results shown in Figure 3. Definite optimum combination treatments are indicated, the best being 6 percent lime plus 2 percent sodium carbonate, and 6 percent lime plus 2 percent sodium phosphate. The former treatment gave 7 and 28 day cured immersed strengths of 251 and 292 psi; the latter treatment gave 183 and 278 psi, compared to 117 and 210 psi with 6 percent lime and 0 percent chemical. Since sodium phosphate is more expensive than sodium carbonate and did not produce as high strengths, it was not evaluated further.

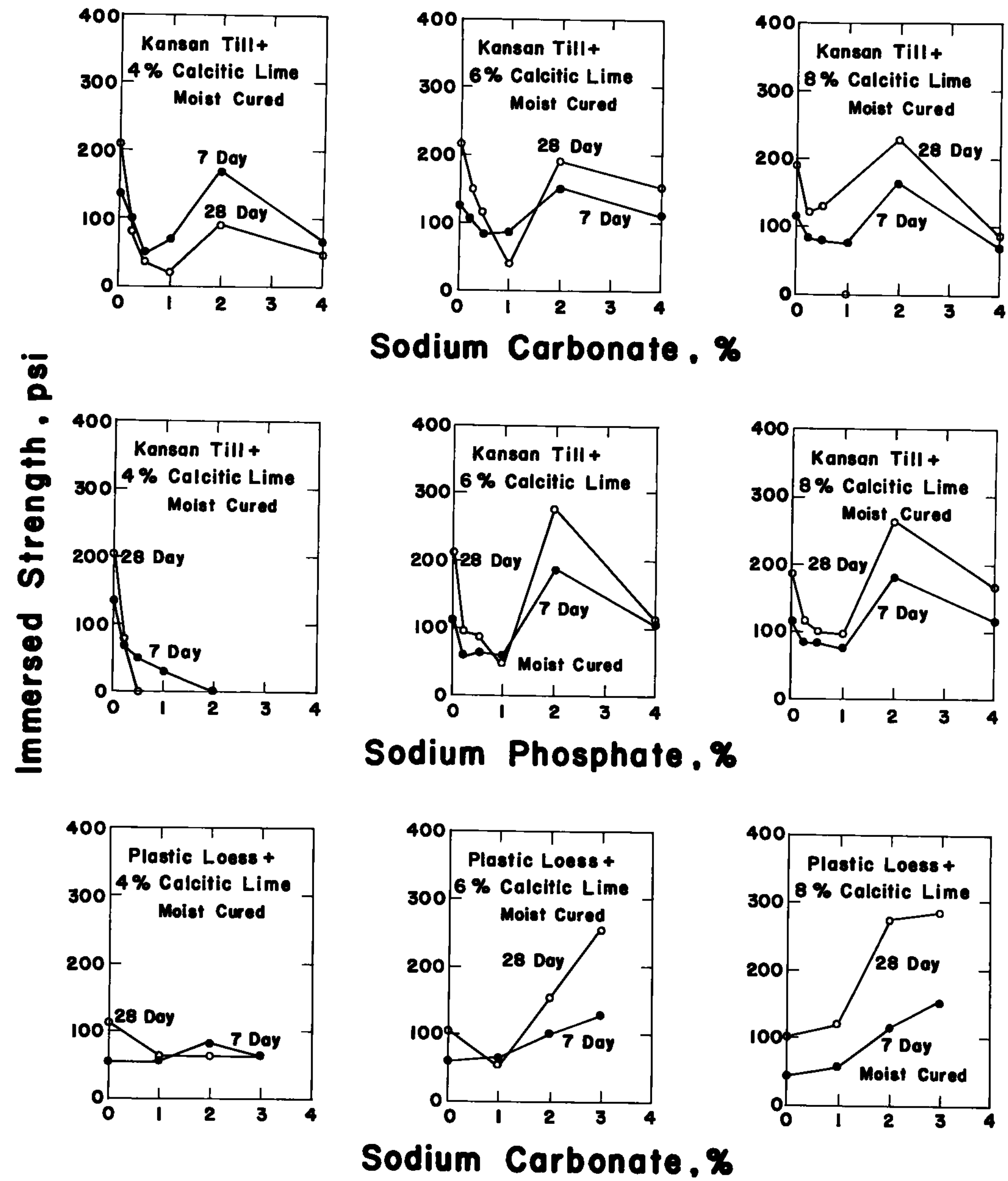

Figure 3. Immersed strength-sodium carbonate or sodium phosphate content relationships for calcitic lime-treated Kansan till and plastic loess.

The effects of additions of 1, 2 and 3 percent sodium carbonate on the immersed strength of plastic loess-lime mixtures are shown in Figure 3. Smaller amounts of sodium carbonate were not tried because of the adverse effects observed with Kansan till-lime mixtures (Figure 3). A good combination treatment of plastic loess was 6 percent lime plus 3 percent sodium carbonate; the 7 and 28 day cured immersed strengths were 130 and 256 psi. Another, slightly better but more costly, was 8 percent lime plus 3 percent sodium carbonate; the 7 and 28 day strengths were 143 and 291 psi. For comparison, the 7 and 28 day strengths of plastic loess-6 percent lime were 56 and 109 psi, and of plastic loess-8 percent lime were 45 and 99 psi.

The combination treatments used with plastic loess also were tried with Kansan gumbotil. Test results are not shown, because all amounts of sodium carbonate decreased the immersed strength of Kansan gumbotil-lime mixtures, both after 7 and 28 day curing.

Summary—Sodium Carbonate and Sodium Phosphate.—The foregoing test results indicated that the search for a chemical additive to improve clayey soil-lime mixtures was not ended. Additives of sodium carbonate and sodium phosphate decreased the immersed strengths of the soil-dolomitic lime mixtures. Optimum combination treatments of lime and chemical gave marked improvements to the immersed strengths of Kansan till and plastic loess, but use of a combination treatment other than the optimum generally had an adverse effect on strength. Sodium carbonate was judged more promising than sodium phosphate, but even sodium carbonate decreased the immersed strength of Kansan gumbotil-calcitic lime mixtures. Thus it was decided to continue the search for a more versatile and beneficial additive. Exploratory tests indicated that sodium hydroxide was a likely prospect.

Each Lime Plus Sodium Hydroxide.—The sodium hydroxide treatments of each soil-lime mixture were 0, 0.5, 1, 2 and 3 or 4 percent. The following mixtures were so treated: each soil plus 4, 6, and 8 percent dolomitic lime, and each soil plus 4, 6 and 8 percent calcitic lime. Specimens were moist cured 7 and 28 days at temperatures in the range 75 to 80 F, which were 5 to 10 F higher than the curing temperature of the specimens in the previously discussed tests. The resulting improvements of immersed strength are seen by comparing the strength values for soil-lime mixtures (0 percent sodium hydroxide) in Figures 4, 5, and 6, with those for identical mixtures in Figure 3.

Kansan Till.—Test results with Kansan till are shown in Figure 4. Sodium hydroxide, in amounts of 1 to 4 percent, improved the 7 and 28 day cured immersed strengths of both dolomitic lime and calcitic lime treated-soil mixtures; 0.5 percent sodium hydroxide was detrimental to the strengths of all mixtures. There was generally an optimum amount of chemical for each Kansan till-lime mixture, and strength improvements at and near the optimum treatment were exceptional. For example, the 7 day strength of the Kansan till-6 percent calcitic lime mixture was 135 psi; 1 percent sodium hydroxide boosted it to 363 psi. The 28 day strength was improved even more: 240 psi without chemical, 582 psi with 1 percent chemical. Sodium hydroxide treatments made possible 7 day strengths near or above 350 psi with all Kansan till-lime mixtures regardless of the type of lime; the same treatments produced 28 day strengths of 500 psi or more. A comparison of the following mix designs, which might be considered satisfactory for a road base course, illustrates the possibilities for economical stabilization of Kansan till: 6 percent dolomitic lime (marginal), 6 percent dolomitic lime + 2 percent NaOH (safe), 4 percent calcitic lime + 1 percent NaOH (safe).

Plastic Loess.—Test results with plastic loess (Fig. 5) indicate that although the optimum amounts of sodium hydroxide were generally beneficial to immersed strength of dolomitic lime-treated mixtures, best strength improvements were obtained with the calcitic lime-treated mixtures, which needed the most improvement. It is evident that the extent of improvement of plastic loess-lime mixtures was not as exceptional as with Kansan till-lime mixtures, but economical mix designs which may meet base course requirements are made possible by use of sodium hydroxide. For example, plastic loess plus 6 or 8 percent calcitic lime and 2 percent NaOH look promising. Plastic loess plus 8 percent or 10 percent dolomitic lime and 2 percent NaOH would probably

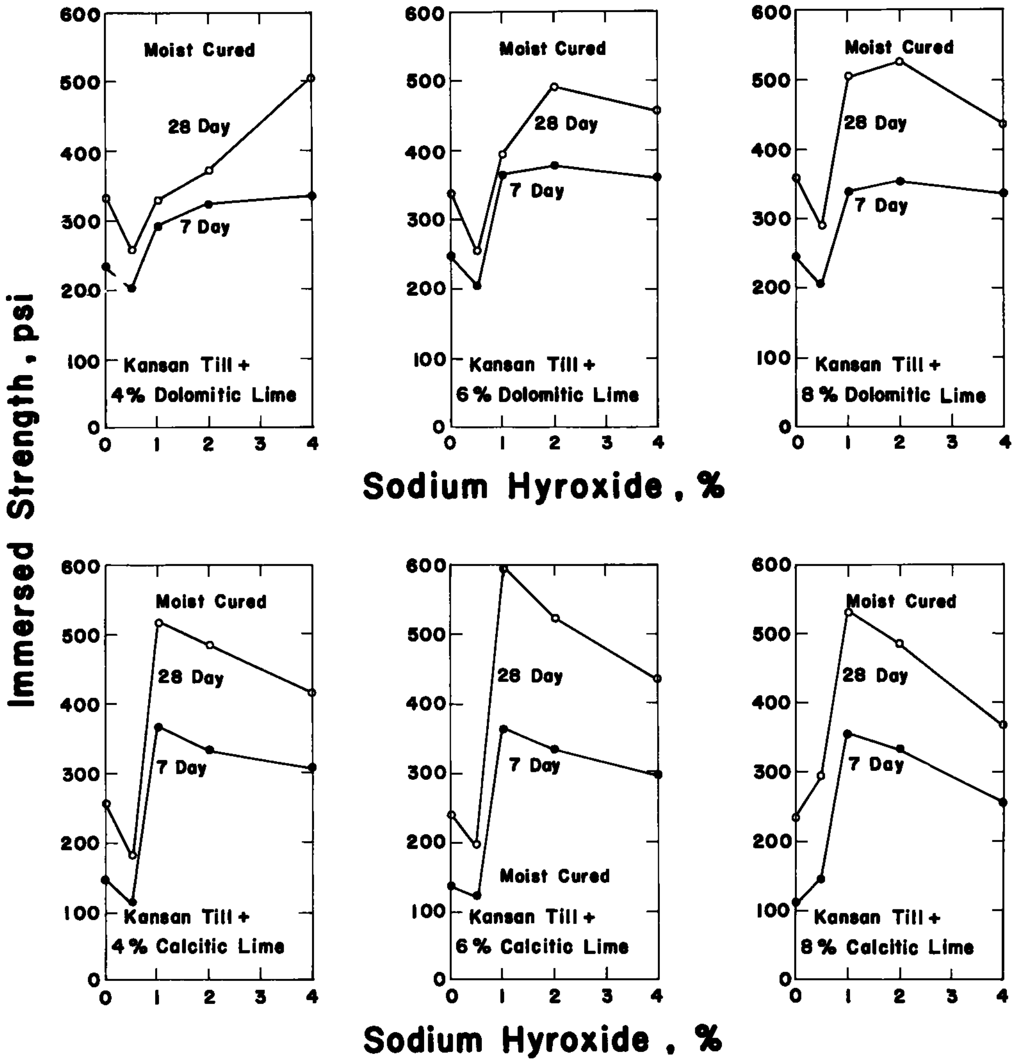

Figure 4. Immersed strength-sodium hydroxide content relationships for dolomitic lime-treated and calcitic lime-treated Kansan till.

give equivalent performance, although no data are shown for 10 percent dolomitic lime.

Kansan Gumbotil. —The optimum amount of sodium hydroxide for each Kansan gumbotil-lime mixture (Fig. 6) greatly improved 7 day cured immersed strength, and, in the case of the calcitic lime mixtures, also 28 day strength. The 28 day strengths of the dolomitic lime mixtures did not show such marked improvements. For example, 2 percent sodium hydroxide increased the 7 and 28 day strengths of the 8 percent calcitic lime-treated mix-

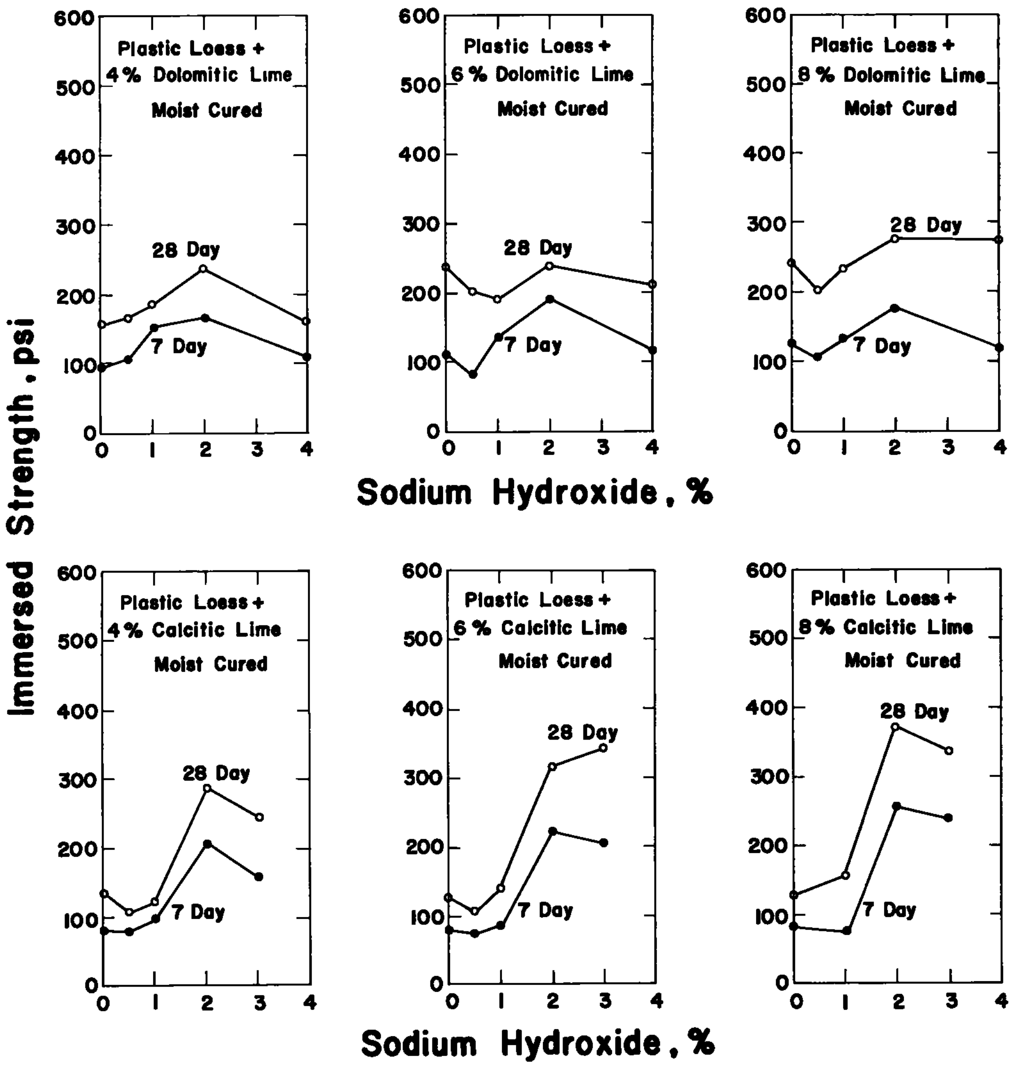

Figure 5. Immersed strength-sodium hydroxide content relationships for dolomitic lime-treated and calcitic lime-treated plastic loess.

ture from 155 and 271 psi to 348 and 421 psi, respectively, and the same amount of chemical increased the 7 and 28 day strengths of the 8 percent dolomitic lime-treated mixture from 211 and 382 psi to 324 and 390 psi, respectively. Satisfactory mix designs for road base courses might be with: 8 percent dolomitic lime, 6 or 8 percent dolomitic lime plus 2 percent NaOH, 6 or 8 percent calcitic lime plus 2 percent NaOH.

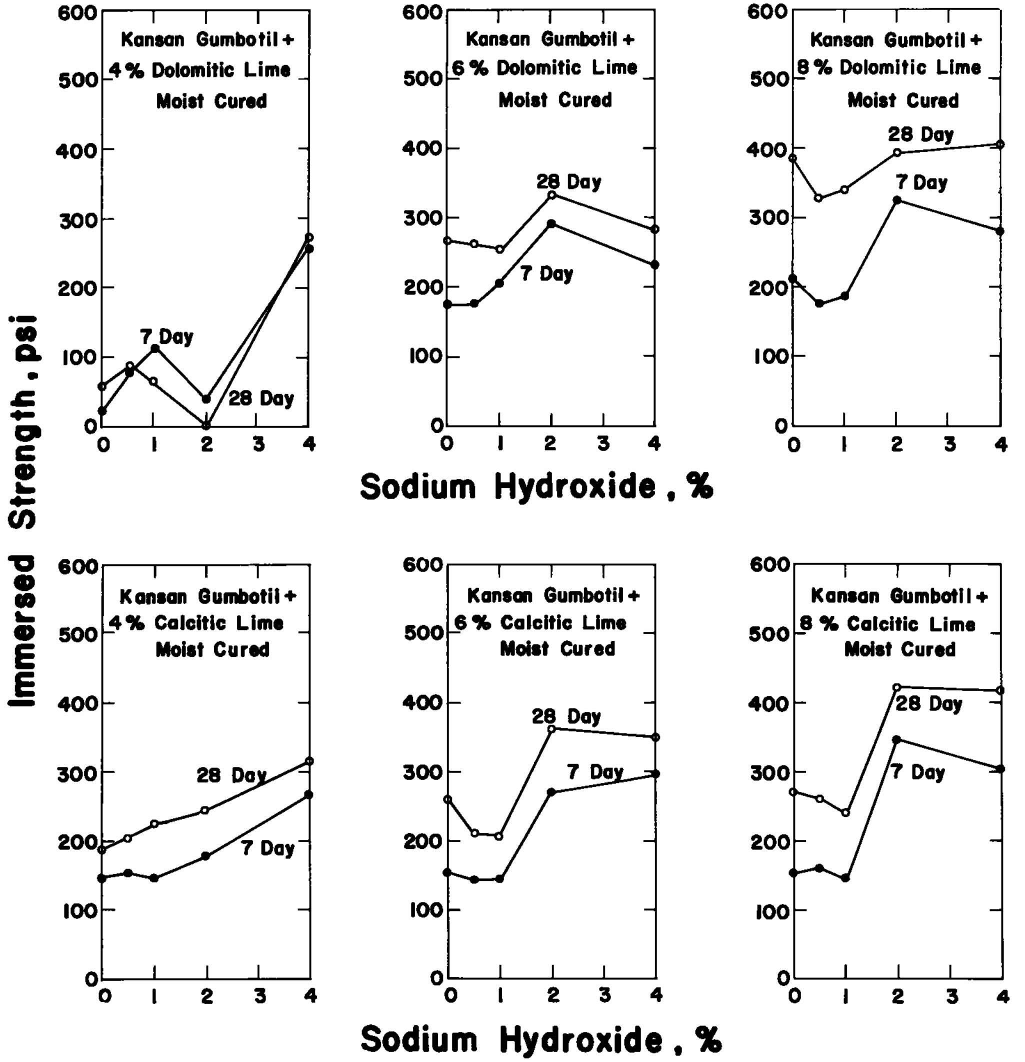

Figure 6. Immersed strength-sodium hydroxide content relationships for dolomitic lime-treated and calcitic lime-treated Kansan gumbotil.

Summary—Sodium Hydroxide.—Sodium hydroxide may be the much need chemical activator for pozzolanic reactions in clayey soil-lime mixtures. The clayey soils used in the tests contained montmorillonite as the dominant clay mineral (Table 2), and hence represent about as difficult materials to stabilize as will be found anywhere. Work now in progress will show whether combination treatments of lime and sodium hydroxide are equally beneficial to soils dominated by other clay materials.

The test data indicate that most montmorillonitic clay soils can probably be stabilized satisfactorily with lime and sodium hydroxide to meet minimum road base course strength requirements. Apparently the amounts of lime and chemical needed vary only slightly with the amount of clay in the soil, because the clay (0.005 mm) contents of the soils used in the tests covered a wide range (38.5 to 70.5 percent), and best immersed strengths generally were obtained with 6 or 8 percent lime and 1 or 2 percent NaOH. Lime contents higher than 8 percent were not tried, but they may give added strength to soils such as plastic loess and Kansan gumbotil. The exceptional response of the Kansan till to lime-NaOH treatments may be related to its gradation: approximately equal parts by weight of sand, silt and clay sizes. Plastic loess, with approximately the same amount of clay as Kansan till, but no sand, was improved to a considerably lesser extent by the same treatments.

A most encouraging finding was that sodium hydroxide made the calcitic hydrated lime equally or more reactive than the dolomitic monohydrate (Type N) lime with the clayey soils. It is hoped that further study will confirm that sodium hydroxide is an equalizer for hydrated limes in soil stabilization, thus eliminating the need for specifying dolomitic monohydrate (Type N) lime for base course stabilization in Iowa.

Effect of Curing Temperature on Immersed Strength

The following four treatments of Kansan till were selected for the immersed strength-curing temperature relationship study: 6 percent dolomitic lime, 6 percent calcitic lime, 6 percent calcitic lime plus 2.25 percent sodium carbonate, 6 percent calcitic lime plus 1 percent sodium hydroxide. Specimens of these mixtures were cured at 50, 70, 100 and 140 F for 3, 7, 14 and 28 days. Cured specimens were immersed for 24 hr, then tested for unconfined compressive strength. The test results are shown two ways in Figure 7, immersed strength versus curing time for each temperature, and immersed strength versus curing temperature for each time.

Kansan Till Plus 6 Percent Dolomitic Lime.—At each curing temperature, immersed strength increased with curing time up to 14 days; thereafter except at 50 F, the rate of increase was less. At 140 F, 28 day strength was less than 14 day strength. The greatest rate of strength gain up to 28 days was at 100 F; the immersed strength increased from 300 psi at 2 days to over 600 psi at 28 days. The least change of strength was at 140 F; at this temperature the soil-lime reaction may have been nearly completed at 2 days.

It appears that for emergency mix design purposes, accelerated curing for 3 or 7 days at 140 F could be used to obtain a fairly accurate estimate of immersed strength after 28 days curing at 100 F. Similarly, 3 days curing at 100 F was comparable with 28 days curing at 70 F.

The plots of immersed strength versus curing temperature further illustrate the beneficial effect of high temperature curing on strength after each curing period. At 7 days, where the relationship was nearly linear, the increase in immersed strength per degree Fahrenheit increase in curing temperature was roughly 6 psi. The effect of curing temperature on 14 and 28 day strengths, if anything, was even greater.

There would be little question of the adequacy of this mixture for a road base in regions having atmospheric temperatures of 100 F during the construction season; three days of such curing would probably suffice.

Kansan Till Plus 6 Percent Calcitic Lime.—The results of tests with this mixture may explain why calcitic lime is considered satisfactory for soil-lime stabilization in southern climates, and why it may not be equally satisfactory for base course stabilization in the north. At curing temperature of 50 and 70 F, immersed strengths up to 28 days are too low for base courses, if the curing period is to be followed by freeze-thaw cycles. At 100 F the hardening mechanism was tremendously accelerated, and immersed strength increased from about 140 psi at 3 days to about 750 psi at 28 days, adequate for base courses in any climate. At 140 F the hardening was about completed at 7 days, and the immersed strength was over 1,000 psi.

Indications are that for speedy mix design the immersed strength after 3 days curing at 140 F could be used to predict immersed strength after 28 days curing at 100 F.

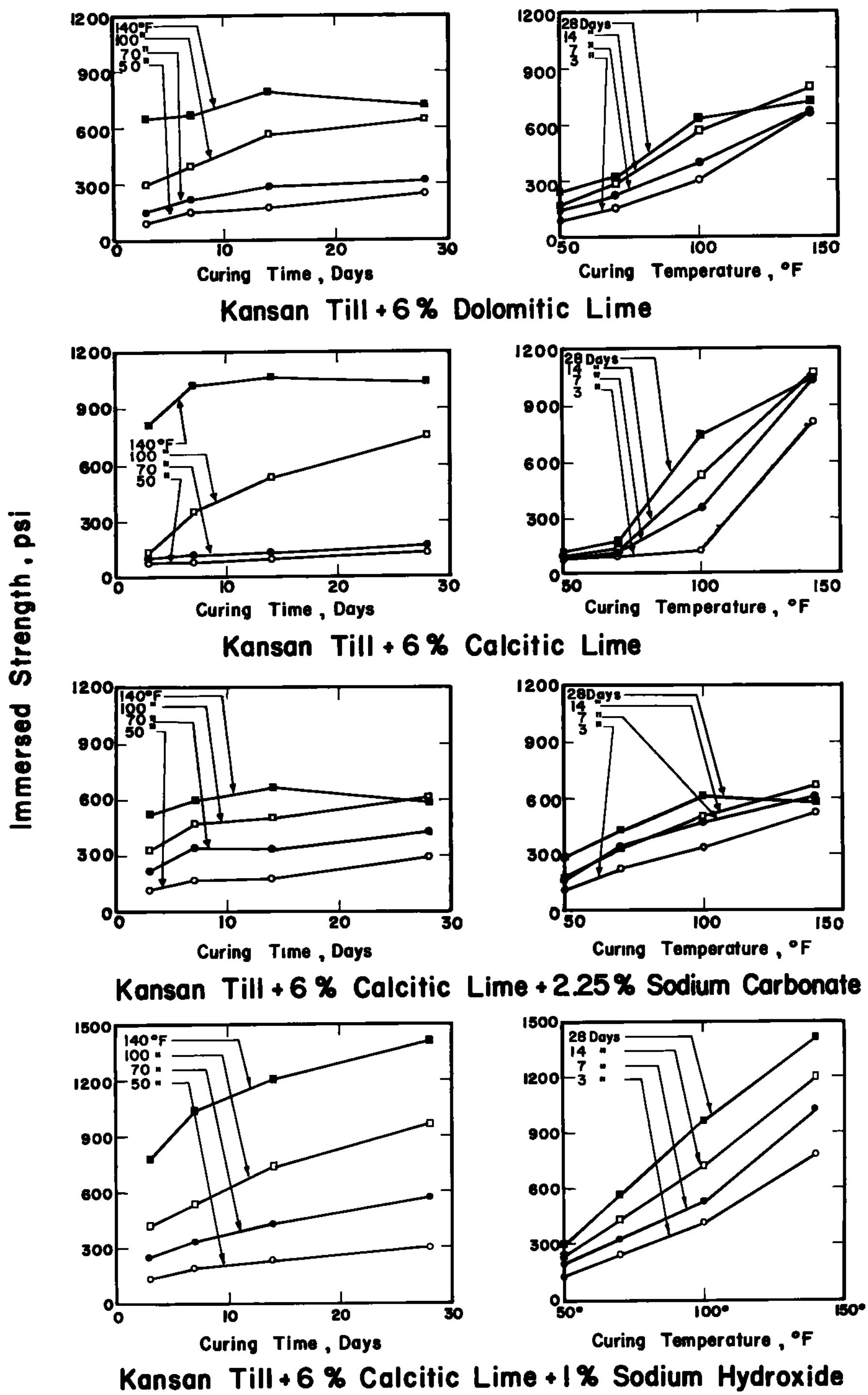

Figure 7. Immersed strength-curing temperature and curing time relationships for Kansan till treated with 6 percent dolomitic lime, 6 percent calcitic lime, plus 2.25 percent sodium carbonate, or 6 percent calcitic lime plus 1 percent sodium hydroxide.

Also, 3 day strength at 100 F seems indicative of 28 day strength at 70 F.

The immersed strength versus curing temperature curves also illustrate the great benefit to strength gain of curing temperatues above 70 F. Fourteen days strength showed a linear relationship in the temperature range between 70 and 140 F; each degree Fahrenheit increase in temperature increased (14 day immersed) strength about 13 psi.

Kansan Till Plus 6 Percent Calcitic Lime and 2.25 Percent Sodium Carbonate.- A comparison of the plotted test data for this mixture of Kansan till plus 6 percent calcitic lime (0 percent sodium carbonate) indicates that use of the chemical additive would be worthwhile only when early strength up to 3 days is of paramount importance, or when curing would be at temperatures around 50 F to 70 F. At 100 F curing there was little or no benefit to immersed strength, except at 3 days, from use of the chemical, and at 140 F the chemical additive was definitely detrimental to strength at all ages. It appears that either high temperatures or sodium carbonate can accelerate the pozzolanic reactions. Of the two, high temperature is more effective.

Kansan Till Plus 6 Percent Calcitic Lime and 1 Percent Sodium Hydroxide.—This mixture showed exceptionally good immersed strength gains with increase of curing at 50 F from 137 psi at 3 days to 297 psi at 28 days; at 70 F, this increase was from 250 psi to 567 psi; at 100 F, this increase was from 418 psi to 960 psi; at 140 F, this increase was from 780 psi to 1,426 psi. It is of interest to note that 7 day strength at 140 F is approximately equal to 28 day strength at 100 F; and that 7 day strength at 100 F is approximately equal to 28 day strength at 70 F.

The immersed strength versus curing temperature relationship was nearly linear for each curing period. For 7 and 28 day curing, each degree Fahrenheit increase of temperature increased immersed strength about 10 and 13 psi, respectively.

Comparison of the strength data for Kansan till plus 6 percent calcitic lime with and without sodium hydroxide treatment, indicates that inasmuch as both heat and sodium hydroxide benefit the hardening mechanism, the sodium hydroxide treatment would be advantageous for base course construction in any climate, but particularly so in warm climates, where appreciable reductions in lime content might be made possible.

Summary—Curing Temperature.—High temperature curing greatly accelerated the hardening mechanism of Kansan till stabilized with 6 percent of either dolomitic monohydrate (Type N) lime or calcitic hydrated lime. At 100 F, both mixtures gave immersed strengths which exceeded 300 and 600 psi after 7 day and 28 day curing, respectively.

The 2.25 percent additive of sodium carbonate to the Kansan till-calcitic lime mixture accelerated hardening at curing temperatures of 50 and 70 F; but at 100 F curing the chemical was beneficial only to 3 and 7 day strengths; and at 140 F curing the chemical greatly nullified the beneficial effect of heat on strength at all periods up to 28 days. The adverse effects of sodium carbonate on strength may have been due to heat-induced swelling, and consequent weakening by disruptive internal pressures.

The addition of 1 percent sodium hyroxide to the Kansan till-6 percent calcitic lime mixture acted as an excellent accelerator for the hardening mechanism, both at normal and high curing temperatures. Thus its beneficial effects were in addition to those due to heat, a desirable trait in a chemical accelerator.

Durability of Lime, or Lime and Chemical-Treated Kansan Till

The four mixtures used to study immersed strength-curing temperature relationships were further evaluated by the modified British freeze-thaw test (11). The control and freeze-thaw specimens of each mixture were moist cured 7 days at 50, 70, 100, or 140 F prior to evaluation. Cured control specimens were immersed in distilled water for 15 days, then tested for unconfined compressive strength (p_c). Cured freeze-thaw specimens were immersed for 1 day, subjected to 14 freeze-thaw cycles (14 days), then tested for unconfined compressive strength (p_f). Test results and the calculated indices of the resistance to the effect of freezing (R_f) are given in Table 4.

TABLE 4

RESULTS OF FREEZE-THAW TESTS BY MODIFIED BRITISH METHOD, B.S. 1924: 1957

Additive (s)	As-molded Density (pcf)	Curing Temperature (7 days), deg F	p_f (psi)	p_c (psi)	R_f[1] (%)
6% Dolomitic mono-					
hydrate	107.5	50	177	277	65
(Type N) lime	107.5	70	235	254	90
	107.5	100	367	392	95
	107.5	140	617	653	95
6% Calcitic hydrated					
lime	106.2	50	109	138	80
	106.2	70	103	122	85
	106.2	100	277	289	95
	106.2	140	798	974	80
6% Calcitic hydrated	107.0	50	225	351	65
lime plus 2.25 %	107.0	70	322	418	75
sodium carbonate	107.0	100	421	472	90
	107.0	140	650	597	110
6% Calcitic hydrated	110.2	50	212	357	60
lime plus 1%	110.2	70	341	420	80
sodium hydroxide	110.2	100	449	599	75
	110.2	140	981	828	120

[1] $R_f = \frac{100 p_f}{p_c}$ reported to nearest 5 percent.

Criteria of Durability.—The criteria which may be used to evaluate the results of the modified British freeze-thaw test are: (1) the R_f value should equal or exceed a specified value, (2) the individual p_f and p_c values should equal or exceed a specified value. The following minimum values appear to be conservative for the design of stabilized mixtures for road base courses in climates such as that in Iowa: R_f = 80 percent, p_c = 250 psi, p_f = 250 psi. A discussion of these criteria may be found in reference (11). When both p_c and p_f values greatly exceed 250 psi, a lower minimum R_f may be permissible, for example, 75 percent as used in England.

Interpretation of Test Results.—High temperature curing improved the freeze-thaw resistance of specimens of the Kansan till-6 percent dolomitic lime mixture, and those cured at 100 and 140 F showed satisfactory durability. The specimens cured at 70 F were indicative of marginal quality for road bases, and those cured at 50 F failed to meet the recommended minimum durability values. Thus a road base of this mixture should have some hot weather curing before undergoing wintering in Iowa, and completion of construction in August, at the latest, would be recommended.

If the mixture of Kansan till and 6 percent calcitic lime is judged on the basis of test results after 50 or 70 F curing, it does not meet base course requirements. However specimens cured at 100 or 140 F proved more than adequate, indicating that this mixture might make a satisfactory road base in warm climate.

For northern climates where temperatures of 70 F or higher prevail during the construction season, the test results in Table 4 indicate that the Kansan till-6 percent calcitic lime mixture could be brought up to base course quality by the addition of either 2.25 percent sodium carbonate or 1 percent sodium hydroxide. Of the two chemical accelerators, sodium hydroxide would permit the greatest flexibility in construction planning and the longest construction season.

Summary—Durability.—The durability test data for Kansan till indicate that, whereas dolomitic monohydrate (Type N) lime stabilization may give adequate durability for road bases in Iowa, calcitic hydrated lime stabilization may not, unless a chemical accelerator is used. Sodium hydroxide appears especially promising for this purpose.

CONCLUSIONS

1. Addition of a small amount of sodium hydroxide to mixtures of montmorillonitic clay soil and lime acts as an effective accelerator for the hardening mechanism of the compacted mixture. The optimum sodium hydroxide treatment is about 1 to 2 percent, based on the dry weight of the soil component.
2. Sodium carbonate and sodium phospate are not as promising as sodium hydroxide for improving lime stabilization of montmorillonitic clay soils, particularly when the lime is dolomitic monohydrate (Type N).
3. The magnitude of strength improvement up to 28 days, due to the use of sodium hydroxide, varies with the composition of the lime and the clay soil; calcitic (high-calcium) hydrated lime may give somewhat better results than dolomitic monohydrate (Type N) lime, but the presence of sand-size quartz in the soil is definitely beneficial.
4. Heat also accelerates the hardening of compacted mixtures of montmorillonitic clay soil and lime, and temperatures around 100 F or higher during the early curing period are extremely beneficial to strength and durability, the beneficial effects apparently supplementing those obtainable from the use of sodium hydroxide as an additive.
5. Dolomitic monohydrate (Type N) lime should be used for lime stabilization of montmorillonitic clay soils for road base courses in Iowa or regions of similar or more severe climate, unless an additive of sodium hydroxide is specified; in which case, either the dolomitic lime or a calcitic hydrated lime may be used. In Iowa, without sodium hydroxide additive, calcitic lime appears satisfactory only for subbase or subgrade stabilization.

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