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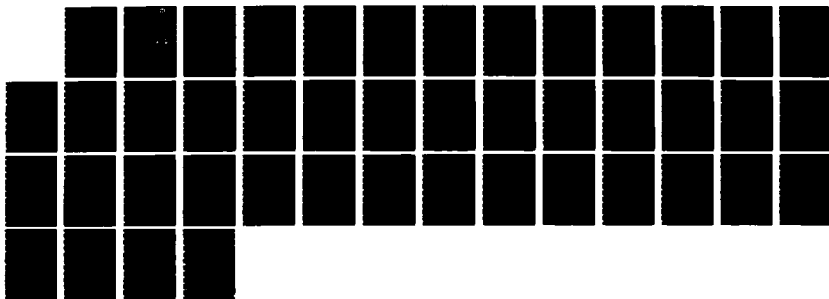
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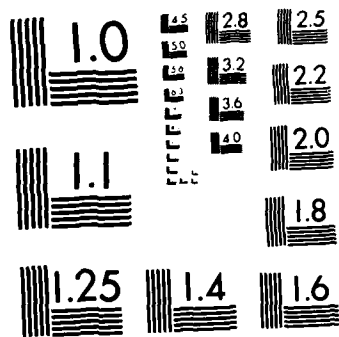
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# Special Report 86-21

July 1986



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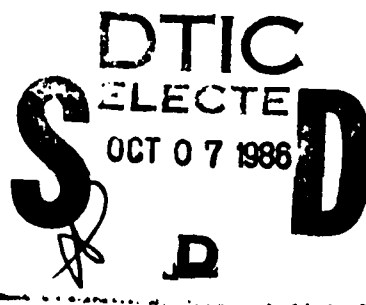
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## *Stabilization of fine-grained soil for road and airfield construction*

Lawrence S. Danyluk

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) A laboratory study was conducted to determine the feasibility of stabilizing an organic silt for use in sub-base or base courses for all-weather, low-volume roads and airfields in Alaska. The soil used in this study has an organic content of 12% and a modified Proctor value of 79.1 lb/ft <sup>3</sup> at a 29% moisture content. The stabilizers evaluated were: cement, cement with additives (calcium chloride, hydrogen peroxide, sodium sulfate, and lime), lime, lime/fly ash, asphalt emulsion, tetrasodium polyphosphate, and calcium acrylate. Unconfined compressive strengths obtained were: 39 lb/in. <sup>2</sup> with 20% cement, 64 lb/in. <sup>2</sup> with 20% cement and 2% calcium chloride, 51 lb/in. <sup>2</sup> with asphalt emulsion, and 348		

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20. Abstract (cont'd).

1b/in.<sup>2</sup> with calcium chloride. Lime and lime/fly ash proved to be ineffective for this soil. Although tetrasodium polyphosphate did not improve the soil's strength it did reduce frost susceptibility and permeability.

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## PREFACE

This report was prepared by Lawrence S. Danyluk, Research Civil Engineer, Geotechnical Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory. Funding was provided by the State of Alaska Department of Transportation and Public Facilities under Project F15611. David C. Esch was the Contract Manager for the DOT&PF.

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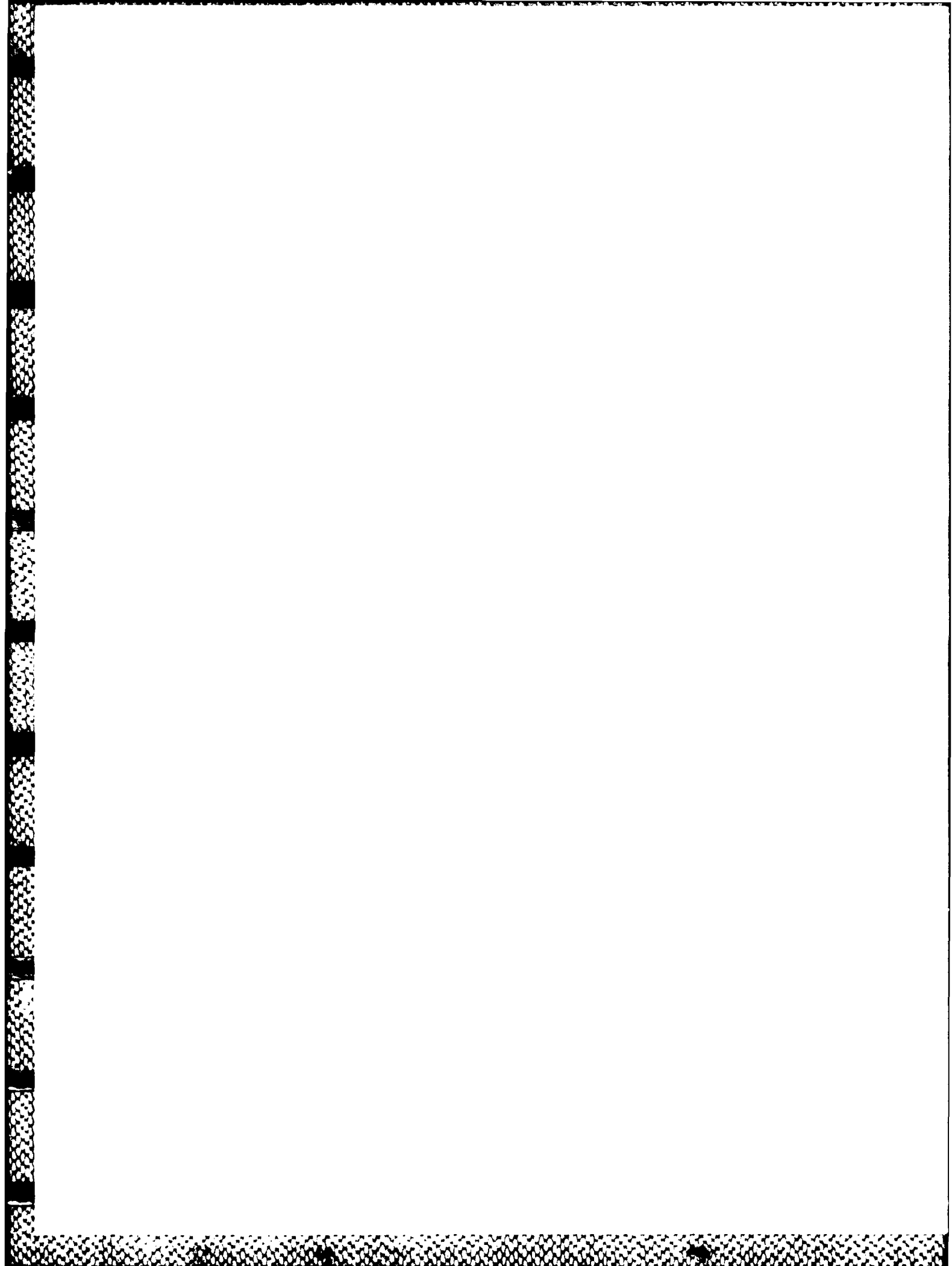
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## INTRODUCTION

It has been common engineering practice to use a granular, non-frost-susceptible soil as a means to deter frost heaving and thaw weakening and their destructive effects. However, the supply of select material in many areas is diminishing if not already nonexistent. Altering the properties of native soil to make it adequately serve an engineering purpose has many advantages:

- The cost for transporting a suitable soil to the construction site is reduced or eliminated.
- The time required for transporting the replacement material may often be significantly greater than the time required to stabilize the in-situ soil.
- The removal and disposal of the unsuitable soil is no longer necessary.

Community improvements in the lower Yukon and Kuskokwim Delta regions of Alaska have required the construction of all-weather, low-volume roads and airfields. In this gravel-deficient area of Alaska, select construction gravels must be imported by barge at a cost as high as \$100/yd<sup>3</sup>. This study, funded by the Alaska Department of Transportation and Public Facilities, reports the results of a laboratory study to investigate potential stabilizers for fine-grained organic soils common to the area for use in sub-bases or base courses of low-volume roads or airfields.

### Characteristics of the soil

The soil used in this study was supplied by the Alaska Department of Transportation and Public Facilities and is typical of the soil found in the lower Yukon and Kuskokwim Delta regions of Alaska. The results of a laboratory analysis of the soil are presented in Table 1.

### Selection of Stabilizers

The physical properties of a soil can be improved for engineering purposes in many ways, among which are thermal, electrical, mechanical, chemical, and other less used means. The method or methods chosen should upgrade specific engineering requirements, i.e., volume stability, strength, permeability, and freeze-thaw durability. It should be noted, however, that because of the great variety of soils, no one method is successful for all cases.

Thermal stabilization of soils occurs when they are exposed to high or low temperatures. The former is usually economically prohibitive because

Table 1. Soil analysis.

Classification: Dark Brown Organic Silt  
 Unified Classifications System - OL  
 AASHTO Classification System - A-5

Percent passing #4 sieve	100%
Percent passing #200 sieve	87% (Fig. 1)
Liquid limit	58%
Plastic limit	51%
Plasticity index	6%
Specific gravity of fines	2.38
Organic content	12%
Permeability (78.7 lb/ft <sup>3</sup> )	$4.5 \times 10^{-5}$ cm sec <sup>-1</sup>
Optimum density (modified Proctor)	79.1 lb/ft <sup>3</sup> (Fig. 2)
Optimum moisture (modified Proctor)	29% (Fig. 2)
pH	5.3
Frost susceptibility classification (CRREL)	Very high (10.1 mm/day)
CBR (after heave test)	0.4
Unconfined compressive strength (79.0 lb/ft <sup>3</sup> at 29% moisture content)	13.4 lb/in. <sup>2</sup>

temperatures in excess of 600°C are needed to irreversibly dehydrate or fuse soil particles. Freezing of the pore water in a soil strengthens it, but undesirable features such as heaving and cracking may occur if the soil is frost-susceptible.

Electrical stabilization is the application of a direct electrical current to the soil. The current causes the water to migrate to the electrodes, where it is collected and removed. The structural strength of the soil is improved by the loss of moisture. Although this method has had limited success, it is considered expensive.

Mechanical stabilization increases soil stability without the addition of any foreign material. It can be accomplished by:

- Compaction of an in-situ soil or fill at a selected water content and compactive effort, which in turn results in a material that is stronger, less permeable, and less compressible;
- Drainage and maintenance of the water content at a constant level;
- The admixture of different soil types (i.e., mixing a clay binder with a coarse-grained material).

These techniques are usually combined for better results.

Chemical stabilization, when used with mechanical methods, is probably the most widely used method of treating soils. The three most common stabilizers are cement, lime, and bitumen. Less used stabilizers include chlor-

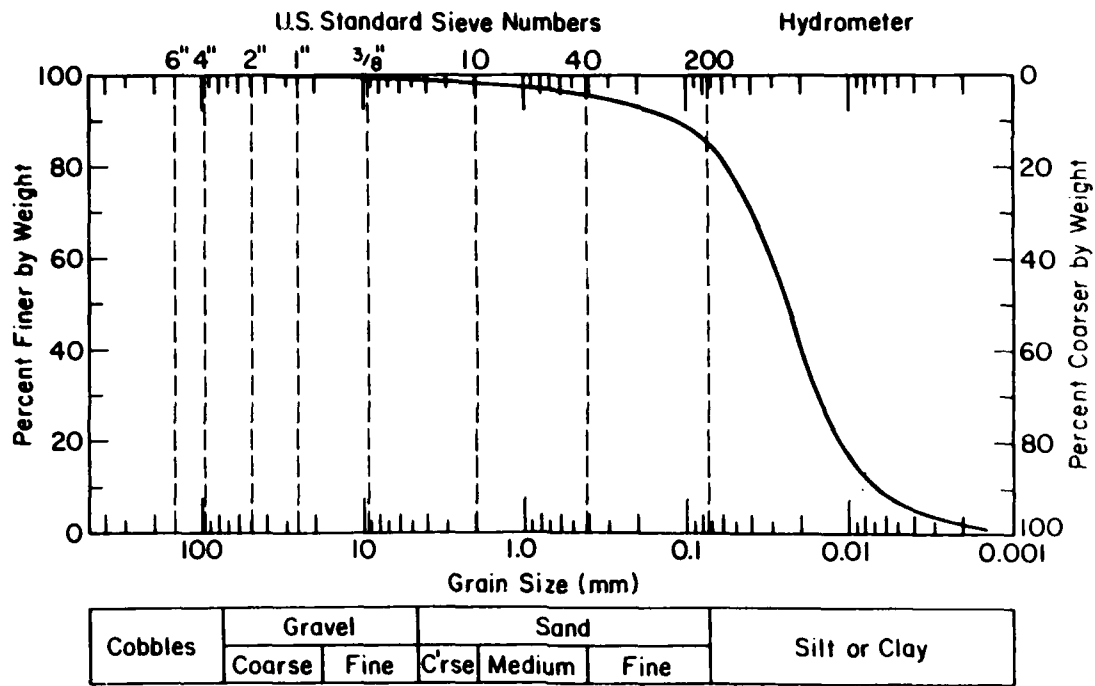


Figure 1. Soil gradation curve.

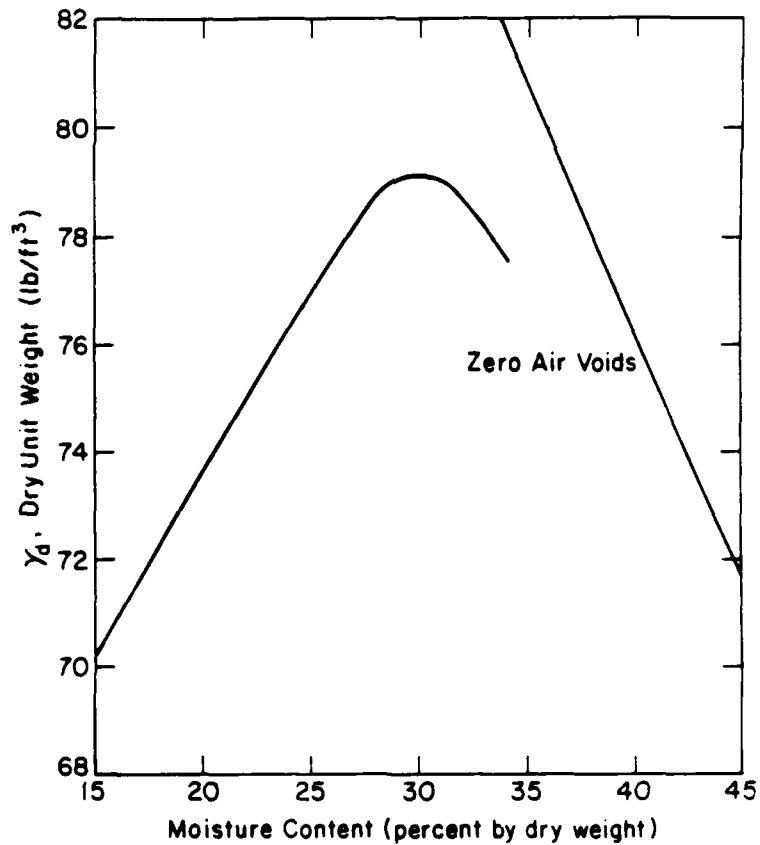


Figure 2. Soil density curve.

ides, natural and synthetic resins and other special case materials (i.e., acids, detergents, carbonates, etc.).

The main factors governing the choice of stabilizing methods for this study were:

- 1) Soil Type - The soil used in this study is a frost-susceptible silt. It has a low maximum density, low pH value, high organic content, and high natural water content.
- 2) Environment - The stabilized soil had to be able to withstand the freezing temperatures experienced in the area, have the capacity to be placed and cured during the short construction season, and be environmentally safe.
- 3) Constructibility - Some of the areas requiring stabilization are rather remote and difficult to reach. Therefore the stabilizer should not require special handling or procedures that necessitate highly trained personnel.

Based on the above criteria and a brief literature search, including the one preceding this study (Phukan, 1981), it was decided to conduct laboratory tests with the common stabilizers (cement, lime, and bitumen). Combinations of these stabilizers in addition to additives (i.e., sodium sulfate, calcium chloride, hydrogen peroxide, and fly ash) were tested. Calcium acrylate (Lambe, 1951) and tetrasodium pyrophosphate (TSPP) (Lambe and Kaplar, 1971) have shown promising results as stabilizers, and they were also tested. Table 2 is a summary of the stabilizers and additives tested.

Table 2. Stabilizers and additives tested.

Stabilizers	<u>Additives</u>					
	Cement	Lime	Hydrogen peroxide	Calcium chloride	Sodium sulfate	Fly ash
Cement	X	X	X	X	X	X
Lime	X	X				X
Asphalt emulsion	X	X				
TSPP						
Calcium acrylate						

## LABORATORY TESTING PROGRAM

### Sample preparation

The soil used in this study was tested at three moisture contents: optimum and  $\pm 5\%$  of optimum. The desired moisture content was obtained by oven-drying the soil and adding a predetermined amount of water. The soil was initially mixed by hand. However, inconsistent results led to the use of a mechanical mixer (kitchen variety mixer with paddles). The soil was mixed for 1 to 2 minutes, covered, and left to stabilize for 24 hours.

The stabilizer was combined with the soil until a uniform mixture was obtained (approximately 1 to 2 minutes). In most cases (except where noted) the treated soil was then compacted by a mechanical compactor at an effort equivalent to an AASHTO T-180 modified Proctor value.

The sample was ejected from the mold and cured at 40°F or 70°F for 7 days (except where noted).

### California Bearing Ratio (CBR)

The California Bearing Ratio test followed the procedure outlined in ASTM D1883. The rate of the penetration piston was 0.05 in. per minute. A surcharge of 0.5 lb/in.<sup>2</sup> was added to simulate field conditions of 6 in. of overburden. The CBR test was run following the completion of the frost heave test and 24 hr of thawing.

### Unconfined compression test

Unconfined compression tests (ASTM-D2166) were run on samples prepared by the Harvard Compaction Apparatus. The samples, 1.3125 by 2.816 in. high, were compacted in 3 layers with 25 blows per layer by a 40 lb prestressed spring tamper. Moistures, stabilizer contents, curing times and temperatures varied; they are explained in their respective sections. All samples were strained at 0.05 in./min. Tests were run in triplicate, with the average values being used in the graphs of this report.

### pH test

An Orion 811 pH meter was used to measure the pH of certain soil-stabilizer mixtures. The meter was standardized with a buffer solution that had a pH of 12.0. The stabilizer was thoroughly mixed with approximately 25 gr of oven-dried soil. Distilled water was added to make a thick paste. After 15 minutes, the paste was transferred to a plastic beaker and the pH was measured.

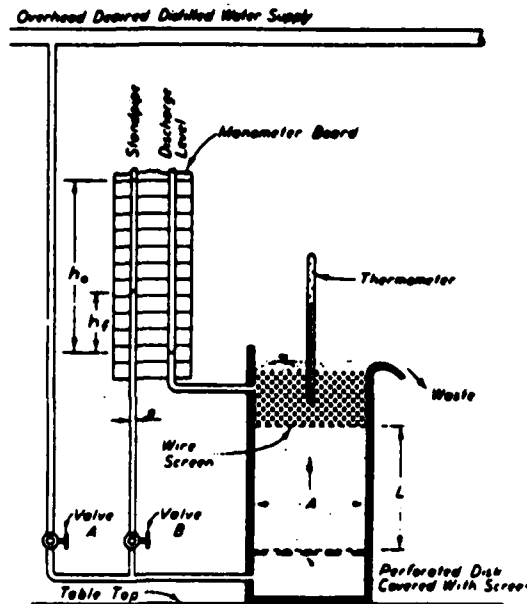


Figure 3. Falling head permeability apparatus.

#### Permeability test

Permeability tests were run on untreated and stabilized samples using the falling-head permeability method (Fig. 3). The samples were compacted in transparent plastic molds (2.75 in. diameter by 7 in. high) at moisture contents and densities similar to values used in the other tests. Filter paper and porous stones were placed at both ends of the sample and the mold was assembled. The assembly was then de-aired by a vacuum pump (approximately 28 in. of Hg) for 2 hours. De-aired, distilled water was slowly fed through the bottom of the mold. The sample was saturated at a slow rate (approximately 2 hr) to ensure that no water channels were made in the sample; the saturation was considered complete when water flowed out of the upper end of the mold. Tests were run until a consistent value of permeability was obtained.

#### Frost heave test

The CRREL frost heave test was used to determine the frost susceptibility of the stabilized soil. A summary of the test method is presented below, see Chamberlain and Carbee (1981) for a more detailed explanation.

Treated and untreated soil samples were compacted in a tapered steel mold that had the same dimensions as the Lucite freezing cylinder (Fig. 4). The samples were tamped at an effort equivalent to the modified Proctor value

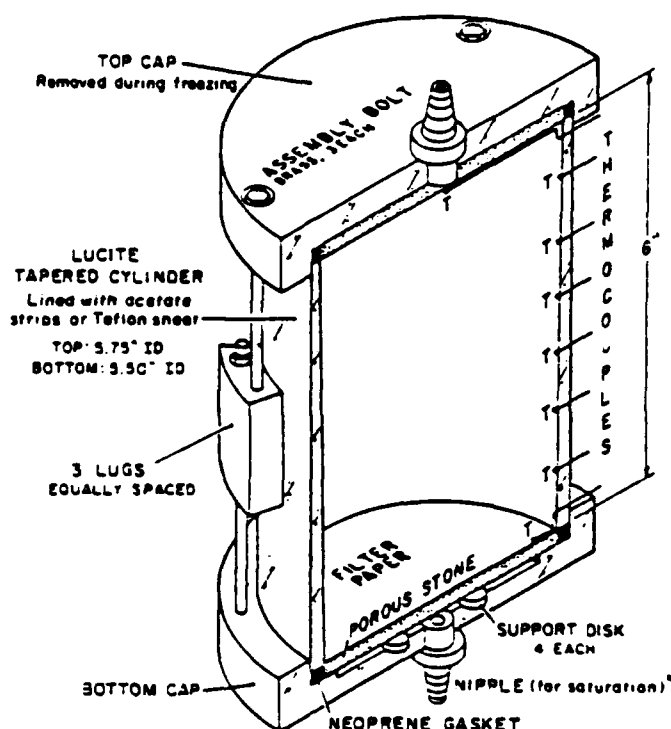


Figure 4. Frost susceptibility freezing cylinder (Kaplur, 1976).

(AASHTO test procedure T180-57 [1958]): five layers with a 10 lb hammer and 18 in. drop.

Specimens were ejected from the compaction mold and transferred to freezing cylinders lined with thermocouples. Filter paper and porous stones were added to each end of the sample, which was then placed in a 40°F coldroom and saturated. Initially, the water level was set 1.0 in. above the bottom of the sample. The water table was raised 1.0 in./hr until it was at the top of the sample and then it was raised 3.0 in. every 2-3 hr until it was 1.0 ft above the sample. A 20.0 lb weight was placed on top of the sample to minimize swelling during saturation.

The samples were placed in a freezing cabinet (Fig. 5) designed to operate at temperatures ranging from the ambient coldroom temperature of 40°F to as low as -22°F. Four specimens were tested simultaneously in each cabinet; the space between samples was insulated with granular cork to minimize radial heat flow and assure essentially one-dimensional, vertical frost penetration. The bottom of the sample was exposed to the ambient room temperature of 40°F.



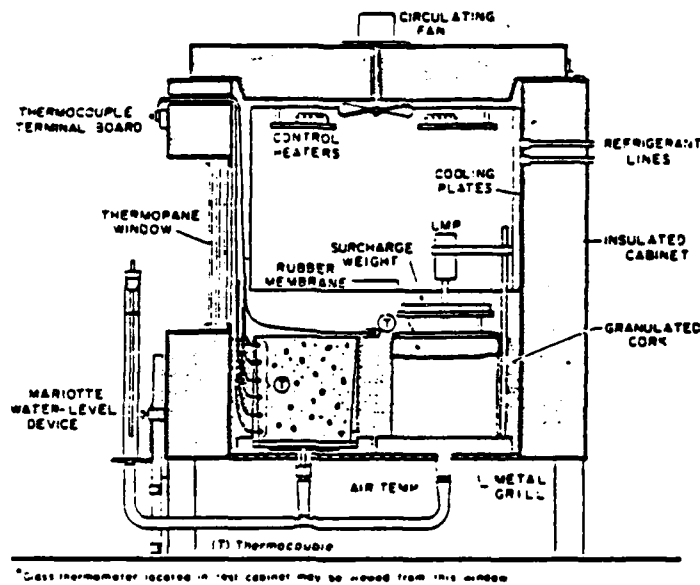


Figure 5. Frost susceptibility freezing cabinet (Kaplur, 1976).

Before freezing, a surcharge load of  $0.5 \text{ lb/in.}^2$  was applied to simulate approximately 6 in. of overburden and the water level was set just above the base of the sample. The sample was then frozen from the top at an approximate rate of 0.5 in./day. The length of the test varied from a minimum of 5 days to a maximum of 12 days. After a 24-hr thaw period, the bearing capacity of the soil was tested using the California bearing ratio (CBR) procedure.

#### Marshall test

Samples treated with asphalt emulsion were tested on the Marshall apparatus. The test specimens (4 in. diameter by 2.5 in. high) were prepared according to ASTM D1559, except that the samples were cured at  $70^\circ\text{F}$  instead of the standard  $140^\circ\text{F}$ . In preparing the sample, 50 blows were applied to both sides of the sample to correspond to a medium traffic category. These changes were made to better simulate field conditions.

#### TEST RESULTS

##### Cement

It is generally recognized that organic matter can retard or prevent the proper hydration of cement in a soil-cement mixture. The organics tend to absorb the calcium ions as they are liberated by the hydrating cement. MacLean

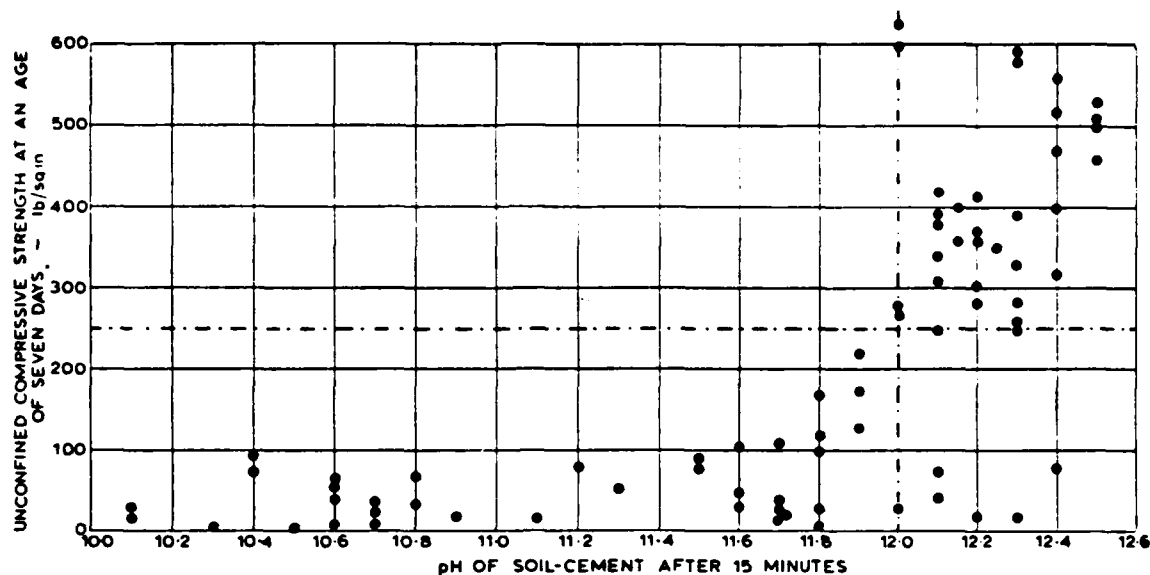


Figure 6. Unconfined compressive strength vs pH (MacLean and Sherwood, 1961).

and Sherwood (1961) developed a quick procedure for determining whether or not the organic matter present will be detrimental to cement hydration. The test stipulates that 15 minutes after mixing a 10:1 soil-cement mixture having a pH of 12 or greater should be suitable for cement stabilization (the authors consider a mixture suitable if it has an unconfined compressive strength of 250 lb/in.<sup>2</sup> after 7 days of curing) (Fig. 6). A pH less than this causes the precipitation of an alumina-silica gel over the cement particles, which in turn inhibits the normal hardening process.

A pH test was run on samples treated with ordinary Portland cement (type I) and high early-strength cement (type III). The type III cement was tested to determine whether the reduced set time would lessen the effects of the organics on the pH. Neither type of cement achieved a pH of over 11.6 at the 10% cement content (Table 3).

Unconfined compression test samples were prepared at the unstabilized optimum moisture content and various cement contents (2, 5, 10, 15 and 20% by weight) (Fig. 7). The samples were cured for 7 days at 70°F. At the end of the curing period, the samples still did not appear to have hardened; this was reflected by the low strength values in the range of 10-45 lb/in.<sup>2</sup> The mixtures with the lower cement contents (2, 5, and 10%) exhibited little or no bonding of the soil particles; the samples usually crumbled when loaded. Since the type III cement strengths were not significantly different from the type I, no further testing was done with the type III cement.

Table 3. pH tests

Stabilizer (percent by weight)		Additive (percent by weight)		pH*
Cement (type I)	10%	None		11.4
Cement (type III)	10%	None		11.6
Cement	10%	Calcium chloride	0.5%	11.8
Cement	10%	Calcium chloride	1.0%	11.9
Cement	10%	Calcium chloride	2.0%	12.1
Cement	10%	Sodium sulfate	0.5%	11.1
Cement	10%	Sodium sulfate	1.0%	10.8
Cement	10%	Sodium sulfate	2.0%	10.7
Cement	10%	Hydrogen peroxide	5.0%	11.2
Cement	10%	Hydrogen peroxide	10.0%	11.3
Cement	10%	Hydrogen peroxide	15.0%	11.5
Cement	10%	Hydrogen peroxide	20.0%	11.7
Cement	10%	Lime	5.0%	11.4
Cement	15%	Lime	5.0%	11.7

\*pH was measured 15 minutes after mixing.

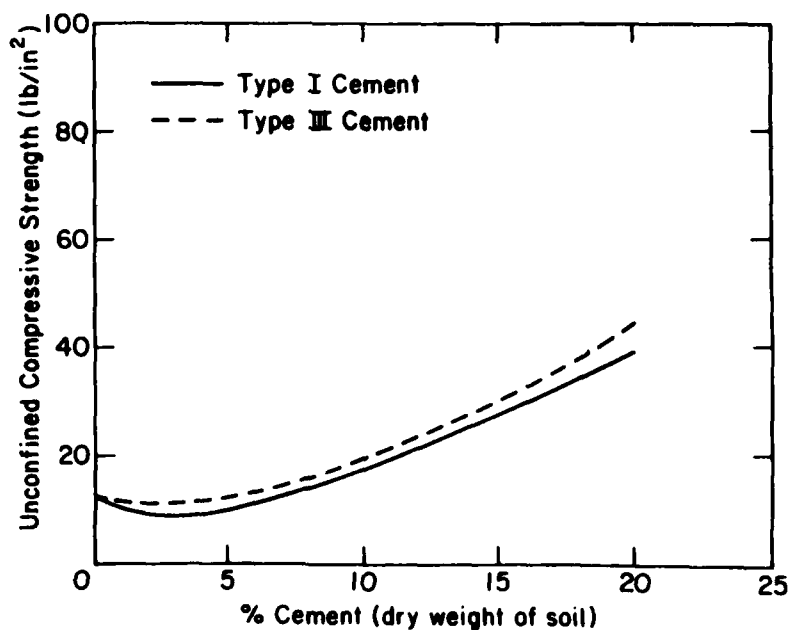


Figure 7. Unconfined compressive strength vs cement content.

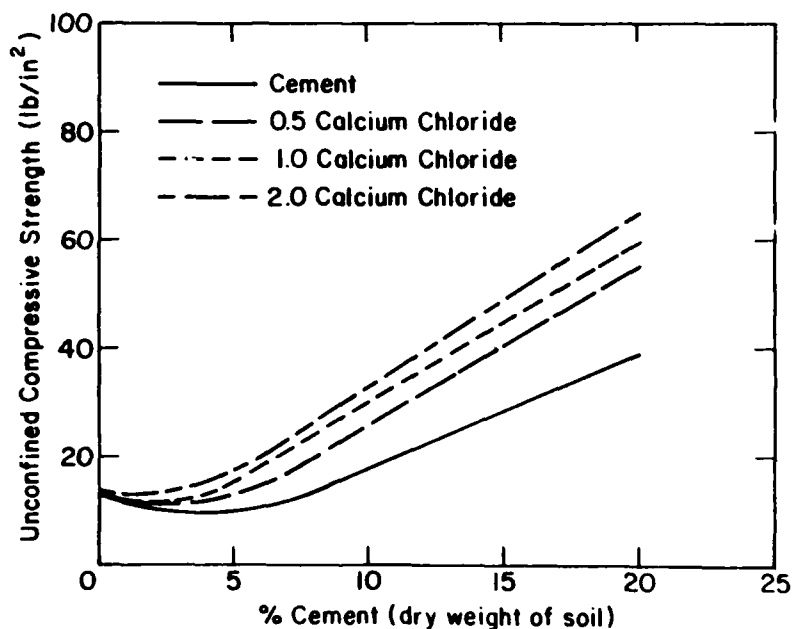


Figure 8. Unconfined compressive strength vs cement content with calcium chloride additive.

#### Cement/calcium chloride

Experiments were conducted using type I Portland cement with calcium chloride as a secondary additive. Samples were prepared at 5, 10, 15, and 20% cement with 0.5, 1, and 2% calcium chloride by weight of dry soil. The samples used in the unconfined compression strength test were compacted at optimum moisture content and cured for 7 days at 70 F. Results of the pH and strength tests are shown in Table 3 and Figure 8 respectively. The calcium chloride increased both the pH and the strength of the soil when compared to cement alone. Although the pH exceeded 12 using 2% calcium chloride, the corresponding strength was only 64 lb/in.<sup>2</sup>. Compressive strengths increased with percent of calcium chloride; however, it was noted that higher concentrations of calcium chloride were most effective at lower cement contents. For cement contents above 10%, the additive was most cost-effective at the 0.5 concentration; further increasing the concentration resulted in only minor improvements.

#### Cement/sodium sulfate

Some organic soils have been successfully stabilized by adding sodium sulfate to the soil-cement mixture (Lambe et al., 1960). It is believed that in the presence of the sulfate, the pH of the soil-cement mixture is initially lowered. This causes the organic material to remain inactive or less active,

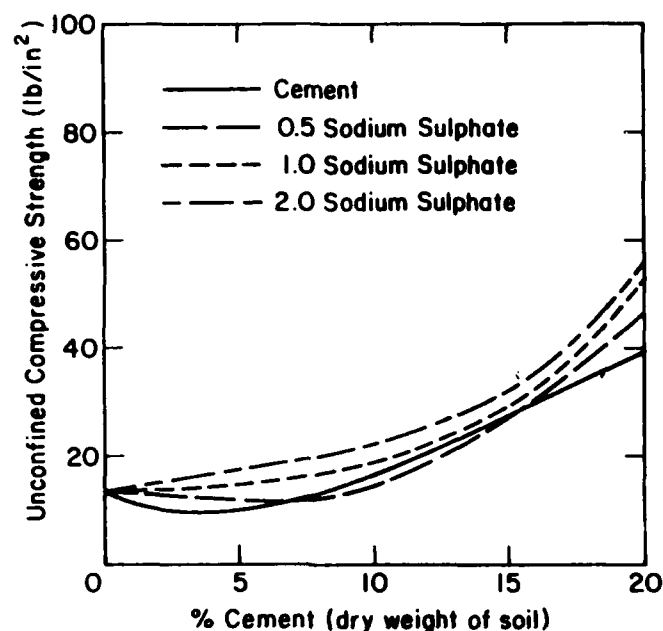


Figure 9. Unconfined compressive strength vs cement content with sodium sulphate.

so the usual benefit of the sodium ions increasing the strength of the soil-cement mixture can be achieved.

Sodium sulfate contents of 0.5, 1, and 2% (by weight of dry soil) were added to soil-cement mixtures containing 5, 10, 15, and 20% cement. The pHs of the 10:1 soil-cement-sulfate mixtures were slightly less than the values obtained with cement alone (see Table 3); however, Figure 9 shows that at 20% cement, the addition of 2.0% of sulfate increased the compressive strength by 16.0 lb/in.<sup>2</sup> compared to using cement alone.

#### Hydrogen peroxide/cement

An attempt was made to counteract the effects of the organics by pre-treating the soil with hydrogen peroxide. A 35% solution of hydrogen peroxide was used in this test since it is readily available and solutions with higher concentrations require special handling. Soil samples were prepared at a water content of 25%, which is understood to be close to a typical in-situ value. Hydrogen peroxide contents of 5, 10, 15, and 20% by dry soil weight were added to the soil and thoroughly mixed. The reaction of the peroxide and soil seemed to be sensitive to temperature. When temperatures were below 40°F, the hydrogen peroxide would not react with the organics, but as the temperature was raised to 70°F, it would react. Reactions started immediately after

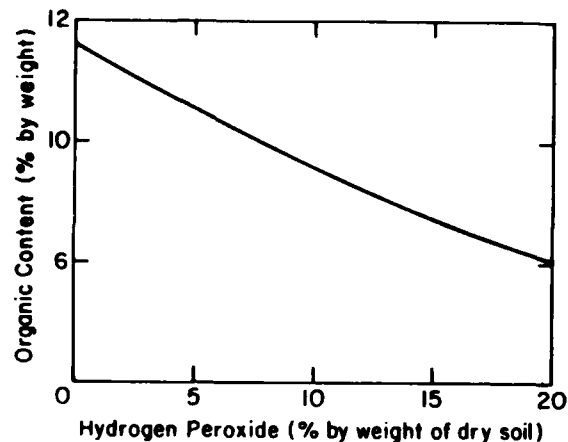


Figure 10. Organic content vs hydrogen peroxide content.

the soil and peroxide were mixed and were usually complete in an hour; however, the samples were left to equilibrate for 24 hours. Hydrogen peroxide concentrations of 10% and above completely evaporated all of the water in the soil sample. To determine if this drying had an effect on the final organic content, the initial moisture content of the soil was increased to 35% for samples treated with 10% or more peroxide. Final organic contents were then measured and it was found that the added water had no substantial effect; if anything, the additional water diluted the effects of the peroxide. Samples were then diluted with distilled water (to stop any further reactions) and placed in an oven to determine the final organic content. Figure 10 shows the results of the tests. A 20% treatment of hydrogen peroxide resulted in an organic content of 8.3%, as compared to an untreated content of 12.0%.

The pH of the cement mixtures increased for hydrogen peroxide concentrations higher than 15% (Table 3). In the 5 to 15% cement range, the unconfined compression strengths were increased by the hydrogen peroxide, but at 20% cement the strength values decreased (Fig. 11). This might indicate that the organics remaining after treatment with the hydrogen peroxide could require, as a result of oxidation, a greater affinity for the calcium in the cement.

#### Lime

The lime chosen for this study was a common dolomitic lime. Studies (Wang and Handy, 1966) recommended this type of lime for a cool climate or an area with a short construction season. Lime contents of 5, 8, 10, 15, and 20% by

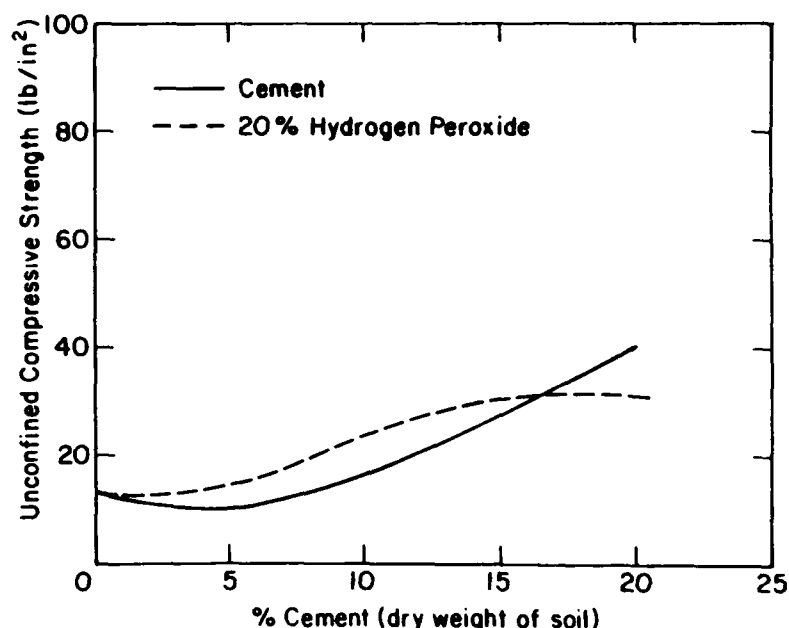


Figure 11. Unconfined compressive strength vs cement content, pretreated with hydrogen peroxide.

weight were tested. Although lime is usually cured at high temperatures (120°F), the samples in this study were cured for 7 days at 70°F to approximate field conditions. Samples cured at 40°F showed no improvement over the unstabilized material.

Lime, like cement, requires a high alkaline condition to be effective. Eades and Grim (1966) found that, for a pozzolanic reaction to occur, the soil-lime mixture must have a pH of 12.4 one hour after mixing. As the pH approaches 12.4, calcium ions become available to form calcium silicates, thus completing the soil-lime reaction. Arman and Munfakh (1972) compared the pH values of soil-lime mixtures cured for 1 hour and for 7 days. They found that the pH values had changed very little with time and are at a maximum 1 hour after mixing.

Figure 12 shows that this soil, when combined with 20% by weight lime, achieved a pH of 12.2. For lime contents of more than 10%, little increase in pH occurred for each increase in lime content. Results of the unconfined compressive strength test are shown in Table 4. A 20% lime content yielded a strength value of only 29.2 lb/in.<sup>2</sup>; similar strength improvements were realized for lower lime contents. These values indicate that lime has very little effect in stabilizing this organic soil.

Table 4. Cement/lime tests

Stabilizer (% dry weight soil)	Maximum density (lb/ft <sup>3</sup> )	Optimum moisture content (% dry weight soil)	Unconfined compressive strength (lb/in. <sup>2</sup> )	Permeability (cm sec <sup>-1</sup> x 10 <sup>-5</sup> )	Frost-Heave ratio ( $\frac{\text{Treated}}{\text{Untreated}}$ )	Afterthaw CBR
Untreated	79.1	29.0	13.4	4.5	1.0	0.4
Cement 5%	80.0	28.5	10.0	2.9	1.2	0.0
10%	80.6	28.5	17.7	2.2	1.3	0.7
20%	76.3	30.5	39.2	1.2	1.12	3.1
Cement/calcium chloride						
10%C, 0.5% CC	81.2	28.5	26.8	1.2	0.95	1.2
10%C, 2.0% CC	80.7	28.6	36.1	1.2	1.01	1.7
20%C, 0.5% CC	78.5	29.0	55.9	0.83	0.98	5.7
20%C, 2.0% CC	78.7	29.5	64.0	0.70	0.91	7.2
Cement/sodium sulfate						
10%C, 0.5% SS	79.8	29.9	14.6	1.1	0.93	0.7
10%C, 2.0% SS	80.1	29.8	22.5	1.15	0.96	0.8
20%C, 0.5% SS	79.2	29.8	46.4	1.2	0.89	2.6
20%C, 2.0% SS	79.6	30.3	55.1	0.8	0.85	2.3
Cement/hydrogen peroxide						
10%C, 20% HP	80.1	24.2	24.2	3.7	1.09	1.9
20%C, 20% HP	79.6	31.8	31.8	1.4	1.05	4.3
Lime 5%	78.5	30.4	18.5	8.1	1.35	0.0
10%	78.1	32.6	20.2	7.9	1.19	0.7
20%	76.9	33.2	29.2	8.5	1.11	0.6
Lime/fly ash						
5%L, 5% FA	79.6	31.2	14.1	20.5	1.15	0.0
10%L, 10% FA	80.0	30.7	21.1	14.2	1.20	0.7
Lime/cement						
5%L, 10% C	81.5	30.2	15.6	11.1	1.12	0.7
5%L, 15% C	82.0	31.3	23.2	8.7	1.06	1.3

Lime-fly ash

The fly ash used in the test was obtained from a power plant in Lowell, Massachusetts. It is realized that the composition of fly ash varies with place of origin, and the ash used in this study may be different from what would be used in the field, but the initial tests were conducted to determine whether or not more specific tests are warranted. Samples were prepared at various lime and fly ash combinations, but the total percent by dry weight of soil never exceeded 20%. Results of the laboratory tests (Table 4) indicate



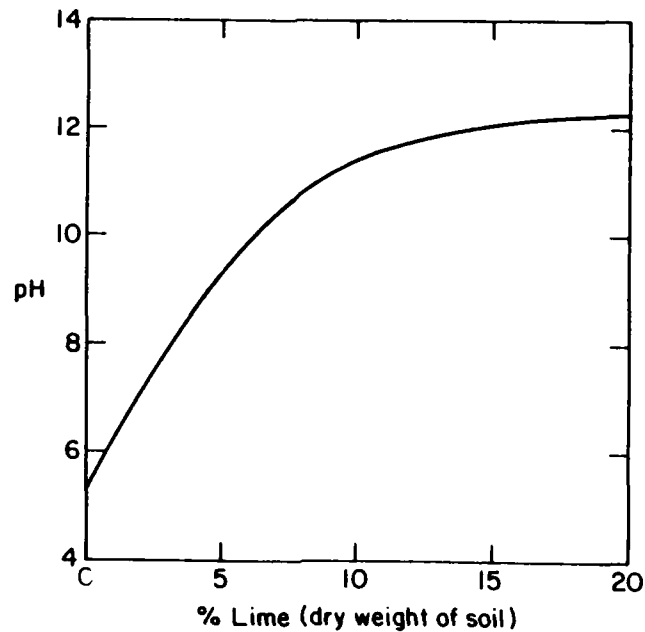


Figure 12. pH vs lime content.

that the addition of fly ash to a lime-stabilized soil has no significant effect on the unconfined compressive strengths (i.e., the strength at 10% lime without fly ash is 20.2 lb/in.<sup>2</sup> and with fly ash is 21.1 lb/in.<sup>2</sup>

#### Lime-cement

Lime was added to the soil as a pretreatment of the cement. The lime was mixed with the soil. After an hour of curing, cement was then combined with the mixture. Various combinations of lime and cement were tested, but none of these ever exceeded 20% total additives (cement and lime) by dry weight of soil. The pH and unconfined compressive strength of the lime-cement mixtures are shown in Tables 3 and 4 respectively. Contrary to what was expected, the lime appeared to interfere with the cement instead of enhancing it. At the 10 and 15% cement contents, adding 5% lime decreased the strengths from 17.7 to 15.6 lb/in.<sup>2</sup> and 28.5 to 23.2 lb/in.<sup>2</sup> respectively.

#### Summary of tests for cement and lime

##### Compaction test

For continuity, samples were compacted at three moisture contents -- optimum (29%) and  $\pm 5\%$  by dry weight of the untreated soil -- by a compactive effort equivalent to an AASHO T-180. If it was found that the three points were not sufficient to define the compaction curve, additional moisture contents were tested for that particular stabilizer. It was found that none of

the stabilizers had a major effect on the maximum dry density. The cement-stabilized soils tended to have densities slightly less than the untreated soil, particularly at high cement contents. The optimum water content was usually slightly higher for the treated samples than for the untreated soil. The lime-stabilized soils decreased in density and increased in optimum moisture content as the percentage of lime increased.

#### Permeability test

Samples were compacted at optimum moisture content and cured for 7 days at 70°F before running the permeability tests. The results of the tests are shown in Table 4.

The permeability of the cement-stabilized soil decreased with increasing cement content. Adding calcium chloride or sodium sulfate with cement further reduced the permeability compared to that of the cement-only stabilized soil. Results also indicate that the longer the cement has to hydrate (before the organics interfere) the larger the decrease in permeability. There is no correlation between lime content and permeability, but all of the lime-stabilized samples increased in permeability. When combined with cement and added to the soil, the lime seemed to counteract or hinder the performance of the cement, which in turn resulted in an increased permeability.

#### Frost heave

The samples were prepared as described in Frost Heave Test above, except that the soil was allowed to cure for 7 days at 70°F before beginning the test. In Table 4 the frost heave is expressed as a ratio of the rate of heave of the treated soil divided by the rate of heave of the untreated soil. Therefore a ratio of less than 1.0 is an improvement over the untreated sample.

A rather minor improvement in the frost susceptibility was realized for samples at a high cement content (10 to 20%) when treated with calcium chloride or sodium sulfate. It appears that when an ineffective stabilizer was present in the soil structure (i.e., low cement contents or lime), the frost heaving potential was increased.

#### California Bearing Ratio (CBR)

The CBR tests were conducted on the frost heave samples following 24 hours of thawing. A summary of these tests is shown in Table 4. CBR values increased with increasing cement contents; from 0.0 for 5% cement to 3.1 for 20% cement. At a cement content of 10 or 20%, the addition of 2% calcium

chloride more than doubled the original CBR values (i.e., at 20% cement, the CBR went from 3.1 to 7.2). Pretreating the soil with 20% hydrogen peroxide and then adding 20% cement resulted in a CBR of 4.3, compared to 3.1 for cement alone. Sodium sulfate increased the CBR values for low cement contents but decreased the CBR for high cement contents. Lime and/or fly ash had little effect on improving the CBR values of the untreated soil.

It should be noted that although the higher CBR values correspond fairly well to the lower permeabilities and lower frost heave ratios, the values were so low that small sample variations may have caused the differences in the results. For example, under normal conditions (CBR values of 50 or more), a CBR value change or discrepancy of 1 is usually considered irrelevant. However, a CBR value difference of 1 compared to the values in Table 4 is significant.

#### Asphalt emulsion

##### Asphalt emulsion alone

An emulsified asphalt of the slow-setting (SS) grade was used in this study. The SS grades have low viscosities and long workability times to ensure good mixing with the fine-grained soils. A cationic (CSS1) emulsion was chosen for the program because it performs better over a wider range of conditions (i.e., temperature, moisture, and soil type).

In asphalt stabilization, unlike that of cement and lime, the basic mechanism involved is waterproofing the material. Ideally, the asphalt covers the individual grains with a film that is thin enough not to reduce interparticle friction, but thick enough to allow for intergranular adhesion. Therefore, a complete blending of the soil and stabilizer is required. It is recommended (Scrimher et al., 1972) that the mixing time be limited to 1 to 2 minutes to prevent the asphalt from being stripped away from the soil particles. It was found during the testing program that it was virtually impossible to coat all of the soil particles in a silt. However, if agglomerations of the soil particles were coated with asphalt, the mixture would still be improved.

Asphalt emulsion contents of 2, 4, 6, 8, and 10% by weight of dry soil were tested. Figure 13 shows that the maximum density of the stabilized soil decreased as the emulsion content increased. It was also noted that the optimum liquid content (water plus emulsion) increased as the emulsion content increased, but the optimum water content slightly decreased (see Table 5). It appears that the emulsion displaced some of the water in the mixture.

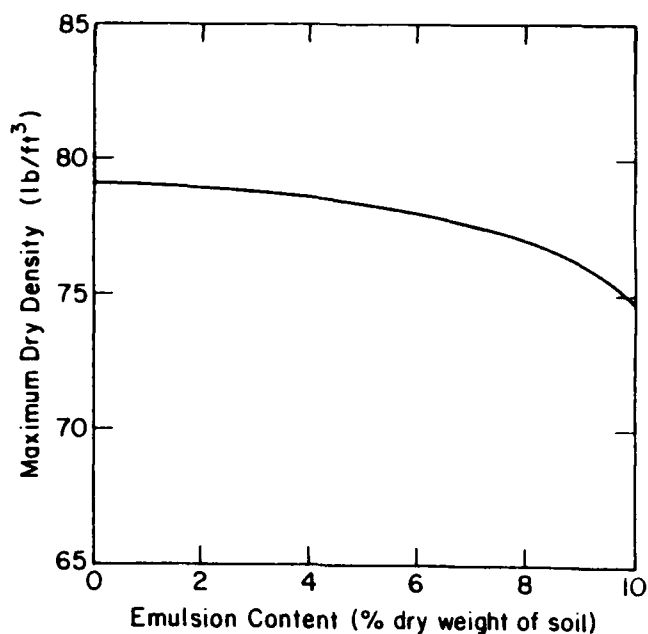


Figure 13. Soil density vs asphalt emulsion content.

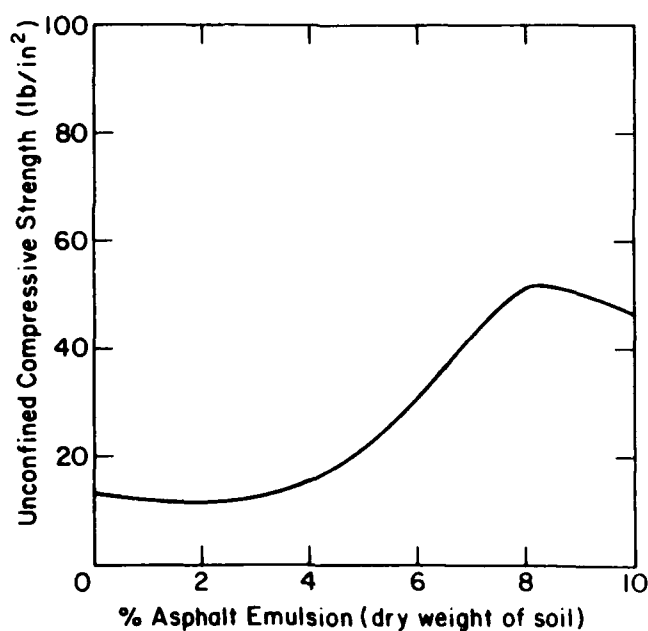


Figure 14. Unconfined compressive strength vs asphalt emulsion content.

Samples for the unconfined compression strength, Marshall stability, frost susceptibility, and permeability tests were prepared at the maximum densities mentioned above. The strength and stability curves, Figures 14 and 15 respectively, illustrate that the optimum amount of emulsion is approximately 8%. Permeabilities of the mixtures are shown in Table 5. There was no direct

Table 5. Asphalt emulsion tests

Asphalt emulsion (% dry weight soil)	Maximum density (lb/ft <sup>3</sup> )	Optimum liquid content (water + emulsion) (% dry weight soil)	Optimum water content (% dry soil)	Unconfined compression strength (lb/in. <sup>2</sup> )	Marshall stability strength (lbs)	Permeability (cm sec <sup>-1</sup> × 10 <sup>-5</sup> )	Frost-Heave ratio $\left( \frac{\text{Treated}}{\text{Untreated}} \right)$	After-thaw CBR
Untreated	79.1	29.0	29.0	13.4	0.0	4.5	1.0	0.4
2	79.4	29.6	27.6	11.6	72.1	7.2	1.72	1.1
4	78.6	30.8	26.8	15.2	104.7	5.7	1.26	2.6
6	77.7	31.7	25.7	30.9	206.2	1.3	0.98	3.2
8	77.4	33.7	25.5	51.6	211.3	0.28	0.85	3.7
10	74.9	34.2	26.2	46.1	205.5	0.18	0.81	3.8

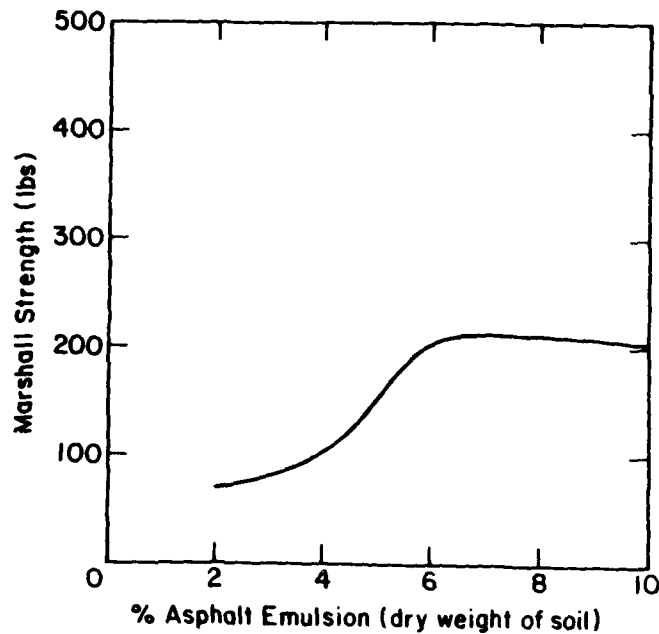


Figure 15. Marshall stability strength vs asphalt emulsion content.

correlation between asphalt content and permeability; the lower emulsion contents (2, 4, and 6%) increased the permeability where higher concentrations decreased it. This may be because the lower concentrations only partially coat the soil particles, which in turn results in paths along which the water can migrate. The frost heave ratio (heave of treated soil/heave of untreated soil) was indicative of the permeability: lower permeabilities resulted in lower frost heaves. After-thaw CBR values (Table 5) increased with increasing emulsion content.

The organics and fine-grained particles seem to be responsible for the relatively low values in Table 5. The large percentage of fines in the soil made it difficult to obtain a uniform mixture or complete coating of the particles. The role of the organics is unknown, but it is possible that the organic material interferes with the asphalt-soil-water reaction or that it coats the soil particles and prevents adequate adhesion between the emulsion and soil.

#### Lime/cement/asphalt emulsion

Lime and/or cement are often added to a soil prior to stabilizing with asphalt emulsion to increase the rate of curing, decrease permeability, and increase strength. Lime or cement values of 1, 3, and 5% of dry soil weight

were tested as additives. As in the previous experiments, the organics in the soil rendered the lime and cement ineffective. The unused lime/cement then compounded the problems of obtaining a uniform mixture and adequately coating the soil particles that had previously been experienced with the soil-emulsion mixture. As a result, strength, permeability, and frost susceptibility values were less than those for the normal soil-emulsion combination. No further testing was conducted.

#### Calcium acrylate

Calcium acrylate is an organic salt produced by compounding calcium carbonate and acrylic acid. The acrylate along with a catalyst (ammonium persulfate) and an activator (sodium thiosulfate) are mixed with the soil. Polymerization takes place and as a result the soil particles become linked by a strong and flexible polymer chain.

Lambe recommended using a 1:1 ratio of persulfate to thiosulfate. In this study, it was found that a 12% total catalyst (catalyst and activator), based on the acrylate weight, provided the optimum mixture. Therefore, the overall chemical mixture had the formula: 1 part persulfate, 1 part thiosulfate, and 16.6 parts acrylate.

The chemical was added to the soil by two methods: first, the dry acrylate, catalyst, and activator were mixed with the soil, which was already at the desired water content, and second, the soil was dried and the three components were added to the water needed to achieve the desired water content; the solution was then mixed with the soil. Preliminary results indicated no significant difference between the two application methods. Therefore, the chemicals were premixed with the water and then added to the dry soil. This made it easier to mix the material and to ensure a uniform distribution of the chemical in the soil. Percentages of calcium acrylate of 2.5, 5, 7.5, and 10% by weight of dry soil were tested. To be consistent throughout the evaluation process, the samples were moist-cured at 70°F for 7 days even though the reaction appeared complete after a few hours.

Tests showed that the 2.5% calcium acrylate had no significant effect on the soil properties. It is possible that such a small quantity of chemical cannot be thoroughly distributed in the soil mixture. Compressive strengths of the mixtures are shown in Figure 16. Strength increased with percent acrylate. At any given percentage of stabilizer, the maximum strengths occurred

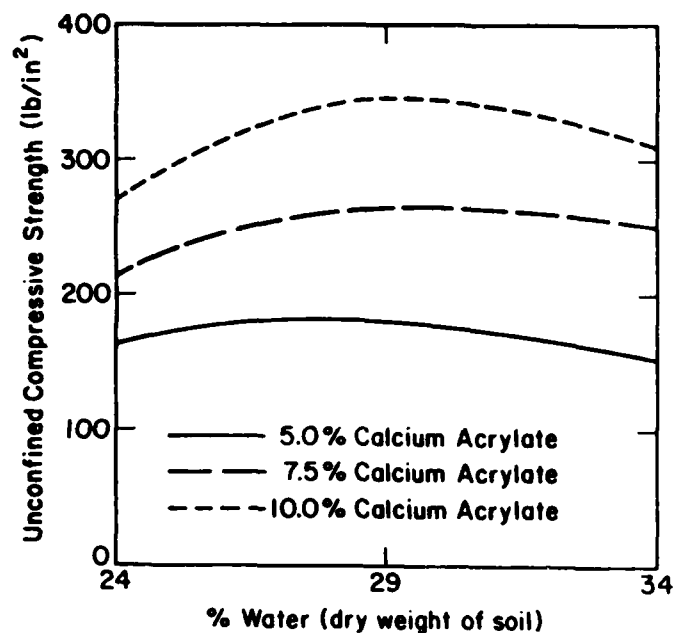


Figure 16. Unconfined compressive strength vs calcium acrylate content.

Table 6. Calcium acrylate tests

Calcium acrylate (% dry weight soil)	Unconfined compressive strength (lb/in. <sup>2</sup> )	Permeability (cm sec <sup>-1</sup> x 10 <sup>-5</sup> )	Frost-Heave ratio ( $\frac{\text{Treated}}{\text{Untreated}}$ )	After-thaw CBR
Untreated	13	4.5	1.0	0.4
2.5	17	4.2	1.03	0.68
5.0	170	0.81	0.59	6.7
7.5	264	0.25	0.39	16.3
10.0	348	0.09	0.35	21.2

near the optimum water content. The permeability and frost susceptibility decreased and thawed CBR values increased as the stabilizer content increased (see Table 6).

#### Tetrasodium pyrophosphate (TSPP)

Tetrasodium pyrophosphate is a dispersant that increases the density and strength of a soil by increasing interparticle repulsion, which in turn allows the particles to be manipulated into a denser and more orderly structure.



Table 7. Tetrasodium pyrophosphate tests

TSPP (% dry weight soil)	Maximum density (lb/ft <sup>3</sup> )	Optimum moisture content (% dry wt soil)	Unconfined compression strength (lb/in. <sup>2</sup> )	Permeability (cm sec <sup>-1</sup> x 10 <sup>-5</sup> )	Frost-Heave ratio ( $\frac{\text{Treated}}{\text{Untreated}}$ )	After-thaw CBR
Untreated	79.1	29.0	13.5	4.5	1.0	0.4
0.1	80.2	29.5	12.7	3.2	1.03	0.9
0.3	80.5	29.6	15.7	0.71	0.31	1.4
0.5	81.8	28.4	17.5	0.37	0.29	2.9
1.0	82.3	28.2	20.8	0.12	0.28	2.6
5.0	81.2	28.5	18.7	0.74	0.32	2.2

Previous tests (Lambe and Kaplar, 1971) revealed that TSPP was effective in decreasing the permeability and frost susceptibility of soil, could be used in small concentrations, was relatively cheap, reacted instantaneously, and required no special curing.

In this study, laboratory samples were treated with 0.1, 0.3, 0.5, 1.0, and 5.0% TSPP by dry weight of soil. Results of the tests are shown in Table 7. The addition of TSPP resulted in a mixture with a higher maximum density and the same, or slightly lower, optimum water content. The permeability (Fig. 17) and frost susceptibility of the soil improved, although the latter to a lesser extent. Contrary to what was expected, increased density and decreased frost susceptibility were not reflected in unconfined compression strengths and after-thaw CBR values, which were only slightly greater than in the untreated soil. This may be due to the high water content and the detrimental effects of the organics.

#### CONCLUSIONS

The results of a laboratory test program that was conducted to evaluate the effectiveness of various materials in stabilizing a fine-grained organic soil for low-volume road bases and/or sub-bases is summarized below and shown in Table 8.

Cement had very little effect on the soil properties. The organics apparently interfered with the cement's reaction and, in turn, the inactive cement caused detrimental side effects (i.e., higher frost-heave ratios).

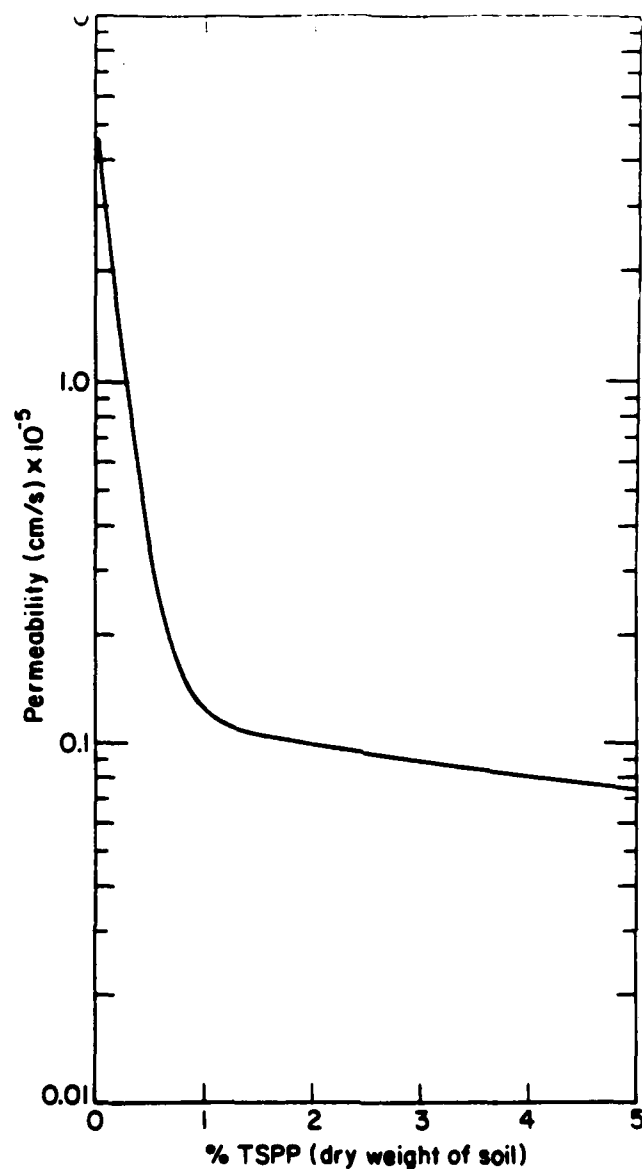


Figure 17. Permeability vs tetrasodium pyrophosphate content.

Best results were obtained at a 20% cement content, which exhibited an unconfined compressive strength of 39 lb/in.<sup>2</sup> and an after-thaw CBR value of 3.1.

Using the additives calcium chloride and sodium sulfate with cement increased the soil parameters slightly. The most promising results were obtained with 20% cement and 2% calcium chloride. The permeability and frost susceptibility were reduced and an unconfined compression strength of 64 lb/in.<sup>2</sup> and an after-thaw CBR value of 7.2 were obtained with these percentages.

Table 8. Results for each stabilizer

Stabilizer (percent by weight)	Unconfined compressive strength (lb/in. <sup>2</sup> )	Permeability (cm sec <sup>-1</sup> x 10 <sup>-5</sup> )	Frost-heave Ratio ( $\frac{\text{Treated}}{\text{Untreated}}$ )	After- thaw CBR
Untreated	13.4	4.5	1.0	0.4
20% cement	39.2	2.9	1.12	3.1
20% cement, 2% calcium chloride	64.0	0.70	0.91	7.2
20% cement, 2% sodium sulfate	55.1	0.80	0.85	2.3
20% cement, 20% hydrogen peroxide	31.8	1.4	1.05	4.3
20% lime	29.2	8.5	1.11	0.6
8% asphalt emulsion	51.6	0.28	0.85	3.7
10% calcium acrylate	348.0	0.09	0.35	21.2
1% TSPP	20.8	0.12	0.28	2.6

An attempt was made to counteract the effects of the organics by pre-treating the soil with lime or hydrogen peroxide prior to adding the cement. Neither stabilizer showed significant promise; the peroxide slightly improved the soil's parameters, but the lime had negative effects.

Lime and lime/fly ash tests indicated that lime was an ineffective stabilizer for this soil, which had a high organic content.

Asphalt emulsion was most effective at the 8 to 10% range. The permeability and frost-heave ratio were lowered to  $0.18 \times 10^{-5}$  cm sec<sup>-1</sup> and 0.81 respectively. An unconfined compressive strength of 51 lb/in.<sup>2</sup> and an after-thaw CBR value of 3.7 were obtained. Adding cement or lime to the soil before adding the emulsion caused no improvements in the soil parameters.

Calcium acrylate caused the highest strength values of all the stabilizers tested; an unconfined compressive strength of 348 lb/in.<sup>2</sup> and an after-thaw CBR value of 21.2. Since acrylate is effective only at concentrations exceeding 5% and the stabilizer is not manufactured on a large scale, it becomes uneconomical for all but special uses.

Tetrasodium pyrophosphate effectively reduced the frost susceptibility of the soil. The stabilizer was most effect at the 0.3-0.5% concentration; using percentages higher than this resulted in little improvement. The stabilizer had little effect on improving the strength of the soil.

A preliminary economic analysis was performed on the following stabilizers: cement, cement plus calcium chloride, asphalt emulsion, and tetrasodium pyrophosphate (see Appendix A). The estimated prices ranged from \$18/yd<sup>3</sup> for TSPP to \$39/yd<sup>3</sup> for cement plus calcium chloride. These estimates are conservative and one should expect the costs to be higher depending on: 1) location in Alaska (prices FOB Anchorage), 2) in-situ moisture content, 3) mixability of the soil and chemicals on a large scale, 4) actual production rate, and 5) length of construction season.

Based on the high unit cost and limited benefits achieved with the stabilizers, a field study with these stabilizers does not seem warranted.

#### RECOMMENDATIONS

The laboratory study summarized in this report produced results that warrant the following recommendations:

- 1) Consider using the stabilized soil in conjunction with another stabilizing system (e.g., TSPP-stabilized silt in a membrane-encapsulated soil layer (MESL)).
- 2) Evaluate adding limited quantities of an acceptable fill to the stabilized silt to improve soil properties otherwise unaffected by the stabilizer.
- 3) Depending on the additive, find an effective method of combining a stabilizer with a fine-grained soil (i.e., silt).
- 4) Further evaluate an effective means of neutralizing the effects of the organics in a soil.

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## APPENDIX A. PRELIMINARY ECONOMIC ANALYSIS

### Stabilizer Costs\*

**1. Cement (20%)**

**Source: Kaiser Cement, Anchorage, Alaska**

**Cost:** \$102.00 per ton or \$0.05/lb

$$(0.20) \times \frac{(79.1 \text{ lb})}{\text{ft}^3} \times \frac{27 \text{ ft}^3}{\text{yd}^3} \times \frac{\$0.05}{\text{lb}} = \$21.75/\text{yd}^3$$

2. Cement (20%) plus calcium chloride (2%)

**Source: Kaiser Cement, Anchorage, Alaska**

DOW Chemical, Midland, Michigan

**Cost:** Cement = \$21.75/yd<sup>3</sup>

Calcium chloride =	\$165.00 per ton or	\$0.08/lb
	shipping	\$0.14/lb
		<u>\$0.22/lb</u>

$$(0.02) \times \frac{(79.1 \text{ lb})}{\text{ft}^3} \times \frac{27 \text{ ft}^3}{\text{yd}^3} \times \frac{\$0.22}{\text{lb}} = \$9.40/\text{yd}^3$$

**Total = cement + chloride**

$$= \$21.75/\text{yd}^3 + \$9.40/\text{yd}^3 = \$31.15/\text{yd}^3$$

### 3. Asphalt Emulsion - CSS1 (8%)

**Source: Chevron USA, Anchorage, Alaska**

**Cost:** \$206.00 per ton or \$0.10/lb

$$(0.08) \times \frac{(79.1 \text{ lb})}{\text{ft}^3} \times \frac{27 \text{ ft}^3}{\text{yd}^3} \times \frac{\$0.10}{\text{lb}} = \$17.60/\text{yd}^3$$

#### 4. Tetrasodium Pyrophosphate (1%)

**Source: SMC, Newark, California**

**Cost: \$42.5 per 100 lbs or \$0.43/lb**

**\$0.06/lb**

\$0.49/lb

$$(0.01) \times \frac{(79.1 \text{ lb})}{\text{ft}^3} \times \frac{27 \text{ ft}^3}{\text{yd}^3} \times \frac{\$0.49}{\text{lb}} = \$10.50/\text{yd}^3$$

## 5. Calcium Acrylate

**Source:** Could not locate source for bulk quantities.

**\*All cost estimates FOB Anchorage, Alaska.**

### Equipment and Labor Costs

Source: Means Building Construction Cost Data 1985

Cost: Dry Chemicals

#### Equipment

1	Stabilizer, 310 HP	\$149.18/hr
1	Chemical spreader	15.90/hr
1	Vibratory roller, 29,000 lb	65.87/hr
1	Water truck, 5000 gal	83.89/hr
1	Motor grader, 30,000 lb	89.12/hr
		<u>\$403.96/hr</u>

#### Labor

1	Highway laborer	\$ 21.84/hr
4	Equipment operator (medium)	113.12/hr
		<u>\$134.96/hr</u>

Total for dry chemical

\$403.96/hr

\$134.96/hr

\$538.92/hr or \$4311.36/day

Assume stabilizer produces 5000 yd<sup>2</sup>/day at a 4-in. depth.

$$5000 \text{ yd}^2/\text{day} \times \frac{4 \text{ in.}}{36 \text{ in./yd}} = 555.6 \text{ yd}^3/\text{day}$$

$$\frac{\$4311.36/\text{day}}{555.6 \text{ yd}^3/\text{day}} = \$7.76/\text{yd}^3$$

Chemicals in solution or asphalt emulsion

#### Equipment

1	Stabilizer, 310 HP	\$149.18/hr
1	Vibratory roller, 29,000 lb	65.87/hr
1	Motor grader, 30,000 lb	89.12/hr
1	Distribution truck, 3000 gal	46.66/hr
		<u>\$350.83/hr</u>

#### Labor

1	Highway laborer	\$ 21.84/hr
4	Equipment operator (medium)	113.12/hr
		<u>\$134.96/hr</u>

\$350.83/hr.

134.12/hr.

Total for solutions or asphalt emulsion \$485.79/hr or \$3886.32/day

$$\frac{\$3886.32/\text{day}}{555.6 \text{ yd}^3/\text{day}} = \$7.00/\text{yd}^3$$

Total Cost

Cost (\$/yd <sup>3</sup> )			
<u>Stabilizer</u>	<u>Stabilizer</u>	<u>Equipment and Labor</u>	<u>Total</u>
Cement	21.75	7.76	29.51
Cement, CaCl <sub>2</sub>	31.15	7.76	38.91
Asphalt emulsion	17.60	7.00	24.60
TSPP	10.46	7.76	18.22



# APPENDIX B. LABORATORY RESULTS

Stabilizer	%	Additive	%	Dry unit weight (lb/ft <sup>3</sup> )	Molding water content (%)	Unconfined compressive strength (lb/in. <sup>2</sup> )	Permeability (cm sec <sup>-1</sup> × 10 <sup>-5</sup> )	Heave rate (mm/day)	After-thaw CBR
Untreated				72.2	24				
				79.1	29	12.1, 12.9, 15.2	4.5	9.6, 9.8, 10.9	0.4, 0.4, 0.5
				76.0	34				
Cement		Type I		79.3	29	5.1, 4.9, 0.0			
			2.0						
			5.0	78.8	24	9.7, 11.3, 10.6			
				79.8	29	8.8, 10.2, 11.0	2.9	12.1, 12.8, 11.5	0.0
				77.7	34	6.8, 8.4, 9.5			
			10.0	79.8	24	14.5, 16.6, 16.2			
				80.5	29	18.2, 18.0, 16.9	2.2	12.8, 13.0, 13.6	0.7, 0.7, 0.6
				77.8	34	17.5, 14.4, 13.8			
			15.0	79.6	29	26.5, 30.1, 28.9			
			20.0	74.1	24	40.1, 33.6, 32.9			
				75.8	29	43.2, 38.6, 35.8	1.2	11.5, 10.8, 11.6	2.6, 3.3, 3.4
				76.1	34	36.4, 33.1, 37.5			
		Type III		79.7	29	7.9, 11.1, 15.4			
			2.0						
			5.0	79.6	29	12.1, 13.3, 12.0			
			10.0	79.6	29	17.6, 19.4, 20.1			
			15.0	78.4	29	27.4, 25.8, 31.1			
			20.0	77.3	29	39.8, 44.4, 47.8			
Cement	5	Calcium chloride	0.5	79.3	29	13.5, 13.9, 12.2			
			1.0	79.7	29	13.6, 15.8, 16.1			
			2.0	79.5	29	16.8, 18.1, 16.6			
	10		0.5	80.0	24	24.5, 26.7, 29.0			
				81.1	29	30.1, 26.0, 24.3	1.2	8.8, 9.7, 10.3	1.4, 1.0, 1.2
				79.7	34	27.6, 24.5, 21.1			

\*Percent dry weight soil

Stabilizer	%	Additive	%	Dry unit weight (lb/ft <sup>3</sup> )	Molding water content (%)	Unconfined compressive strength (lb/in. <sup>2</sup> )	Permeability (cm sec <sup>-1</sup> x 10 <sup>-5</sup> )	Heave rate (mm/day)	After-thew CBR
	1.0		81.1	29	30.6, 35.1, 32.2				
	2.0		79.1	24	30.1, 26.1, 24.7				
			80.6	29	39.7, 33.6, 35.0	1.2	9.6, 10.3, 10.7	2.0, 1.6, 1.5	
			79.3	34	28.9, 26.6, 20.7				
15	0.5		79.4	29	40.0, 38.6, 41.2				
	1.0		79.1	29	45.2, 43.2, 46.4				
	2.0		79.6	29	49.4, 50.3, 47.6				
20	0.5		76.6	24	58.6, 55.2, 52.4				
			78.5	29	59.3, 57.6, 50.8	0.83	9.4, 10.5, 9.8	4.9, 6.5, 5.7	
			77.2	34	48.6, 49.9, 53.1				
	1.0		78.4	29	60.4, 63.2, 56.5				
	2.0		77.1	24	50.2, 46.3, 43.7				
			79.0	29	68.9, 61.8, 61.3	0.70	10.0, 8.9, 8.7	8.2, 6.8, 6.6	
			78.6	34	41.0, 45.6, 43.2				
Cement	5	Sodium Sulfate	78.7	29	11.5, 13.6, 10.8				
			78.8	29	13.9, 14.1, 15.0				
	2.0		78.6	29	18.5, 18.7, 19.4				
10	0.5		78.6	24	17.9, 19.4, 14.2				
			79.7	29	15.0, 13.1, 15.7	1.1	9.8, 8.9, 9.5	0.7, 0.7, 0.8	
			79.0	34	14.8, 12.2, 11.8				
	1.0		79.5	29	18.3, 20.0, 19.6				
	2.0		78.8	24	21.5, 20.2, 17.6				
			80.0	29	23.6, 19.8, 24.1	1.15	10.1, 9.6, 9.4	0.7, 0.8, 0.9	
			79.0	34	18.8, 17.9, 20.5				
15	0.5		79.8	29	29.8, 25.3, 24.6				
	1.0		79.3	29	26.8, 28.9, 30.3				
	2.0		79.6	29	29.7, 34.6, 33.1				
20	0.5		78.1	24	35.7, 36.9, 31.0				
			79.0	29	41.2, 46.8, 51.3	1.2	9.5, 8.8, 8.7	2.3, 2.9, 2.6	
			78.4	34	33.2, 34.1, 31.8				

\*Percent dry weight soil

Stabilizer	g*	Additive	g*	Dry unit weight (lb/ft <sup>3</sup> )	Molding water content (%)	Unconfined compressive strength (lb/in. <sup>2</sup> )	Permeability (cm sec <sup>-1</sup> x 10 <sup>-5</sup> )	Heave rate (mm/day)	After-thaw CBR
Cement	5	Hydrogen peroxide	20	79.2	29	50.1, 54.7, 54.5			
				78.6	24	41.0, 40.4, 37.6			
	10			79.6	29	56.2, 58.9, 60.3	0.8	8.6, 9.1, 8.1	30.0, 1.8, 2.1
				78.3	34	50.7, 51.5, 47.2			
	15			78.4	29	15.2, 13.9, 14.1			
				78.4	24	27.6, 26.5, ----			
	20			79.8	29	28.1, 23.5, 21.0	3.7	9.9, 10.8, 12.3	2.0, 1.6, 2.1
				79.7	34	22.6, 21.5, 20.7			
				78.3	29	32.4, 28.4, 31.3			
				77.7	24	31.0, 33.4, 28.1	1.4	10.8, 11.1, 9.9	5.6, 3.8, 3.5
Lime	5			79.5	29	36.3, 31.5, 27.6			
				79.2	34	31.1, 34.0, 27.1			
				77.2	24	22.8, 18.8, 17.2			
				78.1	29	21.3, 18.5, 15.7	8.1	12.8, 13.9, 14.2	0.0, 0.3, 0.0
	8			77.8	34	23.4, 20.5, 18.9			
				78.1	29	20.4, 15.7, 19.6			
	10			76.2	24	17.6, 15.9, 19.4	7.9	11.0, 12.4, 12.6	1.1, 0.5, 0.6
				77.7	29	19.8, 16.7, 24.1			
	15			78.0	34	19.4, 20.0, 18.3			
				77.4	29	29.6, 22.6, 23.4			
20		74.6	24	31.5, 28.4, 25.4					
		76.3	29	33.2, 25.6, 28.8	8.5	10.8, 10.9, 11.9	0.5, 0.7, 0.6		
Lime	5	Fly ash	5	76.8	34	34.0, 33.2, 35.7			
				79.4	24	13.5, 10.5, 14.3			
				79.5	29	12.8, 17.0, 12.5	20.5	12.2, 11.4, 11.2	0.0
				78.7	34	12.5, 16.8, 17.4			
				78.9	29	15.1, 18.3, 14.6			
				79.2	29	19.6, 15.6, 17.9			
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\*Percent dry weight soil

Stabilizer	%	Additive	%	Dry unit weight (lb/ft <sup>3</sup> )	Molding water content (%)	Unconfined compressive strength (lb/in. <sup>2</sup> )	Permeability (cm sec <sup>-1</sup> x 10 <sup>-5</sup> )	Heave rate (mm/day)	After-thaw CBR
Cement	10		10	78.8	24	15.5, 17.0, 13.6			
				79.9	29	22.2, 18.9, 22.1	14.2	12.5, 12.1, 11.8	0.9, 0.9, 0.4
				79.2	34	12.8, 11.9, 13.4			
	10	Lime	5	80.5	24	13.1, 12.8, 10.9			
				81.4	29	14.6, 15.1, 17.1	11.1	10.9, 12.0, 11.0	0.6, 0.6, 0.8
				81.4	34	15.2, 13.3, 12.7			
	15		5	79.9	24	15.8, 16.1, 13.9			
				81.5	29	25.0, 23.1, 21.5	8.7	10.2, 9.9, 12.0	1.0, 1.4, 1.5
Asphalt emulsion				81.2	34	24.2, 20.7, 18.6			
	2			78.0	4	10.6, 7.9, 8.8			
				79.3	29	12.5, 10.4, 11.9	7.2	15.8, 18.1, 18.2	0.9, 1.0, 1.4
	4			77.4	34	8.5, 7.5, 9.9			
				77.6	24	14.3, 16.1, 13.8			
				78.2	29	17.0, 15.2, 13.4	5.7	13.0, 12.4, 12.8	2.5, 2.5, 2.8
				75.7	34	10.5, 9.8, 12.2			
	6			76.8	24	29.1, 28.6, 31.2			
				77.0	29	28.8, 30.1, 33.8	1.3	9.8, 10.1, 9.7	2.9, 3.6, 3.1
				74.8	34	25.0, 23.7, 22.9			
	8			77.1	24	48.9, 54.2, 50.9	0.28	8.2, 8.5, 9.0	3.5, 3.6, 4.0
				76.7	29	47.2, 48.3, 59.3			
Asphalt emulsion				75.0	34	33.4, 39.8, 31.8			
	10			74.3	24	41.9, 45.6, 39.8			
				74.7	29	43.3, 48.1, 46.9	0.18	9.0, 7.9, 7.6	3.2, 4.0, 4.2
				73.2	34	29.7, 31.2, 32.0			
	8	Cement	1	78.2	29	15.6, 18.1, 20.2			
			3	78.7	29	20.3, 24.5, 26.1			
			5	78.9	29	21.3, 19.7, 18.9			
		Lime	1	78.5	29	24.2, 27.3, 25.6			
Calcium acrylate			3	78.0	29	28.1, 29.0, 29.4			
			5	77.8	29	26.5, 26.1, 23.2			
	2.5			76.4	24	14.3, 12.8, 14.1			
				78.6	29	15.8, 17.1, 18.1	4.2	10.4, 11.1, 9.8	0.6, 0.9, 0.7
				77.8	34	16.3, 16.6, 13.4			
	5			76.6	24	149.8, 176.2, 166.9			

\*Percent dry weight soil

Stabilizer	%	Additive	g*	Dry unit weight (lb/ft <sup>3</sup> )	Molding water content (%)	Unconfined compressive strength (lb/in. <sup>2</sup> )	Permeability (cm sec <sup>-1</sup> x 10 <sup>-5</sup> )	Heave rate (mm/day)	After-thaw CBR
				78.3	29	159.0, 168.3, 182.7	0.81	5.4, 6.0, 6.4	7.5, 6.2, 6.4
	7.5			77.9	34	149.0, 151.2, 155.8			
				76.4	24	221.8, 218.7, 204.5			
				78.0	29	289.4, 256.7, 245.9	0.25	3.2, 4.1, 4.5	14.5, 18.2, 16.2
	10.0			77.6	34	261.3, 255.3, 236.9			
				76.8	24	258.4, 281.6, 273.6			
				77.9	29	334.7, 368.1, 341.2	0.09	2.7, 3.9, 4.1	18.9, 20.3, 24.4
				76.4	34	300.5, 311.6, 329.4			
Tetrasodium pyrophosphate	0.1			78.2	24	11.9, 10.8, 11.5			
				80.1	29	14.1, 12.4, 11.6	3.2	10.3, 11.0, 9.9	0.9, 0.5, 1.2
				78.6	34	13.7, 14.0, 12.1			
	0.3			77.8	24	10.8, 11.3, 11.7			
				80.2	29	14.6, 17.5, 15.0	0.71	2.9, 3.2, 3.3	1.3, 1.4, 1.5
				79.1	34	13.0, 12.6, 11.1			
	0.5			80.0	24	14.4, 15.1, 13.2			
				81.6	29	16.8, 17.7, 18.0	0.37	3.0, 2.8, 2.9	2.5, 3.3, 2.9
				79.2	34	15.6, 16.0, 13.9			
				79.9	24	17.6, 19.5, 19.8			
	1			81.0	29	19.8, 19.5, 23.1	0.12	2.6, 2.7, 3.2	2.1, 3.0, 2.7
				80.2	34	18.7, 17.4, 19.1			
		5.0		78.7	24	14.5, 13.7, 12.6			
				80.9	29	16.9, 18.7, 20.5	0.74	3.1, 3.4, 3.2	1.8, 1.9, 2.9
				78.2	34	13.2, 9.8, 10.5			

\*Percent dry weight soil

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