

# Lime and Sodium Silicate Stabilization of Montmorillonite Clay Soil

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The results and interpretations of a laboratory soil stabilization investigation of combination lime and sodium silicate treatments of a montmorillonite-rich clay soil are presented. Five kinds of powdered sodium silicate were evaluated in mixtures with the soil and a calcitic hydrated lime. Mixtures with sodium sesquisilicate pentahydrate appeared least affected by elapsed time between mixing and compaction. Hence this sodium silicate was selected for studies of the effect of lime and sodium silicate mix proportions on immersed strength versus curing time and on freeze-thaw resistance.

● IN THE DEVELOPMENT of simple, economical methods of soil stabilization for use in Iowa, many chemicals and combinations of chemicals have been evaluated as stabilizing agents. This report covers an investigation of the stabilization of a clayey soil with lime and sodium silicate.

Sodium silicate and calcium chloride have long been combined as a grout to seal foundations and tunnels, but the use of this mixture in stabilizing base and subbase courses of pavements has not been very successful. However, combinations of lime and sodium silicate have given satisfactory laboratory results. This prior investigation suggested that the soil-lime-sodium silicate reaction was such that the final strength of the stabilized soil depended on the elapsed time between the mixing of the soil-lime-sodium silicate-water combination and the final compaction of the mixture (6). In field construction of base and subbase courses, several hours may elapse between the final mixing of the soil and the stabilizing agents and completion of compaction. It is of course desirable for this delay to have little or no effect on the strength of the stabilized soil.

The investigation presented in this report was conducted to determine the use of lime and sodium silicate for stabilizing a clayey soil for use as a base or subbase course of a flexible pavement, as follows:

1. The effect of elapsed time between mixing and molding on the strength and dry density of the soil treated with calcitic hydrated lime and various sodium silicates.
2. The 7-day cured strengths of the soil treated with varying percentages of calcitic hydrated lime and the sodium silicate whose strength is least affected by elapsed time.
3. The effect of curing time on the strength of the stabilized soil.
4. The resistance of the stabilized soil to freeze-thaw action.

## REVIEW OF LITERATURE

### Materials

Sodium silicate is a chemical compound manufactured by melting soda ash and selected silica sand ( $\text{SiO}_2$ ) together at high temperatures. The resulting product is a water soluble glass. This glass is ground into various sized particles for different uses. (Fifteen different solid sodium silicates are manufactured by one company alone.) These sodium silicates vary in alkali-silica ratio, water content and particle size, depending on their proposed use. Sodium silicates are used as detergents, deflocculating agents,

films and coatings, sizing, corrosion control agents, bleaching agents, adhesives, and cements (13).

Lime is strictly defined as CaO, but the term is commonly used to include quicklime and hydrated lime. These are oxides and hydroxides of calcium and calcium-magnesium. Commercial lime is manufactured by heating a crushed carbonate rock such as limestone, CaCO<sub>3</sub>, causing a release of CO<sub>2</sub> and leaving a calcitic (high-calcium) lime or CaO. Another type of carbonate rock called dolomite is also used for lime manufacture. Because dolomitic rocks have various ratios of CaCO<sub>3</sub> and MgCO<sub>3</sub>, the resulting lime, called dolomitic lime, is a mixture of CaO and MgO. Quicklime is another term for lime composed of calcium or calcium and magnesium oxides. Quicklime reacts readily with water to produce slaked lime or hydrated lime, in which all the CaO is converted to Ca(OH)<sub>2</sub>. The MgO of dolomitic quicklime hydrates less rapidly, and in normal hydration processes most of the magnesium remains as MgO (11).

### Previous Investigations

Sodium silicate has been used to improve building materials for more than a century. Johann van Fuchs, a pioneer in the commercial development of soluble silicates, proposed in the early Nineteenth Century that soluble silicates could be used as a hardening agent for artificial stone. He also recognized the reaction of silicates with calcium compounds. During the Nineteenth Century several patents were issued for the manufacture of artificial stones from solutions of silicates mixed with solutions of calcium compounds (20).

As early as 1910, sodium silicate is mentioned as being used as a dust palliative. The application of a solution of sodium silicate followed by an application of a soluble aluminum or calcium salt causes the precipitation of an aluminum or calcium silicate in place on the road stone (10). This led to the development of macadam roads in which the crushed stone was held in place by a cementitious matrix formed by a slurry of finely divided limestone and sodium silicate (9, 15, 20).

Around 1915, Albert Francois, a French engineer, found that the effectiveness of cement grout could be increased by preceding the grout with an injection of alum followed by sodium silicate. Apparently the resulting slippery gel (a colloidal solution of a liquid in a solid (8)) coats the granular surfaces and causes greater penetration of the cement grout (20). Later, a Dutch engineer, Jugo Joosten, injected sodium silicate as a grout into deep foundations followed by an injection of calcium chloride (16). The combination of these two chemicals forms an insoluble gel which fills the voids and prevents seepage of water or the continuance of any settlement (20). This injection method with modifications has been extensively used in foundation work and in controlling seepage, but the method is not practical in solidifying the soil within 3 ft of the surface (17). Another injection method, in which the precipitation reaction is much slower, uses a solution containing sodium silicate and sodium bicarbonate. The gel formed is not the insoluble calcium silicate and gradually deteriorates; it does not have the strength of the calcium silicate gel (14).

Sodium silicate alone was investigated as a stabilizer for various soils. The investigators came to the conclusion that although sodium silicates showed promise as stabilizing agents, the soil should be studied and evaluated prior to treatment, because some soils gave a negative response to the treatment (12).

Investigations of soil stabilization at Iowa State University indicate that combinations of sodium silicate and lime show promise, because the reaction is less rapid than that between sodium silicate and calcium chloride. The chemical reaction produces sodium hydroxide which has a desirable effect on soil stability. These incomplete investigations indicate that a wide range of soils from fine sands to montmorillonitic clay soils can be stabilized with lime and sodium silicate (7).

### Mechanism of Sodium Silicate Stabilization

The exact mechanism of sodium silicate soil stabilization is not known. Laws and Page (12) found that sodium silicate reacted with the clay minerals present in the soil, but they did not make a detailed study of the nature or possible mechanism of the assumed reaction.

Sodium silicate is used in soil stabilization mainly because it reacts with soluble calcium salts in water solutions to form insoluble, gelatinous calcium silicates (9). This reaction is advantageous, because water is necessary for the proper compaction of a soil to a desired density (9).

That hydrated calcium silicates are cementing agents has been fairly well established (5). Hydration, a process of a solid combining with water (8), is the essential mechanism of "setting" or hardening of a gel (19). The exact nature of the bonding action of hydrated calcium silicates has been the subject of much investigation, but it has not been fully explained. In addition to its cementing properties, the gelatinous calcium silicate improves the stability of the soil by filling voids, thereby excluding water from the soil. Excessive moisture in ordinary soil causes loss of strength and reduces the soil stability (9).

## PROPERTIES OF MATERIALS

### Soil

Kansan till, comprised of approximately equal portions of sand, silt and clay-sized materials, was the soil used throughout the investigation. This soil was chosen be-

TABLE 1  
SAMPLING LOCATION OF SOIL

Location:	SW <sup>1</sup> / <sub>4</sub> SE <sup>1</sup> / <sub>4</sub> of Section 23, Tier 68 North, Range 31 West, Benton Township, Ringgold County, Iowa
Geological description:	Kansan-age glacial till, plastic, calcareous
Soil series:	Shelby
Horizon:	C
Sampling depth:	4 <sup>1</sup> / <sub>2</sub> -10 <sup>1</sup> / <sub>2</sub> ft
Laboratory no.:	409-12C

cause it is considered an in-between soil; it is not the worst soil found in Iowa for road building, and it is not the best. Another reason for this choice was that some data on Kansan till had been collected in a previous investigation of lime-sodium silicate stabilization (6). The field location of the sample is given in Table 1, and physical and chemical properties are given in Table 2.

### Lime

Calcitic hydrated lime was the only lime used in the investigation, because calcitic hydrated lime gave better results than other types of limes (6).

The properties of the commercial grade lime used are given in Table 3.

### Sodium Silicates

Five powdered sodium silicates were used. These sodium silicates varied in molecular ratio of Na<sub>2</sub> to SiO<sub>2</sub> and in degree of hydration. By using sodium silicates that varied in these properties it was hoped that some indication of the influence of these variables on the final results would be obtained. Powdered sodium silicates were used because Ellis (6) had found that adding the sodium silicate in a liquid form caused the soil-lime-sodium silicate mixture to set up or solidify too rapidly to permit proper molding of specimens.

The sodium metasilicate enneahydrate was an analytical grade reagent. The other four sodium silicates—sodium metasilicate pentahydrate, sodium metasilicate anhydrous, sodium sesquisilicate pentahydrate and sodium orthosilicate—were commercial grade sodium silicates. A general description of the sodium silicates is given in Table 4. The sodium silicates are identified by their laboratory designations.

TABLE 2  
PROPERTIES OF SOIL

Physical properties:	
Textural composition (% by wt):	
Gravel (above 2.0 mm)	0
Sand (2.0-0.074 mm)	33.9
Silt (0.074-0.005 mm)	27.6
Clay (below 0.005 mm)	39.5
Colloidal (below 0.001 mm)	29.0
Textural classification: <sup>a</sup>	Clay
Atterberg limits:	
Liquid limit, %	39.4
Plastic limit, %	16.5
Plasticity index, %	22.9
Shrinkage limit, %	8.2
Engineering classification: <sup>b</sup>	A-7-6(11)
Predominant clay mineral: <sup>c</sup>	Montmorillonite
Chemical properties:	
Cation exchange capacity (whole soil) me/100 gm	29.46
pH	8.0
Carbonates, %	6.4
Organic matter, %	0.2

<sup>a</sup>By the triangular chart developed by the U. S. Bureau of Public Roads (18, p. 48): 0.074 mm was used as the lower limit of sand fraction.

<sup>b</sup>AASHO Method ML45-49 (1).

<sup>c</sup>Determined by X-ray analysis of the fraction passing the No. 200 sieve.

## METHOD OF PROCEDURE

### Preparation of Mixtures

The required amount of air dried soil passing the No. 10 sieve was dry mixed with the powdered lime and sodium silicate additive for 2 min by a Hobart Model C-100 mixer modified by attaching a scraper blade to prevent the mixture from caking in the mixing bowl. Sufficient carbon dioxide-free distilled water was added to bring the mixture to the desired moisture content, and mixing was continued for 2 min. The mixture was then hand mixed long enough to loosen any of the material stuck to the sides of the mixing container. Immediately after mixing, the mixture was placed in a covered container and allowed to age.

This order of mixing was chosen for the following reasons: In the field the probable method of mixing would be either to mix the lime with the soil, add the sodium silicate and remix, then add needed water and mix again; or to mix the lime and sodium silicate with the soil and then add the water and remix. Because the latter method seemed to be the simplest and most likely to be employed in the field, it was chosen for this investigation. The water was not added until the lime and sodium silicate were thoroughly mixed with the soil so that the best possible

TABLE 3  
PROPERTIES OF LIME

Chemical analysis, (% by wt):	
Silicon dioxide	0.28
Iron and aluminum oxide	0.6
Magnesium oxide	0.59
Sulfur trioxide	0.25
Carbon dioxide	N. D. <sup>a</sup>
Total calcium oxide	73.82
Available calcium oxide	70.3
Loss on ignition	24.1
Combined H <sub>2</sub> O	N. D. <sup>a</sup>

<sup>a</sup>Not determined.

distribution of reaction products would be obtained. Carbon dioxide-free distilled water was used to reduce the number of variables involved in the investigation. The mixture was aged in a covered container to prevent evaporation of moisture and to prevent the lime from reacting with the carbon dioxide in the air.

TABLE 4  
PROPERTIES OF SODIUM SILICATES

Laboratory Designation	Trade Name	Chemical Name and Formula	Molecular Ratio Na <sub>2</sub> O:SiO <sub>2</sub>	H <sub>2</sub> O (%)	Na <sub>2</sub> O (%)	SiO <sub>2</sub> (%)
Silicate A	Reagent	Sodium meta-silicate enneahydrate Na <sub>2</sub> SiO <sub>3</sub> · 9H <sub>2</sub> O	1:1	57.1	21.8	21.1
Silicate B <sup>a</sup>	Metso Anhydrous	Sodium meta-silicate anhydrous Na <sub>2</sub> SiO <sub>3</sub>	1:1	0.5	51.0	45.5
Silicate C <sup>a</sup>	Metso Granular	Sodium meta-silicate pentahydrate Na <sub>2</sub> SiO <sub>3</sub> · 5H <sub>2</sub> O	1:1	41.7	29.5	28.7
Silicate D <sup>a</sup>	Metso 99	Sodium sesqui-silicate pentahydrate Na <sub>3</sub> HSiO <sub>4</sub> · 5H <sub>2</sub> O	3:2	38.1	36.7	24.2
Silicate E <sup>a</sup>	Metso 200	Sodium ortho-silicate concentrated Na <sub>4</sub> SiO <sub>4</sub>	2:1	9.5	60.8	27.5

<sup>a</sup>Data from Philadelphia Quartz Company, Philadelphia, Pennsylvania.

All additive percentages used in this study are based on the weight of oven dry soil. Moisture contents are based on the weight of the oven dry treated soil.

#### Molding of Specimens

After being aged the mixture was molded into cylindrical-shaped specimens, 2 in. high and 2 in. in diameter, with a density near AASHTO density (AASHTO Method T99-57) (2). The molding method used is described in detail by Davidson and Bruns (4).

#### Curing of Specimens

Specimens made for the strength vs aging time study, and for the best lime-sodium silicate mixture study were cured for 7 days in a moist curing room. The relative humidity in the room was 95 percent or higher; the temperature was maintained at 75 ± 5 F. After being molded and before being placed in the curing room, each specimen was sealed in wax paper to reduce evaporation of moisture and to prevent carbon dioxide of the air from reacting with the lime during curing. Specimens for the strength vs curing time study were cured for 3, 7 and 28 days.

#### Strength Testing

All specimens except those specifically designated were immersed in distilled water for 24 hr after curing and before being tested for strength. The immersion reduces or destroys any apparent cohesion in the soil and tests the true cohesion and other stabil-

izing effects of the soil-lime-sodium silicate mixture. Strengths were measured by unconfined compression testing. The rate of loading was 0.1 in. per min. The maximum load causing failure was considered the compressive strength of the specimen. All of the unconfined compressive strengths were maintained within 10 percent of the average values as required by ASTM Designation: C109-54T (3), or tests were repeated.

### Freeze-Thaw Testing

A modified British freeze-thaw test was used to evaluate the resistance of selected mixtures to the seasonal influence of freezing and thawing. Five specimens from each mixture were molded and cured for 7 days, then immersed in distilled water at room temperature for 24 hr. Three specimens from each mixture were then tested for unconfined compressive strength; one specimen was left immersed for 14 more days; and the last specimen was exposed alternately to temperatures of -5 C and 25 C for 14 cycles, each cycle lasting 24 hr. After these 14-day treatments the freeze-thaw specimen and the immersed specimen were tested for unconfined compressive strength. A comparison of these values was used to determine the ability of the lime-sodium silicate stabilized soil to resist freezing and thawing. The details of this test are given by Davidson and Bruns (4).

## PRESENTATION AND DISCUSSION OF TEST RESULTS

### Effect of Aging Time on Dry Density and Strength

This phase of the investigation had two purposes. The first was to determine the effect of aging time, defined as the elapsed time between mixing and molding, on the strength and dry density of specimens of soil treated with calcitic hydrated lime and each of the sodium silicates. The second was to determine which sodium silicate gave the highest strength and/or was least affected by aging time.

To accomplish these objectives the number of variables affecting the results were reduced to a minimum. Previous laboratory work with lime-sodium silicate soil stabilization indicated that the elapsed time between the addition of water to the soil-lime-sodium silicate mixture and the completion of molding greatly affected the density of the specimen, and suggested that strength might likewise be affected. It was also found that the lime-sodium silicate combination that gave the best results in stabilizing Kansan till was 6 percent calcitic hydrated lime and 6 percent sodium metasilicate pentahydrate (6). Because the aqueous portion of the sodium silicate does not react with the lime, although it does affect the reaction, it was decided to compare the effectiveness of the sodium silicates on an equivalent anhydrous weight basis. Therefore, combinations of 6 percent lime and an amount of each sodium silicate, such that the anhydrous portion was equal in weight to the anhydrous portion of 6 percent sodium metasilicate pentahydrate, were used in the study.

The aging time was the time, recorded to the nearest minute, between the addition of water to the dry soil-lime-sodium silicate mixture and the final compaction of the specimen. Specimens with aging times of approximately 9 min and 1, 2, 3, and 5 hr were molded. The specimens were weighed and measured immediately after molding. At the same time, samples were taken from the mixture to determine the molding moisture content of the specimen. This molding moisture content includes the water present in the sodium silicate as well as the water added. The dry density of the specimen at the time of molding was calculated from the equation:

$$\text{Dry density} = \frac{1.2125 \times \text{weight of specimen}}{(1 + \text{moisture content}) \times \text{height of specimen}}$$

To determine the influence of molding moisture content on the effect of aging time on strength and dry density, the soil-lime-sodium silicate mixtures were molded at various moisture contents. The optimum moisture content for near 100 percent Standard AASHTO dry density of Kansan till stabilized with 6 percent calcitic hydrated lime was found to be 17.0 percent. For the soil-lime-sodium silicate mixtures with each of

the sodium silicates, it was originally planned to use five different molding moisture contents; two below this optimum for the soil-lime mixture and three above this optimum. These planned moisture contents were 13, 15, 17, 19 and 21 percent. The amount of water needed to reach these molding moisture contents was calculated; however, because the chemical reaction between the lime and sodium silicate differed for each sodium silicate, the actual molding moisture contents differed from the planned molding moisture contents by varying amounts.

The specimens after being molded were moist cured for 7 days and then were immersed in distilled water for 24 hr before they were tested for ultimate unconfined compressive strength. Unless otherwise stated, the term strength when used in this report means unconfined compressive strength after 24-hr immersion.

### Discussion

Specimens of Kansan till stabilized with 6 percent calcitic hydrated lime and varying amounts of sodium silicates were molded. The anhydrous portion of 6 percent sodium metasilicate pentahydrate used was equal in weight to the anhydrous portion of each of the other silicates used. This was done as a control. Different molding moisture contents change the effect of aging on dry densities (Fig. 1). The percentages of the different sodium silicates are based on the weight of the sodium silicate in its normal state of hydration. The points are the average of three specimens, molded at as nearly the same time as possible, plotted at the average aging time of the specimens. The molding moisture content shown is the range of the molding moisture contents of the specimens molded at the five different aging times.

In all except one of the soil-lime-sodium silicate-water mixtures, the highest dry densities were obtained at aging times near zero (Fig. 1). This one mixture showed a higher dry density after 2 hr of aging than at shorter aging times; however, this density was so close to the dry densities of the same mixture with greater and lesser aging times that it seems safe to consider that the discrepancy is due to experimental error. As the aging time increased, the dry density of the specimens molded from all the mixtures decreased, thus confirming the indications of the previous Iowa State work (6).

The molding moisture content influenced dry density, but the molding moisture content that gives highest dry density at the shortest aging time does not usually give highest dry density at the longest aging time. This indicates that the optimum moisture content for maximum dry density varies with aging period.

An explanation of the dependence of dry density and optimum moisture content for maximum dry density on aging time is related to the chemical reaction between lime and sodium silicate. As water comes in contact with lime and sodium silicate, the chemicals dissolve and then react to form an insoluble calcium silicate gel. Inasmuch as lime is slowly soluble, the quantity of gel formed is gradually increased as the reaction between the lime and sodium silicate continues. The gel absorbs water and at the same time begins to hydrate. As the gel hydrates, it hardens. The longer this process continues, the more gel is converted into a hydrated calcium silicate.

Both the processes of gel formation and hydration remove free water from the mixture. This free water is necessary to act as a lubricant for the compaction process (9). The gel may possibly act as a lubricant in place of the absorbed water, but further investigation is necessary to determine this. The change in the amount of lubricant present may account for the change in optimum moisture content for maximum dry density.

As the gel hydrates the character of the soil changes because the hydrated gel is cementing soil particles together, thus changing the effective gradation of the mixture and increasing its resistance to the compaction force. This not only affects the optimum moisture content for maximum dry density but it affects the maximum dry density itself. Because the amount of compactive effort applied in the standard density test is held constant, an increase in soil resistance to compaction will cause a decrease in density. The foregoing seems to be an explanation for the dependence of dry density and optimum moisture content for maximum dry density on aging time.

The type of sodium silicate also influenced dry density and the amount of decrease

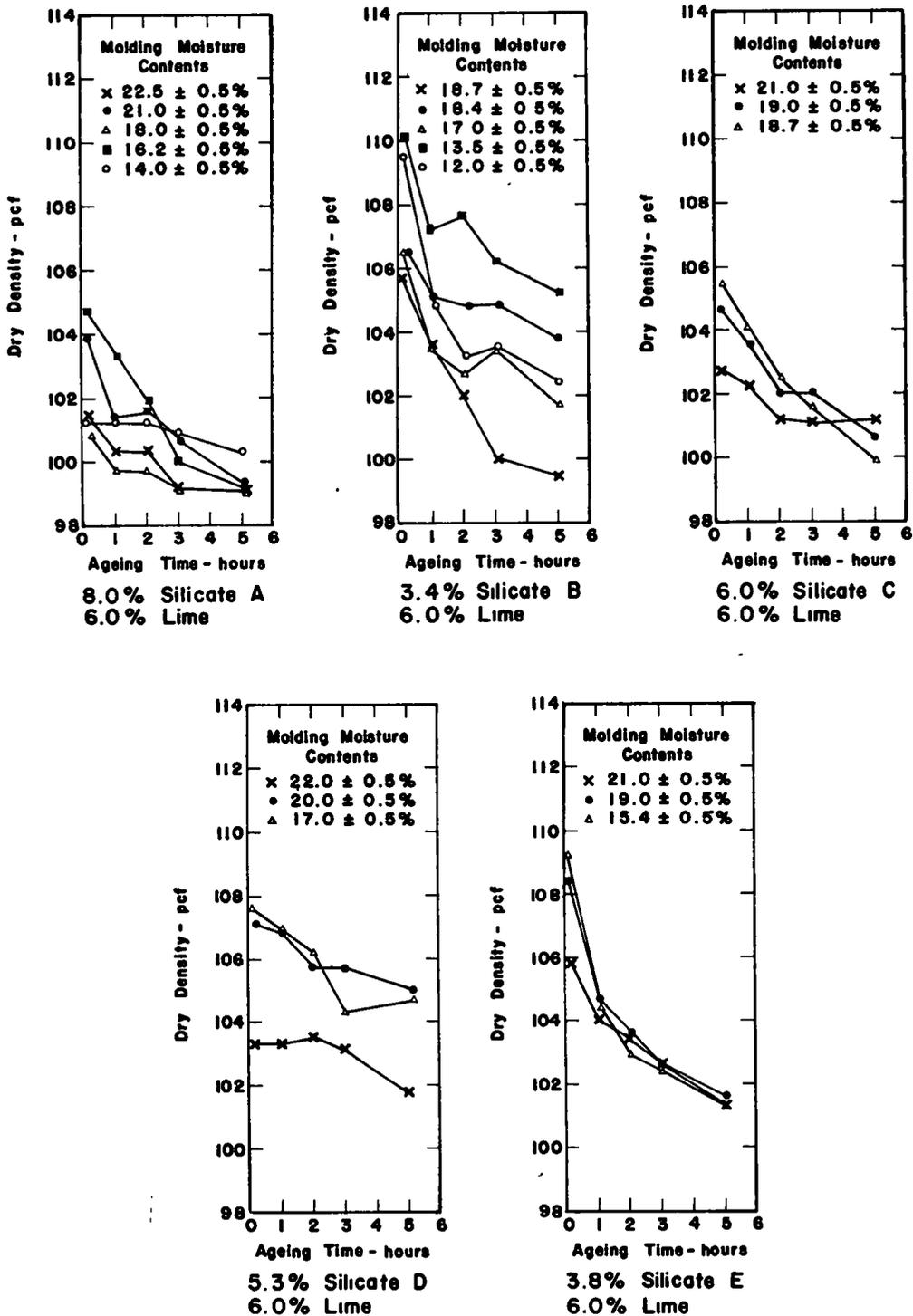


Figure 1. Influence of molding moisture content on the effect of aging time on dry density at time of molding Kansan till stabilized with 6 percent calcitic hydrated lime and indicated percentages of various sodium silicates.

in dry density with aging time. Highest dry densities were obtained with Silicates B and E. But mixtures with these silicates also had the greatest decrease in dry density with increase in aging time (Fig. 1). Silicates A and C gave the lowest dry densities, and they had a smaller decrease in dry density with increase in aging time. The dry densities achieved by Silicate D mixtures were between those of the other two groups, and the decrease in dry density with aging time appeared to be smallest.

The explanation of this possibly is related to the gel-forming ability of the different sodium silicates. In the explanation given earlier for the dependence of dry density on aging time, emphasis was placed on the controlling function of the amount of gel present. A difference in the rate of gel formation by different sodium silicates would produce different rates of increase of dry density with aging time. A difference in the rate of gel formation might also account for the difference in dry densities obtained from the different sodium silicate mixtures.

**Strength.**—As was true with dry densities, different molding moisture contents change the effect of aging on strength (Fig. 2). The percentages of the different sodium silicates are based on the weight of the sodium silicate in its normal state of hydration. The points are the average of three specimens, molded at as nearly the same time as possible, plotted at the average aging time of the specimens. The molding moisture contents shown are the range of the molding moisture contents of the specimens molded at the five different molding times.

It is difficult to make any general statements about the effect of aging time on strength that would apply to all of the soil-lime-sodium silicate mixtures. Each mixture was affected differently by water content and aging time (Fig. 2).

Mixtures made with Silicate A showed a decrease in strength with an increase in aging time. The mixtures with the highest and lowest molding moisture contents had strengths that were least affected by aging time. At an aging time of 5 hr, the Silicate A mixture with the highest molding moisture content had the highest strength.

Silicate B mixtures showed a more marked decrease of strength with aging time than Silicate A mixtures, but the strengths of the Silicate B mixtures in general were higher than those of the Silicate A mixtures molded at approximately the same moisture content. Silicate B mixtures could not be molded at moisture contents above 19.5 percent because the material solidified in the mixer.

Based on the results obtained with Silicate A and Silicate B, it was decided to evaluate the other sodium silicate mixtures at only the three highest moisture contents.

Silicate C mixtures also decreased in strength as aging time increased. Again the mixture with the highest molding moisture content showed the least effect of aging time on strength and had the highest strength with an aging time of 5 hr.

The molding moisture content had a strange effect on the strength of the Silicate D mixtures. At the lowest molding moisture content the Silicate D mixture behaved the same as the aforementioned silicate mixtures, but at the next higher molding moisture content the strength of the mixture increased between aging times of 0 and 1 hr and then decreased until at an aging time of 5 hr the strength was approximately the same as at an aging time of 0.25 hr. At the highest molding moisture content the mixture actually showed a gain in strength with an increase in aging time. However, the highest strength at an aging time of 5 hr was with the Silicate D mixture molded at the middle moisture content.

Silicate E mixture molded at the highest molding moisture content displayed the same characteristic as the Silicate D mixture molded at the middle molding moisture content. The other two molding moisture contents caused the strength of the mixture to decrease as the aging time increased. It is noteworthy that, at an aging time of 5 hr, the strength appears to be independent of molding moisture content.

The optimum moisture content for maximum strength changes with aging time and is not the same as the optimum moisture content for maximum dry density (Fig. 1 and 2). Strength is not correlated with dry density, which means that it is not possible to achieve a desired strength in the field by compacting the treated soil to a specified dry density. Nor is it possible to check field strengths by checking dry densities.

An explanation of the decrease in strength with increase in aging time may be given along the same line as the explanation for the decrease in dry density. If the amount

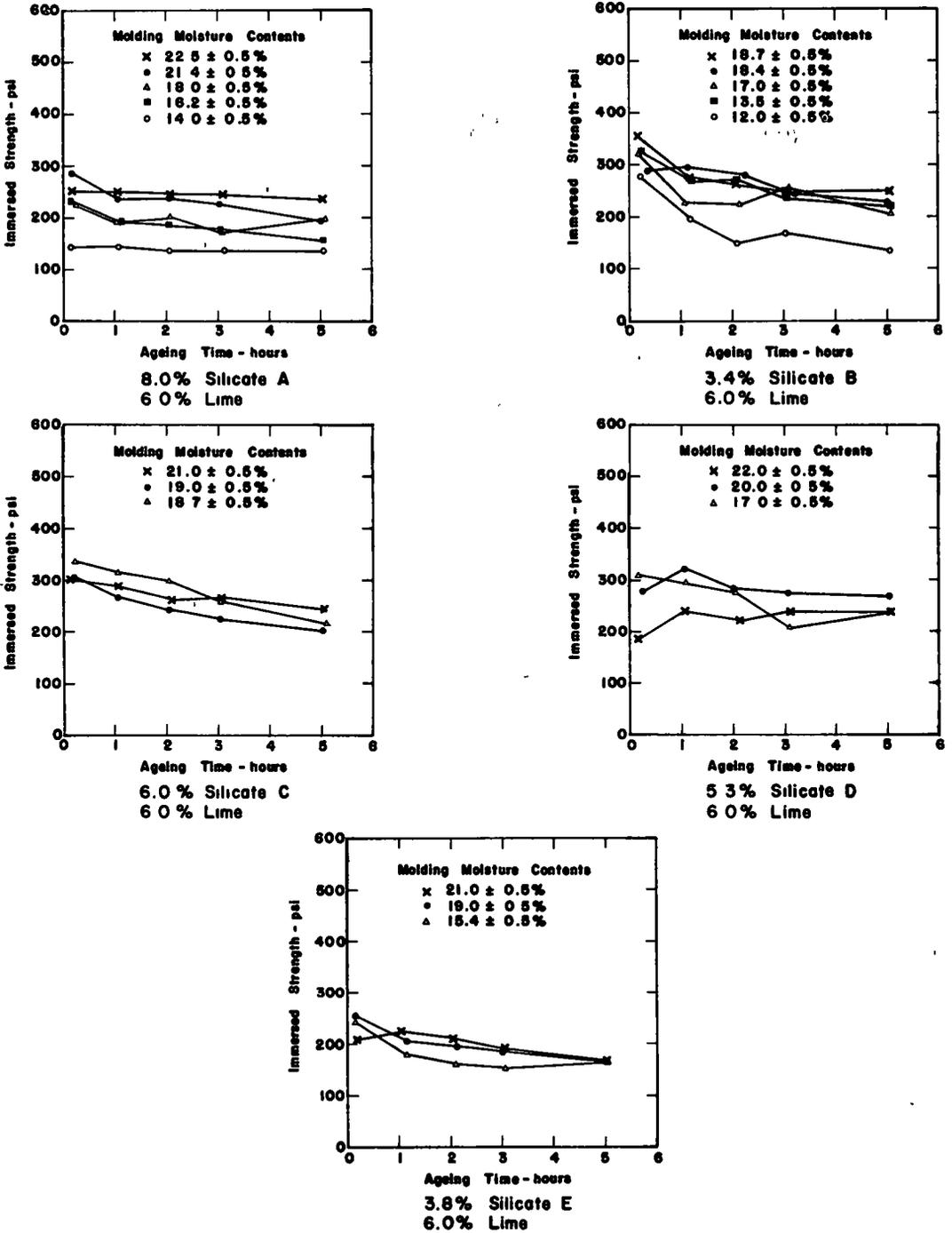


Figure 2. Influence of molding moisture content on the effect of aging time on 7-day cured, 1-day immersed unconfined compressive strength; Kansan till stabilized with 6 percent calcitic hydrated lime and indicated percentages of various sodium silicates.

of gel formed by the reaction between the lime and the sodium silicate increases with time, then as the aging time increases the amount of gel present at the time of molding increases. In the absence of any information to the contrary, it is assumed that the

gel-forming ability of the mixture is unaffected by the compaction. The structure of this gel can be broken by compaction and will reform, but the reformed gel will not form as strong a cementing agent (19). The amount of gel present at a given time depends on the amount of water in the mixture and on the rate of gel formation (19).

While gel formation rates of lime and sodium silicate mixtures have been studied (19), no investigation has been made to determine the rate of this gel formation in the soil-lime-sodium silicate-water mixture. From the results of this investigation it has not been possible to determine the exact effect of the  $\text{Na}_2\text{O}:\text{SiO}_2$  ratio and the degree of hydration of the sodium silicate on the strength of the lime-sodium silicate stabilized soil, but it is probable that these properties affect the rate of gel formation. This is only a possible explanation for the observed decrease of strength with increase of aging time, but it does account for some of the results of this investigation.

**Selection of Sodium Silicate to Be Further Evaluated.**—To assist in determining the sodium silicate whose strength was least affected by the aging time, the following criterion was adopted. The lime-sodium silicate stabilized soil should have a strength of more than 225 psi for the specimens molded after an aging time of 5 hr. This criterion recognizes that a stabilized soil must be frost resistant. Previous work had shown that

TABLE 5

LIME-SODIUM SILICATE MIXTURES FOR EACH SODIUM SILICATE  
THAT BEST SATISFY CRITERION FOR FURTHER EVALUATION

Type <sup>e</sup>	Sodium Silicate Content %	Molding Moisture Content, <sup>a</sup> %	Strength		Amount of Decrease, <sup>d</sup> %
			At Approx. 0.25 Hr, <sup>b</sup> psi	At Approx. 5 Hr, <sup>c</sup> psi	
A	8.0	22.5 ± 0.5	251	231	7.99
B	3.4	18.4 ± 0.5	289	225	22.15
C	6.0	21.0 ± 0.5	301	240	20.25
D	5.3	20.0 ± 0.5	277	267	3.61
E	3.8	21.0 ± 0.5	209	167	20.10

<sup>a</sup>Range of molding moisture contents of specimens molded at five different molding times.  
<sup>b</sup>7-day cured, 1-day immersed unconfined compressive strength with approximately 0.25-hr aging time.

<sup>c</sup>7-day cured, 1-day immersed unconfined compressive strength with approximately 5 hr aging time.

<sup>d</sup>
$$\frac{(\text{str at } 0.25 \text{ hr}) - (\text{str at } 5 \text{ hr}) \times 100}{(\text{str at } 0.25 \text{ hr})}$$

<sup>e</sup>Legend for sodium silicate type:

- A - sodium metasilicate enneahydrate,
- B - sodium metasilicate anhydrous,
- C - sodium metasilicate pentahydrate,
- D - sodium sesquisilicate pentahydrate, and
- E - sodium orthosilicate.

materials with a 7-day cured, 1-day immersed unconfined compressive strength between 200-250 psi probably will satisfactorily resist freeze-thaw action (4). Further, the criterion recognizes that field compaction may not be completed before 5 hr after the water has been added to the lime-sodium silicate treated soil. Therefore any mixture that does not have the minimum strength at an aging time of 5 hr should be eliminated from further consideration.

Table 5 gives the lime-sodium silicate mixture with each sodium silicate that either best satisfies the foregoing criterion or comes closest to satisfying it. From this table it is seen that Silicate D mixture not only satisfies the criterion but also has the

least over-all decrease in strength between aging times of approximately 0.25 hr and 5 hr. Therefore Silicate D was chosen as the admixture for the remaining phases of the investigation.

Because the strengths of Silicate D mixtures showed such a slight dependence on aging time, it was decided to allow the mixtures used in the remainder of the investigation to age 2 hr. This time of 2 hr was chosen because the elapsed time between mixing and compaction in the field, using a multi-pass mix-in-place procedure to mix the stabilized soil, is from 2 to 3 hr (21).

**Determination of Optimum Combination of Lime and Silicate D**

The purpose of this study was to determine the combination of lime and Silicate D that produced the best results in stabilizing Kansan till, and at the same time to find the optimum molding moisture content for maximum strength of this combination.

Sufficient soil for three specimens was mixed with the desired amount of water to obtain a moisture content on the dry side of optimum moisture content for maximum dry density. The mixture was allowed to age 2 hr and then specimens were molded, measured and weighed (4). Two samples of the mixture were taken

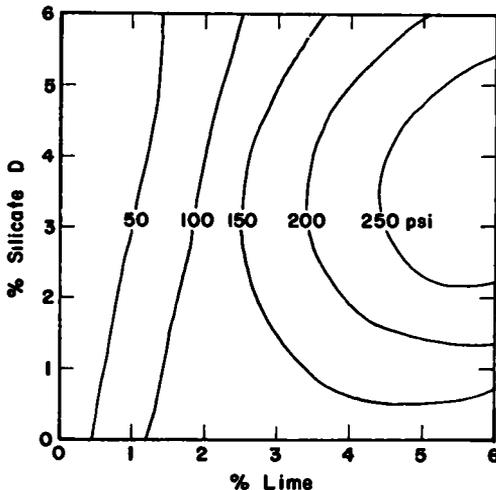


Figure 4. Iso-strength contour chart showing variation of 7-day cured, 1-day immersed unconfined compressive strength of Kansan till stabilized with calcitic lime and Silicate D.

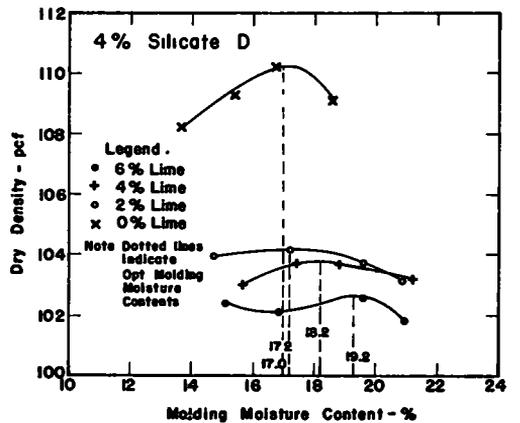
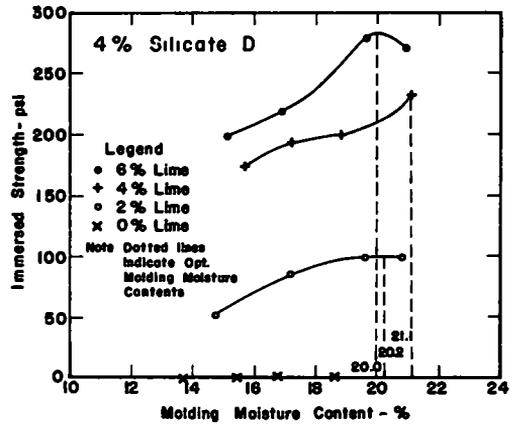


Figure 3. Typical moisture-density and moisture-strength curves for calcitic hydrated lime and Silicate D soil mixtures studied. (The molding moisture contents indicated for each curve are the selected optimums for that combination of lime and Silicate D.)

for moisture content determination at the time of molding. The procedure was repeated three times with the moisture content of the mixture increased approximately 2 percent for each repetition.

Specimens were molded with 0, 2, 4, and 6 percent calcitic hydrated lime plus 0, 2, 4, and 6 percent Silicate D. The specimens molded with varying moisture content were cured for 7 days, immersed in distilled water for 24 hr, and then tested for unconfined compressive strength.

Average values of dry density (at time of molding) and of immersed strength were calculated for each moisture content. From these data comparisons were made of the

Optimum moisture requirements for maximum dry density and maximum strength obtained from curves such as those for the 4 percent Silicate D plus 0, 2, 4, and 6 percent calcitic hydrated lime-treated Kansan till mixtures (Fig. 3).

TABLE 6  
SUMMARY OF TEST RESULTS FOR DETERMINATION OF OPTIMUM  
COMBINATION OF CALCITIC HYDRATED LIME  
AND SILICATE D

Lime (%)	Silicate D (%)	Maximum Strength <sup>a</sup> (psi)	Maximum Dry Density <sup>b</sup> (psi)	Optimum Molding Mois- ture Content, for	
				Maximum Strength <sup>a</sup> (%)	Maximum Dry Density <sup>b</sup> (%)
0	0	0	117.3	c	14.0
0	2	0	109.1	c	15.6
0	4	0	110.2	c	17.0
0	6	0	110.7	c	18.2
2	0	128	109.6	18.0	18.0
2	2	120	c	19.3	c
2	4	100	104.1	20.2	17.2
2	6	76	105.0	16.2	16.8
4	0	128	108.2	18.8	18.4
4	2	205	c	19.0	c
4	4	232	103.8	21.1	18.2
4	6	164	104.0	20.3	19.2
6	0	105	106.6	18.6	18.7
6	2	242	c	20.9	c
6	4	285	102.6	20.0	19.2
6	6	221	c	21.5	c

<sup>a</sup>7-day cured, 1-day immersed unconfined compressive strength.

<sup>b</sup>Dry density at time of molding.

<sup>c</sup>Unable to determine from data.

Table 6 is a summary of the results obtained from these curves. In cases typified by the 4 percent lime and 4 percent Silicate D mixture in Figure 3, where the moisture-strength curve did not pass through a maximum, the highest molding moisture content at which specimens were molded was taken as the optimum moisture content for maximum strength.

To evaluate this data an iso-strength contour chart was used (Fig. 4).

### Discussion

Silicate D used alone produced no increase in the immersed strength of the soil (Table 6). The use of amounts of Silicate D greater than 2 percent had no appreciable effect on the maximum dry density. About the only effect Silicate D had was to increase the optimum moisture content for maximum dry density. However, when calcitic hydrated lime was also added to the soil, the effect of Silicate D on maximum dry density remained the same but the effect on optimum moisture content for maximum dry density was unpredictable.

Figure 4 is an iso-strength contour chart for Kansan till stabilized with calcitic hydrated lime and Silicate D. This chart, based on the maximum strengths obtained from

each of the mixtures tested, indicates that the optimum mix design for maximum strength of the combinations tested was approximately 6 percent lime and 4 percent Silicate D. For this mixture the optimum molding moisture content for maximum strength is on the wet side of optimum for maximum dry density. That this was not true for all the combinations of lime and Silicate D tested (Table 6) is further indication that strength is not correlated with dry density in lime-sodium silicate stabilized soil.

### Effect of Curing Time on Strength

Based on the results obtained in the optimum lime-Silicate D study the following mixtures were selected for an investigation of the effect of length of curing time on one day immersed unconfined compressive strength: 6 percent lime, 1 percent Silicate D; 6 percent lime, 2 percent Silicate D; 6 percent lime, 3 percent Silicate D; and 6 percent lime, 4 percent Silicate D.

Specimens from each of these mixtures were molded after allowing the mix to age for 2 hr, then cured for 3, 7, and 28 days. At the end of each curing period the samples were immersed in distilled water for 24 hr and then tested for unconfined compressive strength (Fig. 5).

### Discussion

The effect of curing time on 1-day immersed unconfined compressive strength of Kansan till stabilized with 6 percent calcitic hydrated lime and varying percentages of Silicate D is shown in Figure 5. All four mixtures continued to gain strength throughout the entire period investigated. The average rate of strength increase for all mixtures was greatest in the period 3 to 7 days. The more Silicate D added, the higher the average rate of strength gain was for this period. For the period 7 to 28 days, the average rate of strength gain for the 1, 2 and 3 percent Silicate D mixtures was approximately the same. The addition of 4 percent Silicate D, however, increased the average rate of strength gain for this period. Further investigation of the reaction products formed by these combinations of soil, lime and Silicate D are needed before an explanation for this can be given.

### Resistance to Freeze-Thaw Action

The four mixtures investigated in the curing time study were used for a study of their resistance to freezing. The four mixtures, after curing for 7 days were subjected to 14 cycles of freezing and thawing and then tested for unconfined compressive strength (Table 7).

### Discussion

Tentative criteria for durable soil-cement from the data obtained in the modified British freeze-thaw test have been adopted at Iowa State University. The first criterion is the  $R_f$  value (the ratio of the unconfined strength of the immersed specimens to the unconfined compressive strength of the freeze-thaw specimen expressed to the nearest 5 percent) which must equal or exceed 80 percent for soil-cement. The second criterion is that the unconfined compressive strength of both the control specimen and the freeze-thaw specimen must equal or exceed 250 psi (4).

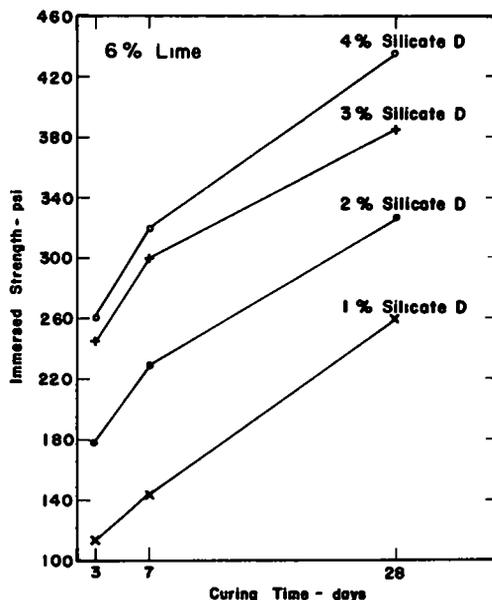


Figure 5. Effect of curing time on 1-day immersed unconfined compressive strength of Kansan till stabilized with 6 percent calcitic hydrated lime and various percentages of Silicate D.

There is no reason to dispute the second criterion in the evaluation of the durability of the lime-Silicate D stabilized soil. However, the validity of the first criterion (the  $R_f$  value) as applied to lime-Silicate D stabilized soil is questionable.

It has been found that after an initial moist curing of 1-day specimens of lime-sodium silicate stabilized soil immersed in distilled water for 7 days yielded higher unconfined compressive strengths than specimens cured for 7 days in the moist room and immersed for one day before testing (6). This coupled with the probability that the freezing inhibits the gain of strength of the specimen during the freeze-thaw tests, seems to indicate that an  $R_f$  value of 80 percent may not be a valid criterion for freeze-thaw resistance of this type of stabilized soil. Further investigation of this criterion is needed before any final evaluation of results of the freeze-thaw tests of lime-sodium silicate stabilized soil can be made.

TABLE 7

RESULTS OF MODIFIED BRITISH FREEZE-THAW TESTS OF KANSAN TILL  
STABILIZED WITH 6 PERCENT CALCITIC HYDRATED LIME AND  
DIFFERENT PERCENTAGES OF SILICATE D

Silicate D Content (%)	$p_c^a$ (psi)	$p_f^b$ (psi)	$R_f^c$ (%)
1	195	6	5
2	281	116	40
3	307	179	60
4	429	218	50

<sup>a</sup>Unconfined compressive strength of immersed specimen.

<sup>b</sup>Unconfined compressive strength of freeze-thaw specimen.

<sup>c</sup>Index of the resistance to the effect of freezing.

None of the mixtures tested were able to pass the criterion of an unconfined compressive strength equal to or in excess of 250 psi after 14 freeze-thaw cycles (Table 7). However, the addition of Silicate D increased the strength of the specimens at the end of 14 cycles of freezing and thawing until the combination of 6 percent calcitic hydrated lime and 4 percent Silicate D came very close to meeting the criterion. The iso-strength contour chart (Fig. 4) indicates that a combination of 7 percent calcitic hydrated lime and 4 percent Silicate D would produce a stabilized soil with greater strength than the combination of 6 percent lime and 4 percent Silicate D. It is probable then that Kansan till can be made resistant to freeze-thaw action by treatment with a combination of calcitic hydrated lime and Silicate D. The exact combination of these materials needed is subject to further investigation.

## SUMMARY

The investigation reported in this paper is divided into four parts.

The first part reports, discusses, and offers an explanation for the effect of aging time (elapsed time between mixing and molding) on dry density on 7-day cured, 1-day immersed unconfined compressive strength, and on optimum molding moisture content for maximum dry density and maximum strength of Kansan till stabilized with 6 percent calcitic hydrated lime and five different powdered sodium silicates. The amounts of sodium silicates used were adjusted so that the anhydrous portion of each was equal in weight to the anhydrous portion of 6 percent sodium metasilicate pentahydrate.

The second part reports the selection of the optimum combination of lime and sodium sesquisilicate pentahydrate, the sodium silicate whose strength was least affected by aging time. The effect of various combinations of lime and this sodium silicate on

the optimum molding moisture content for maximum dry density and maximum strength is also commented on.

The third part reports and discusses the effect of curing time on strength of various combinations of sodium sesquisilicate and calcitic hydrated lime.

The fourth part reports and discusses the resistance of the soil stabilized with 6 percent calcitic lime and various percentages of sodium sesquisilicate to freeze-thaw action.

### CONCLUSIONS

1. Kansan till treated with 6 percent calcitic hydrated lime and any one of the five powdered sodium silicates investigated displays the following characteristics:

- a. As aging time increases, dry density decreases at a rate dependent on the type of sodium silicate.
- b. Aging time affects optimum molding moisture content both for maximum dry density and for maximum strength, but the effect is not the same.
- c. As aging time increases, strength decreases. The amount of this decrease depends on the molding moisture content as well as the type of sodium silicate.
- d. Strength is not correlated with dry density.

2. Sodium sesquisilicate pentahydrate (Silicate D) when mixed with 6 percent calcitic hydrated lime and Kansan till produces a stabilized soil whose strength and dry density at time of molding are less affected by aging time than any of the other sodium silicates studied.

3. Of the combinations of lime and Silicate D studied, the optimum mix design for maximum strength was 6 percent lime plus 4 percent Silicate D.

4. For the mixtures of lime and Silicate D studied, the rate of strength increase with curing time is greater in the period 3 to 7 days than in the period 7 to 28 days.

5. In the period 3 to 7 days the rate of strength increase with curing time increases as the Silicate D content increases.

6. Three-day cured, 1-day immersed unconfined compressive strengths of more than 250 psi can be achieved by mixtures of calcitic hydrated lime and Silicate D.

7. Kansan till stabilized with 6 percent calcitic hydrated lime and amounts of between 2 and 4 percent Silicate D probably would perform satisfactorily as a pavement base course in an area with a mild climate.

8. In field construction using lime-sodium silicate stabilized soil, strict controls over moisture content and elapsed time between final mixing and compaction will be necessary to obtain the desired strength.

### ACKNOWLEDGMENTS

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