A LITERATURE SEARCH FOR
SUBSTITUTE MATERIALS IN
FROST PROTECTING LAYERS

Final Report

by

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This report summarizes results of a literature search on soil stabilizers to reduce frost action in highways, railways, and airfields, and concentrates primarily on cements and asphalt stabilizers. Construction measures such as membrane encapsulated soil layers (MESL) were also evaluated.

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Soil Stabilization, Highways, Asphalt, Cement, Encapsulation

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1. INTRODUCTION

Damage to highways, railways, and airports due to frost action is a major concern in cold climates. Generally, this is prevented by use of clean sands and gravels known as non-frost susceptible (NFS) materials since they are not susceptible to ice-segregation and growth when frozen.

Since sands and gravels, and alternative manufactured materials are often expensive, hard to find, or are becoming environmentally sensitive to acquire, it becomes increasingly urgent to find substitute materials for use in frost protecting layers. Use of ordinary on-site materials in place of expensive materials which may have to be hauled in from distant borrow areas, should have monetary and time savings in addition to lowering environmental impact.

Many investigators at home and abroad have published information related to substitute NFS material. This data and facts to be rediscovered by a new research project are given too little consideration in the preparation of standards and specifications, etc. Moreover, some of the information may not be pertinent to the substitute material although it may be useful for the protection of frost penetration layers.

The main purpose of this report is to make a literature search of the available data and facts which may be useful for the detection of potential substitute materials, such as asphalt or cement treated materials. The potential substitute materials are analyzed in terms of physical and mechanical characteristics to increase strength, decrease their frost susceptibility, and upgrade their quality for construction.

Construction measures such as membrane encapsulated soil layer (MESL) are evaluated. Recommendations are given for future research works.
2. STABILIZATION TECHNIQUES

2.1. Introduction

There are many techniques to stabilize soil (1,2,3,4,5). Out of these, Portland cement and emulsified asphalt seem most promising in the proposed study.

Various aspects of cement treated and asphalt emulsified materials are covered in the following sections. A detailed literature search is also made and the related information is given in Appendix A and Appendix B.

2.2 Soil-Cement

The basic concept of soil-cement or cement stabilized soil is not new. Investigators of mixtures of soil and cement began in the early 1930's. During the period of 1933 and 1934, many test sections were investigated and the performance of these test sections showed that soil-cement can be mixed together to form a low-cost base material for roads. In 1929, the discovery of the moisture-density relationship was an important factor to soil-compaction technology and its development. As a result of these studies, dependable and predictable test methods were developed which can be used to determine the quantities of soil, cement, and water to use. Research by the Portland Cement Association led to the development of the basic cement factors for soil-cement construction. In using soil-cement, proper considerations must be given to mix design, thickness design, and construction procedures.

Robbins and Packard (6) discussed the cement-stabilized soil as a construction material. Various reports by the Portland Cement Association (7,8,9,10) outline laboratory properties, mix design, and construction guidelines. Various highway research records (11,12,13,14) reported laboratory results of cement-treated soils. Special freeze-thaw methods and durability tests were developed to determine the strength and behavior of cement-treated soils.
Arman, et al (15) investigated the effect of admixtures and delayed compaction on stabilized soil-cement. He concluded that admixtures like calcium lignosulfonate and hydroxylated carboxylic acid are effective in creating a bond between subsequent layers of soil-cement and the admixtures generally improved the durability of the stabilized materials. Lamb (16,17) presented laboratory data on soil-cement to show that plasticity and frost susceptibility of fine-grained soils can be altered by trace amounts of dispersants such as polyvinyl alcohol and calcium sulfonate.

In later analysis Moh and Lamb (18) showed the sodium carbonate, sodium hydroxide, sodium sulfate and potassium permanganate are the most effective additives used in improving the strength of soil treated with Portland cement.

Jessberger (19) completed a doctorate thesis on the frost-resistant paving of frost-sensitive gravel and sand mixtures. He reported laboratory test results of cement treated silty gravelly and sandy soils which are generally considered as frost susceptible. Jessberger and Ebel (20) published data on the frost susceptible test for soil compaction with cement and lime.

The search for frost susceptibility of cement stabilized soils has a limited background. Johnson et al (21) studies the frost susceptibility characteristics of cement stabilized soils. Their laboratory studies did not show a definite relationship between hydraulic conductivity and frost susceptibility of cement stabilized soils. The Civil Engineering Department, University of Alaska, Fairbanks (22) studies the stabilization of silty soils in Alaska for highway construction and concluded that there was no single solution to the silt stabilization problem from the frost effects point of view. Possible solutions were: addition of economical percent of cement, addition of sodium phosphate dispersant and enclosure of the fill in a plastic membrane.
Construction with soil-cement stabilized material requires the uniform application and mixing of portland cement, moisture control at time of compaction, density control, curing, and time restrictions to prevent partial hardening of the mix before compaction. Based on available data (23), the portland cement is best suited for soils with a PI less than 10 and less than 25% passing the no. 200 sieve. The factors that affect the stabilized soil-cement are type of soil, percentage of cement, moisture content, and density. A selected bibliography on the soil-cement stabilization is given in Appendix A.

2.2.1 Soil-Cement Mix Design

Several mix design procedures such as the Portland Cement Association (PCA) method, the U.S. Air Force method (24) and others have been used in cement stabilization of soils. Generally, durability tests and/or the unconfined compressive strength tests serve as criteria for determining the minimum cement requirements. The maximum allowable weight loss and usual range of cement required for soil-cement mixtures are presented in Table 1 (25). The usual range of seven day unconfined wet compressive strengths for soil-cement mixes are given in Table 2. The durability test consists of 12 cycles of wetting and drying tests. (AASHO T-135-70) and 12 cycles of freezing and thawing tests (AASHO T-136-70). The samples are brushed at the end of each cycle and the weight loss of tested samples is determined after the 12 cycles of tests.

A quick method may be used for sandy soils (8) to determine the mix design from the relationships given in Figures 1 and 2.

2.2.2 Evaluation of Cement-Stabilized Soil

In addition to unconfined compressive strength and durability, other types of tests are used to evaluate the properties of soil-cement mixtures, such as tensile strength, flexural strength, modulus of elasticity,
Table 1  SOIL-CEMENT MIXTURES (25)

<table>
<thead>
<tr>
<th>AASHTO Group</th>
<th>Unified Soil Group</th>
<th>Usual Cement Requirements&lt;sup&gt;a&lt;/sup&gt; % By Vol.</th>
<th>% By Wt.</th>
<th>Max Allowable Wt. Loss %</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-1-a</td>
<td></td>
<td>5-7</td>
<td>3-5</td>
<td>14</td>
</tr>
<tr>
<td>A-1-b</td>
<td></td>
<td>7-9</td>
<td>5-8</td>
<td>14</td>
</tr>
<tr>
<td>A-2</td>
<td></td>
<td>7-10</td>
<td>5-9</td>
<td>14&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>GP, SP, SM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-3</td>
<td></td>
<td>8-12</td>
<td>7-11</td>
<td>14</td>
</tr>
<tr>
<td>A-4</td>
<td></td>
<td>8-12</td>
<td>7-12</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>CL, ML, MH</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-5</td>
<td></td>
<td>8-12</td>
<td>8-13</td>
<td>10</td>
</tr>
<tr>
<td>A-6</td>
<td></td>
<td>10-14</td>
<td>9-15</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>CL, CH</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A-7</td>
<td></td>
<td>10-14</td>
<td>10-16</td>
<td>7</td>
</tr>
</tbody>
</table>

<sup>a</sup> Soil-Cement Laboratory Handbook (8)
<sup>b</sup> Except A-2-6, A-2-8 where 10% is max. allowable

Also 1. Maximum ∆V during durability test <2% of initial volume.

2. Maximum water content during test < quantity to saturate at time of molding.

3. Compressive strength must increase with age.
<table>
<thead>
<tr>
<th>Soil Type</th>
<th>7-Day Wet Compressive Strength (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandy and gravelly soils:</td>
<td></td>
</tr>
<tr>
<td>AASHO groups A-1, A-2, A-3</td>
<td>300-600</td>
</tr>
<tr>
<td>Unified groups GW, GC, GP, GF SW, SC, SP, SF</td>
<td></td>
</tr>
<tr>
<td>Silty soils:</td>
<td></td>
</tr>
<tr>
<td>AASHO groups A-4 and A-5</td>
<td>250-500</td>
</tr>
<tr>
<td>Unified groups ML and CL</td>
<td></td>
</tr>
<tr>
<td>Clayey soils:</td>
<td></td>
</tr>
<tr>
<td>AASHO groups A-6 and A-7</td>
<td>200-400</td>
</tr>
<tr>
<td>Unified groups MH and CH</td>
<td></td>
</tr>
</tbody>
</table>
Figure 1. Soil-Cement Mixtures
Minimum 7-day compressive strengths required for soil-cement mixtures not containing material retained on the No. 4 sieve.

Minimum 7-day compressive strengths required for soil-cement mixtures containing material retained on the No. 4 sieve.

Figure 2. Minimum Strength Requirements for Soil-Cement Mixtures. (8)
California Bearing Ratio, and fatigue. In order to use the cement-treated soil as substitute materials for the frost protecting layers, it has to make certain that frost heaving will not exceed beyond the acceptable limit. Frost susceptibility tests are required to evaluate such requirements. The literature search for frost susceptibility of cement stabilized soils has a limited background.

Some of the laboratory tests data on frost susceptible soils are reported by Jessberger (Ref. Fig.11(20)). The relationship shown in the figure clearly shows the positive effect of cement treatments as the frost heave is greatly reduced compared to untreated soils. Johnson et al. (21) studied the frost susceptibility of cement stabilized soils. It has been reported by various investigators that the compression resistance values are to be established for the cement stabilized soils in terms of an upper and a lower limit. The lower limit is established by the frost resistance of the soil to be stabilized. In the upper limit, one must observe the crack formation which must be prevented or at least restricted. Such cracks develop in supporting layers, stabilized with cement, due to shrinkage, temperature differences, and traffic loads. Compression resistance figures, therefore, should not be selected too high.

Chang (25) completed a M. S. thesis on the evaluation of selected marginal aggregates stabilized with cement. The tested aggregates were from different locations of the Oregon Coast and typical gradations of aggregates investigated are given in Table 3. Mix properties such as unconfined compressive strength, durability, tensile strength, dynamic modulus, and fatigue were published in the report. The frost susceptibility tests are only missing in the report. Hamze (26) reported the mechanical performance of stabilized sands. Eight sands were chosen to study the effects of grading, angularity and mineralogy on workability, compactability, compaction, and stability in terms of the compaction and temperature resistance to rutting and creep.
### TABLE 3. AGGREGATE GRADATIONS (25)

<table>
<thead>
<tr>
<th>Sieve Size</th>
<th>Big A Sandstone</th>
<th>Marine Basalts</th>
<th>Dredged Spoils</th>
</tr>
</thead>
<tbody>
<tr>
<td>3/4&quot; (20 mm)</td>
<td>100</td>
<td>100</td>
<td>199</td>
</tr>
<tr>
<td>1/2&quot; (13 mm)</td>
<td>93</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>3/8&quot; (10 mm)</td>
<td>89</td>
<td>86</td>
<td>86</td>
</tr>
<tr>
<td>1/4&quot; (6 mm)</td>
<td>81</td>
<td>67</td>
<td>67</td>
</tr>
<tr>
<td>No. 4 (4.76 mm)</td>
<td>75</td>
<td>55</td>
<td>55</td>
</tr>
<tr>
<td>No.10 (2.0 mm)</td>
<td>60</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>No.40 (0.425m)</td>
<td>39</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>No.200 (-.074 mm)</td>
<td>15</td>
<td>9</td>
<td>9</td>
</tr>
</tbody>
</table>
Figure 3 (a). Aggregate Gradations for Basalt and Sandstone.

Figure 3 (b). Dune Sand Gradation (34)
2.3 Asphalt Emulsions

Stabilization of granular base materials, particularly marginal aggregates with emulsified asphalt has increased in recent years because of economical and environmental advantages. Based on field experience and laboratory tests to estimate propositions of materials, various mix designs have been developed (27,28,29,30,31). George (32) investigated the stabilization of sands and sand-clay aggregates with asphalt emulsion. Darter et al (33) summarized procedures that have been developed for both mix and structural design of emulsified aggregate bases for low volume roads. Finn et al (28) reported about projects where asphalt treated bases are used. These studies indicate that mixing asphalt bonding agents into a soil give "lasting stabilization through production of a flexible, frost sand water resistant layer with increased bearing capacity". Evans (34) reported the properties of marginal aggregates treated with asphalt emulsion. Typical gradations of aggregates investigated by Evans are shown in Figure 3 and the results of various tests such as the dynamic modulus, fatigue characteristics, tensile strength, temperature susceptibility and durability characteristics included in the report.

A major research work was carried out at the University of Illinois, sponsored by the Illinois Department of Transportation and the Federal Highway Administration, to develop practical mixture and structural design procedure that could be used for low volume roads. A selected bibliography on the asphalt emulsion stabilization is presented in Appendix B.

2.3.1 Asphalt Emulsions Mixture (AEM)

The mixture design generally involves the following major parts:

(i) Aggregate quality test
(ii) Emulsified asphalt quality tests
(iii) Estimation of amount of asphalt emulsion content
(iv) Compatibility of emulsion and aggregate
(v) Optimum water content at compaction
(vi) Selection of optimum asphalt content

Tests are done to determine aggregate properties and general suitability. A wide variety of aggregates including crushed stone or gravel, pit or bank run gravel, slag, sand, and silty sand has been used. Sub-standard aggregates have made satisfactory AEM bases on low volume roads in Illinois. Only aggregates containing excessive amounts of clay and certain hard to coat aggregates have caused problems in cold AEM. Table 4 presents the design criteria of AEM.

2.4 Other Methods

These include the chemical stabilization of subgrade material and the use of phosphate. The Federal Highway Administration reported (35) various projects where the chemical stabilization of subgrade material was investigated. The stabilization treatment was sought to reduce the high organic content and improve the moisture characteristics of the unsuitable materials. The stabilization would reduce the depth of undercut and the amount of backfill. The chemical/water mixture was provided by Saunders Chemical Company of Greeley, Colorado. A typical chemical/water mixture for application on 587 square yards of subgrade at 8 inches thick contains 15 gallons of cla-pak, 10 gallons of cla-set, 1.5 gallons SA-1, and 1000 gallons of water. Based on the field tests, it was concluded that the chemical stabilization was cost effective and the stabilized material performed well. Floria General Equities Inc. reported the use of the Phoenix method which involves a proprietary formula known as SA-1 chemical per 600 square yards of road surface to one thousand water solution. Before the SA-1 application, the native soil surface of the future road was loosened with a farm disc to provide speedy entry of the chemical solution and to make more air available to expedite its action. Then vibratory compaction was used to finish the stabilized base. It was recommended that the SA-1 chemical
### TABLE 4(a). EMULSIFIED ASPHALT-AGGREGATE MIXTURE DESIGN CRITERIA (33)

<table>
<thead>
<tr>
<th>Test Property</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stability, N (lb) at 22.2°C (72°F)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Paving Mixtures</td>
<td>2224 (500)</td>
<td></td>
</tr>
<tr>
<td>Percent Total Voids</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compacted Mix (granular mixes, no requirement for sand)</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>Percent Stability Loss</td>
<td></td>
<td></td>
</tr>
<tr>
<td>After 4 days soak at 22.2°C (72°F)</td>
<td>---</td>
<td>50</td>
</tr>
<tr>
<td>Percent Absorbed Moisture</td>
<td></td>
<td></td>
</tr>
<tr>
<td>After 4 days soak at 22.2°C (72°F)</td>
<td>---</td>
<td>4</td>
</tr>
<tr>
<td>Aggregate Coating (%)</td>
<td>50</td>
<td>--</td>
</tr>
</tbody>
</table>

### TABLE 4(b). EMULSIFIED ASPHALT PROPERTIES FOR HFE-300 GRADE USED.

- Specific gravity at 15.5°C (60°F) 0.990
- Viscosity, Saybolt Furol, at 50°C (122°F) 110.4 seconds
- Sieve test, retained on No. 20 sieve .016%
- Settlement 1.4%
- Coating test, 3 minutes Passed
- Float test at 60°C (140°F) 1200+ seconds
- Distillation test to 260°C (500°F)
  - Residue from distillation 70%
  - Oil distillate, by volume 1.5%
- Characteristics of residue from distillation test to 260°C (500°F)
  - Specific Gravity at 25°C (77°F) 0.980
  - Penetration at 25°C (77°F), 100 g, 5 sec 380+
be used well in advance of construction - as much as a year if possible. The repeated wet-dry cycles of normal rainfall thus enable maximum benefit of the SA-1 oxygen reaction with the organic matter. The process can be accelerated by increasing the strength of the SA-1 solution and also increasing the rate of application. Where heavy load capacity is required, an addition of two to four inches of sand, clay, shell, or aggregate borrow, disced in thoroughly with one gallon of RC-70 cutback asphalt per square yard of road surface was recommended.

It is reported by various authors (49) phosphoric acid and phosphous compounds are suitable stabilizers for fine-grained soils. There are several variables such as moisture content, degree of compaction, degree of mixing and curing, amount of stabilizer, type of soil and type of exposure that affect the stability of soil treated with phosphoric acid. The effect of concentration range varies from 1 to 5 percent phosphoric acid. The reaction in the treated soil mass clearly requires at least a few days before a substantial amount of cementing takes place. Most acidic soils containing an appreciable amount of clay minerals will respond well to phosphoric acid treatment.

Hemwall and Scott (50) revealed that sulfuric acid in conjunction with either rock phosphate or phosphoric acid does result in improved treatments. Guinnee (51) reported field studies of two clayey soils stabilization with phosphoric acid and found promising results of stabilizing effect. Beltz and Muller-Schiedmayer (52) reported the behavior of three German soils (a loamy soil, silty sand and sandy soil) of different origin stabilized with sodiumtripolyphosphate and sodiumpyrophosphate. They found that the amount of frost heave and water intake vary as functions of the added amounts of polyphosphates. The effectiveness of sodiumtripolyphosphate is somewhat greater than that of sodiumpyrophosphate, especially for the very frost-susceptible fine-grained soil. A polyphosphate admixture of less than 0.5 percent by weight reduces frost heave by at least 85 percent. Also, the total water content after thawing of frost stabilized soils does not exceed the value of the optimum moisture content at standard proctor density.

Other chemicals which can be effectively used to reduce the potential frost heave characteristics are indicated in Table 5 (54).
2.5 Membrane Encapsulated Soil Layer (MESL)

The MESL technique is not new. However, recently more effort has been made to critically evaluate this technique. In 1930, an asphalt membrane was used on a test section of road in Bavaria (36), and various investigators reported on the encapsulation of soils with asphalt membrane (37,38, and 39). Bell and Yoder (40) made a comprehensive research study of MESL and ACFEL (41) concluded that in controlled closed-system freezing of a 0.15 m high soil sample, limiting the initial percent saturation of compacted soil specimens to about 70%, reduced heave substantially and also reduced moisture gain in the upper 20 to 25 mm of the sample.

Peyton et al. (42) reported a laboratory study on the encapsulation with either polyethylene or vinyl plastic sheets of the silt (loess) soil. The use of MESL in construction also has been studied at the Waterways Experimental Station (43). Burns (44) successfully used a MESL containing highly compacted lean clay (CL) to support test traffic of a 12-wheel assembly load on 164,000 kg. Quinn and Johnson (45) reported laboratory studies on three soils: a moderately plastic clay (CL) from Ellsworth Air Force Base, South Dakota, a sandy silt (ML) from Hanover, New Hampshire, and a lean clay (CL) from Elmendorf Air Force Base, Alaska. Various tests such as compaction, CBR and freezing tests were carried out. The test results showed the interdependence of heave and post-thaw CBR. Also the results suggest that the previous indications (40,41) that initial degree of saturation below 70% will serve to restrict heave and moisture migration and inference that thaw weakening can be minimized if encapsulated clay soils are initially compacted at less than 80% saturation, should be applied with caution.

Smith et al. (46) reported repetitive loading tests on MESL road sections located at CRREL in Hanover, New Hampshire. They determined the resilient deformation modulus of the encapsulated soil layers and non-encapsulated soil layers under freeze-thaw cycles. They concluded that soil moisture migration was not a problem in the membrane-enveloped silt and moisture
contents equivalent to about 75% saturation for the 12,000 ft-lb/ft\(^3\) compaction effort. Smith (47) reported the results of field tests conducted on two permanent MESL road test sections located at Anchorage and Fairbanks. Laboratory tests consisting of compaction, freezing and CBR were also carried out on Elmendorf Air Force Base silty clay and Fairbanks silt. The laboratory tests on silty clay showed little heave (0.3 mm) at water contents between ±2% of optimum for the clay (fig. 3 of ref. 47). The after thawing CBR value decreased dramatically with small increase in total heave. The total heave of the clay increased significantly with increased compacting effort.

The closed system laboratory tests on Fairbanks silt under a freezing rate of 0.25 in/day showed an increase of height about 15% of the original 6 in. The moisture redistribution in the sample after the freezing ranged from 6.8% in the bottom unfrozen zone to 45% in the top inch as compared to a uniformly distributed 26.8% before freezing. Likewise, as for the clay, the total heave for the silt is nearly a constant amount for a given degree of saturation regardless of compacting efforts. The after-thaw CBR value for the silt with high moisture content is greatest for the 12,000 lb-ft/ft\(^3\) compacting effort (compared with 26,000 and 55,000 lb-ft/ft\(^3\) compacting effort). Results show a drastic decrease in after-thaw CBR values of the silt at saturation level above 70% for the higher compacting effort.

The field test sections both at Elmendorf Air Force Base, Anchorage, and Ft. Wainwright, Fairbanks, showed slight increase in moisture content and the field CBR values during the spring thaw were the same as the prefreeze values during the construction.
3. DISCUSSION AND CONCLUSIONS

This study shows that different soil types can be stabilized with cement, asphalt emulsions and chemical compounds to meet the requirements of "substitute materials" in place of non-frost susceptible soils in frost protecting layers. The engineering properties of soils can be beneficially modified by admixture stabilization procedures. Guidelines are available for mixture design, construction specifications and procedures on the stabilization techniques. However, information pertaining to use of frost prone materials in frost protection layers is limited. A complete investigation on the use of in-situ materials which may not satisfy the frost susceptibility criteria, is needed to replace the often expensive non-frost susceptible soils.

Various investigators have reported that treated soils with portland cement admixed with various agents like calcium lignosulfonate and hydroxylated carboxylic acid show promising results of improved physical properties. They are effective in increasing bond between subsequent layers of soil-cement and generally improved the durability of the stabilized material. Studies abroad have indicated the reduction of potential frost heave by the use of lignosulfonate admixture in cement treated frost susceptible soils. However, studies in this country show the opposite effects. As such, the limitations on the use of such admixtures in the treated soils remain to be seen.

The use of various additives appears to reduce plasticity and frost susceptibility. Various dispersants such as sodium carbonate, sodium hydroxide, sodium sulphate and potassium permanganate have improved the strength of soils treated with portland cement. However, their influence in the reduction of potential frost heave is not clearly established. An overall evaluation of additives as frost heave modifiers was reported by Lambe et al. (53,54). The additives were divided into four major
groups according to their action in soil: (i) void fillers and cementing agents, (ii) aggregants, (iii) water proofers and (iv) dispersants (Ref. Table 5). The overall evaluation of additives is presented in Table 6.

A recent study on the use of marginal aggregates treated with cement and asphalt emulsions as base or subbase materials shows promising results. Standard durability tests including wet/dry and freeze/thaw test, unconfined compression, tensile strength and fatigue test showed many favorable results. However, additional investigations are required to determine their frost susceptibility characteristics and performance under thaw-weakening period. Such treated marginal aggregates can provide high quality base for the pavement.

Though various chemical compounds may be successfully used to stabilize soils, they are not suitable for large scale use for one or more of the following reasons:

i) The stabilizing agent and soil cannot be blended and intimately mixed because of the high plasticity, high clay content, excessive moisture content, lack of workability of the natural soil,

ii) general construction problems such as effective dispersion, time limitations,

iii) logistics with storage and transportation,

iv) high cost,

v) it may be dangerous to work with some stabilizers,

vi) water attack and leaching to pollute environments.

The MESL concept and the related field-laboratory studies have shown that it is a viable construction technique to use frost susceptible soils as base or subbase materials. However, there are some limitations as to the compacting effort, density and moisture content. Additional field tests are needed to further evaluate higher density soils to determine
<table>
<thead>
<tr>
<th>Item</th>
<th>Additive</th>
<th>Registered trademark</th>
<th>Supplier</th>
<th>Approx. price 9/15/1967</th>
<th>Form</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Void fillers and cementing agents</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Portland cement</td>
<td></td>
<td>Marek &amp; Co., Inc., Rabway, N.J.</td>
<td>0.015</td>
<td>Powder</td>
</tr>
<tr>
<td>2</td>
<td>Sodium sulfide</td>
<td></td>
<td>Allied Chemical &amp; Dye Corp., New York</td>
<td>0.025</td>
<td>Granular</td>
</tr>
<tr>
<td>3</td>
<td>Sodium metasilicate</td>
<td></td>
<td>U.S. Gypsum Co., Chicago, Ill.</td>
<td>0.04</td>
<td>Crystalline</td>
</tr>
<tr>
<td>4</td>
<td>Gypsum (laid plaster of approx. 95% purity)</td>
<td></td>
<td>J.J. Baker Chemical Co., Philadelphia, Ill.</td>
<td>0.011</td>
<td>Powder</td>
</tr>
<tr>
<td>5</td>
<td>Quicklime (chemically pure CaO)</td>
<td></td>
<td>Fisher Scientific Co., New York</td>
<td>0.01</td>
<td>Powder</td>
</tr>
<tr>
<td>6</td>
<td>Hydrated lime (calcite)</td>
<td></td>
<td>Detroit Edison Co., Detroit, Michigan</td>
<td>0.01</td>
<td>Powder</td>
</tr>
<tr>
<td>7</td>
<td>Fly ash</td>
<td></td>
<td>Howe &amp; French Inc., Boston, Mass.</td>
<td>0.15</td>
<td>Powder</td>
</tr>
<tr>
<td>8</td>
<td>Phosphoric pentoxide</td>
<td></td>
<td>Fisher Scientific Co., New York</td>
<td>0.08</td>
<td>Powder</td>
</tr>
<tr>
<td>9</td>
<td>Sodium silicate fluoride</td>
<td></td>
<td>Victor Chemical Works, Chicago, Ill.</td>
<td>0.03</td>
<td>Liquid</td>
</tr>
<tr>
<td>10</td>
<td>Benzeno phosphonic acid</td>
<td></td>
<td>American Oil Products Co., Somerville, Mass.</td>
<td>0.03</td>
<td>Liquid</td>
</tr>
<tr>
<td>11</td>
<td>Asphalt emulsion (65% solids)</td>
<td></td>
<td>Standard Oil Co., Everett, Mass.</td>
<td>0.03</td>
<td>Powder</td>
</tr>
<tr>
<td>12</td>
<td>Asphalt cutback (2 parts asphalt: 1 gasoline)</td>
<td></td>
<td>American Cyanamid Co., 30 Rockefeller Plaza, N.Y., N.Y.</td>
<td>0.08</td>
<td>Crystalline</td>
</tr>
<tr>
<td>13</td>
<td>AM-9 (gum gel)</td>
<td></td>
<td>Mallinckrodt Chemical Works, St. Louis, Mo.</td>
<td>0.20</td>
<td>Crystalline</td>
</tr>
<tr>
<td></td>
<td>Sodium thiosulfate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sodium persulfate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Aggregate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Sodium polycarboxylate</td>
<td>Agrilion</td>
<td>Borden Chemicals, Div. of Borden Inc., New York, N.Y.</td>
<td>*</td>
<td>Solution, flakes</td>
</tr>
<tr>
<td></td>
<td>Metallic salts (Aggregates and waterprofiers)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>Thorium chloride</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>Aluminum chloride</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>Aluminum sulfate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>Aluminum phosphate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>Ferric chloride</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>Ferric sulfate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>Zinc sulfate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>Calcium chloride</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>Sodium chloride</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>Lithium chloride</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>Silver nitrate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Waterprofiers</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>Dodecyl dimethyl ammonium chloride</td>
<td>Arquad 2HT</td>
<td>Armour Industrial Chemical Co., Chicago, Ill.</td>
<td>0.24</td>
<td>Solution</td>
</tr>
<tr>
<td>29</td>
<td>Methacrylato chloric chloride</td>
<td>Volan</td>
<td>E.I. duPont deNemours and Company, Grasselli Chemical Dept., Boston, Mass.</td>
<td>1.48</td>
<td>Liquid</td>
</tr>
<tr>
<td>30</td>
<td>Polyethylene glycol</td>
<td>Carbosil PEG 2000</td>
<td>Union Carbide Corp., New York, N.Y.</td>
<td>0.32</td>
<td>Liquid</td>
</tr>
<tr>
<td>31</td>
<td>Octadecyl acrylate</td>
<td>Arvane 15B</td>
<td>Armour Industrial Chemical Co., Chicago, Ill.</td>
<td>0.64</td>
<td>Solution</td>
</tr>
<tr>
<td>32</td>
<td>Ethylene diamine dihydrochloride</td>
<td></td>
<td>Howe &amp; French Inc., Boston, Mass.</td>
<td>0.20</td>
<td>Solution</td>
</tr>
<tr>
<td>33</td>
<td>Alkyl dimethyl benzyl ammonium chloride</td>
<td></td>
<td>Howe &amp; French Inc., Boston, Mass.</td>
<td>0.23</td>
<td>Solution</td>
</tr>
<tr>
<td></td>
<td>Dispersants</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>34</td>
<td>Tetrasodium pyrophosphate (TSP)</td>
<td></td>
<td>Westvaco Chemical Co., New York, N.Y.</td>
<td>0.12</td>
<td>Powder, granular</td>
</tr>
<tr>
<td>35</td>
<td>Sodium tetraphosphate</td>
<td>Quadrafos</td>
<td>Rumford Chemical Works, Rumford, R.I.</td>
<td>0.12</td>
<td>Powder, granular</td>
</tr>
</tbody>
</table>

* Data not available

1 Estimated
<table>
<thead>
<tr>
<th>COMMENTS</th>
<th>EFFECTIVENESS AS INDICATED BY LABORATORY TEST</th>
<th>REQUIREMENTS FOR SOIL-ADDITIVE REACTION</th>
<th>REQUIRED ADDITIVE CONCENTRATION</th>
<th>ADDITIVE COST PER POUND</th>
<th>EFFECT ON SOIL PROPERTIES OTHER THAN FROST ACTION</th>
<th>FIELD USE</th>
<th>COMMENTS</th>
<th>EVALUATIONS AS FROST HEAVE MODIFIERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Void Fillers and Cement</td>
<td>Excellent</td>
<td>Polymerization marked function of temp.</td>
<td>5%</td>
<td>50¢</td>
<td>Beneficial increase in strength and density; decr. in permeability</td>
<td>Difficult to control polymerization</td>
<td>Intended for emergency use</td>
<td>Poor</td>
</tr>
<tr>
<td>a. In situ polymerization (Calcium acrylate)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>b. Resins and asphalt</td>
<td>Promising</td>
<td>Drying after treatment. Some require soil be pre-dried</td>
<td>1%</td>
<td>1 to 15¢</td>
<td>Beneficial</td>
<td></td>
<td>Other than cure requirements, no spec. problems</td>
<td>Promising</td>
</tr>
<tr>
<td>c. Portland cement</td>
<td>Promising (with additives to cement)</td>
<td>Cure period for cement hydration</td>
<td>4%</td>
<td>1 to 2¢ (cmt)</td>
<td>Beneficial</td>
<td>No special problems</td>
<td>Slightly</td>
<td></td>
</tr>
<tr>
<td>Appretantes</td>
<td>Poor to slightly promising</td>
<td>None</td>
<td>1%</td>
<td>12¢ to $1.00</td>
<td>Beneficial</td>
<td>Moderate mixing and proc. prob. expected</td>
<td>Effectiveness unpredictable and is a func. of concentrat</td>
<td>Poor to si. promising</td>
</tr>
<tr>
<td>a. Polymers</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>b. Cations</td>
<td>Excellent</td>
<td>None for some, drying after treatment for others</td>
<td>0.5%</td>
<td>2¢ and up</td>
<td>Beneficial</td>
<td>No special problems expected</td>
<td>Very promising</td>
<td></td>
</tr>
<tr>
<td>Dispersants</td>
<td>Excellent</td>
<td>None</td>
<td>1%</td>
<td>5¢ to $1.00</td>
<td>Beneficial</td>
<td>No special prob.</td>
<td>Very Prom.</td>
<td></td>
</tr>
<tr>
<td>Waterproofer</td>
<td>Excellent</td>
<td>Drying after treatment</td>
<td>0.5%</td>
<td>25¢ to $2.00</td>
<td>Beneficial</td>
<td>Probable need for high degree of drying</td>
<td>Promising</td>
<td></td>
</tr>
</tbody>
</table>

* Additive rating scale: poor; slightly promising; promising; very promising; excellent.
moisture content and redistribution, heave, freezing rates and post thaw
deflection. Additional stabilization with soil reinforcement at the
upper layer may dramatically improve the performance of MESL system.

Overall, this report shows that extensive research works have been
successfully performed by various agencies on the stabilization of soils
and the techniques to reduce the potential frost heave in frost prone
soils. The knowledge gained from both laboratory and field studies of
stabilized soils are to be combined to carry a systematic study on the
use of substitute materials in cold regions. The availability of non-
frost susceptible soils is becoming hard to find, environmentally
sensitive and they are often very expensive to use in frost protecting
layers. Both laboratory and field testings are to be designed properly
such that the substitute materials, especially the marginal aggregates,
can be stabilized economically to meet the required design criteria.
Testing programs should include frost susceptibility test, loss of strength
under freeze-thaw cycles followed by CBR test, loosening of binding
materials under split tension test, strength under consolidated undrained
test and response under repeated loadings. These laboratory modes are to
be executed on promising mix designs to arrive at a design criteria for
substitute materials.

In general, the cement and asphalt-emulsion stabilization technique is
found to be very successful on the silty granular materials, whereas the
chemical compounds are more effective in organic and clayey soils.
However construction problems and limitations make this process
unattractive.
4.0 RECOMMENDATIONS

The literature search summarized in this report has produced results which warrant a future program of research. The following program is therefore recommended:

OVERALL PROGRAM
It is recommended that the emphasis be placed on soils such as silty or dirty sands and gravels, silty sand and sand or marginal aggregate as "substitute materials" which would be satisfactory for base or subbase course materials. The emphasis should also be given to what effects the additives or dispersants have on the sample in terms of aggregation or pore plugging, and possible effect on the mineralological composition of the coarse fraction.

LABORATORY INVESTIGATION
The program should include further tests on soils treated with portland cement and asphalt emulsion with promising additives. The use of admixtures such as sodium or calcium lignosulfonate merits further evaluation. The effectiveness of tetrasodium pyrophosphate, ferric acid, and polyphosphate to modify frost heave in silty sands and gravels, treated with cement or asphalt emulsions, should be studied and evaluations should be made of water attack and leaching or bacterial attack.

The test program should include development of improved mix design procedures to determine the optimum cement or asphalt emulsion contents.

FIELD TEST
It is recommended that the materials which are found to be effective, should be field tested. A small test section using the laboratory findings, should be made to observe the behavior under naturally occurring conditions. In such a test section, the treatment should extend over the entire depth of frost penetration (limited to 7 ft.) underlain by a layer of non-frost susceptible soil. The test section may be selected
at a site where the water table is relatively at a higher level or access of water to the treated base course may be controlled. The test section should also include the use of MESL system accompanied by soil reinforcement at the upper base course. Observations of frost heave and temperature distribution, moisture migration and distribution, post thaw strength and deflection under repeated loadings over several freezing-thawing seasons, in comparison with observations on an untreated section, should be made.
5. REFERENCES


43. Burns, C.D., and W.N. Brabston "Membrane-Envelope Technique for Waterproofing Soil Base Courses for Airstrips; Bare Base Support." Miscellaneous Paper S-68-13, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss., 1968.


48. Waterways Experiment Station (WES), Corps of Engineers, U.S. Army (1953) "The Unified Soil Classification System," Technical Memorandum 3-357.


6.0 ACKNOWLEDGEMENTS

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APPENDIX A

Selected Bibliography With
Abstracts On Soil-Cement
Stabilization
- SOIL-CEMENT-A CONSTRUCTION MATERIAL

The technology of cement-treated materials is summarized. Basic properties of soil-and soil-aggregate-cement mixtures are given to help the reader understand and use the product. The use of soil and cement mixtures as pavement layers is considered. Testing and mix design methods are discussed and approximate cement requirements given. A thickness design procedure is presented. Construction procedures are outlined. Recycling of material with the addition of cement to salvage and strengthen road layers is discussed. It is concluded that cement stabilization can improve the engineering properties of materials and has side application in pavement layers. In using soil-cement, proper consideration should be given to mix design, thickness design, and construction procedures.

This paper appeared in TRB Research Record No. 702, Low Volume Roads: Second International Conference. (Proceedings of a conference conducted by the Transportation Research Board, August 2023, 1979.)

Robbins, EG Packard, Rg (Portland Cement Association) Transportation Research Record No. 702, 1979, pp 173-181, 15 Fig., 6 Tab., 17 Ref.

- THE OPTIMUM USE OF NATURAL MATERIALS FOR LIGHTLY TRAFFICKED ROADS IN DEVELOPING COUNTRIES

The planning, construction and maintenance of lightly trafficked roads are discussed, with particular reference to the optimal use of local materials and resources. Attention is drawn to the importance of terrain evaluation techniques for improved road location and construction material surveys. The importance of an intimate knowledge and appreciation of local conditions and terrain for optimum serviceability is stressed. Foreign aid often covers only the planning construction phases of development and loses interest during the maintenance after completion. The aspect is of particular importance to the financing institutions to expand the export of expertise and equipment for maintenance. The importance of, and examples illustrating procedures to promote labour intensiveness in highway construction in developing countries is mentioned. Examples of materials standards for gravel surfaced lightly trafficked roads, and the experience on which they are based, as well as the novel applications of certain natural resources are discussed. Geometric standards and drainage applications that have been found to be particularly practical are highlighted. Approximate cost estimates are included for the various grades of roads discussed.

This paper appeared in TRB Research Record No. 702, Low Volume Roads: Second International Conference. (Proceedings of a conference conducted by the Transportation Research Board, August 20-23, 1979.)

Mitchell, MF Petzer, ECP Van der Walt, N (Department of Transport, South Africa) Transportation Research Record No. 702, 1979, pp 155-163, 5 Fig., 3 Tab., 10 Ref.
- EFFECTS OF COMPACTION DELAYS AND MULTIPLE TREATMENTS ON THE STRENGTH OF CEMENT STABILIZED SOIL

The effects of delayed compaction on the strength and durability of cement stabilized soils for base courses and subbases has been investigated. It was concluded that time delay does not adversely affect either strength or durability. However, prolonged time delay does increase the required level of compaction necessary to achieve a specified density so that it may be beyond the capability of ordinary highway compaction equipment. An example is given in the report showing how the results of this work can lead to more rational field compaction specifications for cement stabilized materials, in recognition of the fact that time delays are inherent in the construction process.

This paper appeared in TRB Research Record No. 702, Low Volume Roads: Second International Conference. (Proceedings of a conference conducted by the Transportation Research Board, August 20-23, 1979.)

Cowell, MJ (Law Engineering Testing Company) Irwin, LH (Cornell University) Transportation Research Record No. 702, 1979, pp 191-198, 8 Fig., 3 Tab., 25 Ref.

- A CONTRIBUTION TO THE STUDY OF MATERIAL PROPERTIES—STABILIZATION OF SANDS (Contribution a Petude des proprietes de materiaux—Le traitement des sables)

This research report is based on a doctorate thesis maintained at the Pierre and Marie Curie University, 9 February 1977, and deals with the knowledge and improvement (immediate and long term) of the mechanical performance of stabilized sands. Eight sands were chosen to study the effects of grading, angularity, mineralogic type and cleanliness. The sands were treated with cement, slag (granulated and crushed), and bitumen. For sands stabilized with the hydraulic binders the following aspects were studied: the effect of the type of sand and the method of treatment on its compaction properties; compactability; immediate bearing capacity; mechanical strength and modules of elasticity at different ages; immediate stability on the basis of cohesion and the angle of internal friction; the relationship between wave propagation and the modulus of elasticity; thermal shrinkage cracking and the coefficient of expansion. For the sands stabilized with bitumen the following aspects were studied: the effect of grading, angularity and mineralogy on workability; compactability; compaction and stability in terms of the method of compaction; bitumen content and temperature; resistance to rutting and creep. The overall result show that the properties of stabilized sands are very extensive, and that certain combinations of parameters and treatments enable the use of these materials in roadbases nearer to the surface and heavier traffic loads than generally expected.

Hamza, M Central Laboratory of Bridges & Highways, France, (0085 2643) Monograph Research Report 67, July 1977, 140 p., 100 Fig., 41 Tab., Photos., 57 Ref.
- STABILIZATION OF SAND WITH CEMENT AT LOW TEMPERATURES
  (Stabiliseren van zand met cement bij lage temperaturen)

It was investigated whether the production of sand cement is possible
and justified in periods when frost occurs, more particularly during the
night and in the early morning, while the day time temperature level
keeps the average 24 hour temperature a few degrees Celsius above zero.
Furthermore it was investigated whether supplementary arrangements on the
site of the stabilization work are needed in order to ensure that a sand
cement stabilized layer of good quality is obtained. The investigations
relating to keeping the sand bed free from frost were based on a precaution
already commonly applied in practice, namely, the addition of calcium
chloride to the sand. The effect of calcium chloride in the sand upon
the formation of solid frozen zones was studied. Furthermore, the
various methods of introducing the salt into the sand bed were investigated.
The laboratory and field tests concerned are described. The effect of
low temperature and of the presence of calcium chloride on the quality
of the sand cement was the subject of a number of laboratory investigations.
Within the framework of practical research some tests were carried out
on roads under construction. The effect of this salt and of covering
the stabilized sand bed upon the quality of the sand cement was studied.

Mededelingen Studiecentrum Wegenbouw SCW Monograph No. 43, Nov. 1977, 72
p., 14 Fig., 20 Tab., 6 Phot., 7 Ref.

- STUDIES ON ENGINEERING CHARACTERISTICS OF CEMENT-BASE STABILIZED SOIL

This report clarifies the engineering characteristics of cement-base
stabilized soil which is the basis of the deep chemical mixing method,
through various tests using laboratory soil and in situ soil. For
physical characteristics, of stabilized soils, such factors are described
as water contents, unit weights, and coefficients of permeability, while
for its mechanical characteristics, description is given to unconfined
compression, tension, shear and consolidation characteristics. The
characteristics of stabilized soils are clarified centering around the
influences exercised by hardener addition rates and the initial water
contents of samples upon the individual characteristics. Also discussed
are relations of coefficients of permeability before and after stabilization,
factors influencing unconfined compressive strength of stabilized soil,
correlation between simple tension test results and splitting test
results of stabilized soil, and other factors.

Kawasaki, T Nina, A Saito, S Babsaki, R
21 Ref.

Four major stabilizer systems were studied in which the primary additives were (a) portland cement, (b) lime, (c) phosphoric acid, and (d) sodium silicate. Of the four systems evaluated, portland cement was the most generally effective, with 5% treatment by soil weight resulting in 24-hour humidicure compressive strengths well above 100 psi (approximately equivalent to 20 CBR), which represents the maximum requirement for the designations of military roads and airfields under consideration. This treatment also provided very good resistance to strength loss on wetting. The use of secondary or modifying additives with cement was found to be either detrimental or beneficial to strength development or wetting resistance, or both, depending on the type of soil. While the combination of 4% quicklime plus 1% magnesium sulfate was highly effective on the basis of initial strength development, it was relatively poor in preventing strength loss on wetting. The results obtained with the phosphoric acid and sodium silicate formulations were not encouraging, and further investigations of these systems for military purposes are not warranted.

Kozan, George R., Fenwick, William B.
Army Engineer Waterways Experiment Station Vicksburg Miss
U.S. Army Engineer Waterways Experiment Station, Vicksburg,
SOIL STABILIZATION STUDY

This report concerns a laboratory study of the stabilization of soils from the Red River Valley and South-western North Dakota. Stabilizing treatments were Portland cement, hydrated high-calcium lime and dolomitic lime, high calcium lime and flyash, high calcium lime and MC-250 asphalt, and a mixture of 3 percent high calcium lime-mellowed 2 days-plus cement (3 percent less than optimum cement content). Unconfined compressive strengths were determined for soil-stabilizer mixtures after 7 days, 40 days and 1 year of curing. Other tests included: freeze-thaw brush loss, freeze-thaw heave tests, unconfined compressive strength after freeze-thaw and Atterberg limits. In general, the 3 percent lime (followed by 2-day loose curing) plus 3 percent less than optimum cement addition proved to be the most promising stabilizer. The length change coincident with freezing and thawing was found to be a good measure of durability.

Manz, Oscar E., June 69
North Dakota Univ., Grand Forks. Engineering Experiment Station, 67p.

SOIL STABILIZATION LITERATURE REVIEWS

This is a summary report of a research study aimed at development of guidelines and criteria for the stabilization of Illinois soil materials. Techniques studied in depth were cement, bituminous, lime-flyash, blending techniques and combination of procedures (soil-lime stabilization was included in an earlier study). The report contains a literature review of stabilization materials and methods; the nature and distribution of surficial soil deposits in Illinois; a description of the sampling program laboratory testing procedures and results; interpretation of the test results, and guidelines and criteria for implementation of stabilization techniques with Illinois soil materials. (BPR abstract)


Civil Engineering Studies: Highway Engineering Series AUTHOR: Robnett, Q.L., Thompson, M.R. June 69
- EFFECT OF A POLYMER ON THE PROPERTIES OF SOIL-CEMENT

A laboratory testing program was conducted on soil-cement specimens of silty sand and of silt with the monomer methyl methacrylate (MMA) added and polymerized. The purpose was to determine any beneficial effects on the properties of soil cement as used in Bureau of Reclamation construction. By the preformed method, some specimens were impregnated with MMA and polymerization was by gamma radiation from Cobalt 60. Other specimens by the premix method, had 3% or 6% MMA with 1% benzoyl peroxide as a catalyst incorporated during specimen preparation"; polymerization was by heat. The compressive strength of the preformed specimens containing silty sand was increased about 3.4 times that of specimens without MMA, but the premix specimens did not increase in strenght. Results of freeze-thaw tests did not show conclusive trends, but there were indications of improvement with the addition of MMA. The MMA reduced significantly the permeability of the silty sand specimens. Petrographic examinations showed that the MMA penetrated and filled the voids of portions of the silty sand specimens, but the voids in the silt specimens were nearly empty.

Bureau of Reclamation, Denver, Colo. Office of Chief Engineer.
May 70 17p

- SOIL STABILIZATION. EFFECT OF MOLDING CONDITIONS ON THE EFFECTIVE STRESS-STRENGTH BEHAVIOR OF A STABILIZED CLAYED SILT

The influence of molding water content, as-molded dry density, and delay time prior to compaction after mixing in of the molding water on the effective stress-strength behaviour of a clayey silt stabilized with hydrated lime and portland cement is presented in this report. This investigation used the results of high pressure consolidate-undrained triaxial compression tests with pore water pressure measurements.

Wissa, Anwar E.Z., Ferferpaum-Zyto, Samuel, Paniaqua, Jose Guillermo
Jan 70

Massachusetts Inst of Tech Cambridge  Soil Mechanics Div

-36-
- SOIL STABILIZATION: COMPRESSIBILITY-PERMEABILITY BEHAVIOR OF UNTREATED AND CEMENT STABILIZED CLAYEY SILT

High pressure triaxial-permeability equipment was developed to study the compressibility and permeability behavior of compacted untreated and stabilized soils at confining pressures up to 70 kg/sq cm under back pressures up to 15 kg/sq cm. Permeabilities down to 10 to the minus 10 power cm/sec can be measured using cylindrical test specimens 8 cm long and 10 sq cm cross-sectional area. This equipment has been used to study the influence of cement stabilization, molding water content, and type of compaction on the compressibility and permeability behavior of Massachusetts clayey silt (M-21). The results of this investigation show: (1) Both molding water content and type of compaction influence the degree of cracking that occurs during unsealed hot curing of M-21 plus 5% cement; (2) Sealing during curing eliminates cracking; (3) Cracking causes an increase in the permeability and compressibility of the stabilized soil at consolidation pressures up to 50 kg/sq cm; (4) provided cracking during curing is prevented, the stabilized soil shows a much larger decrease in permeability with increasing molding water content than does the untreated soil. Further, kneading compaction results in a lower permeability than static compaction at molding water contents around optimum for the stabilized soil: (5) The permeability of the stabilized soil decreases with increasing curing time and increasing time of permeation. Massachusetts Inst of Tech Cambridge Soil Mechanics Div (22080)

Phase rept. no. 6 Wissa, Anwar E.Z., Monti, Randolph P. Dec 68 165p

- MATERIALS DEVELOPMENT AND UTILIZATION

The general objective of the study was to develop techniques and procedures for achieving maximum utilization of local and on-site materials in pavement construction with particular reference to Illinois soils and materials. Stabilization techniques considered were cement, lime, bituminous, lime-fly ash, and combination (lime-cement, lime-bitumen). Research findings from the study have been previously disseminated in various reports. The reports are referenced and abstracted in the final summary report. Comments concerning research implementation, research benefits, and follow-up research are presented.

Thompson, M.R.

Illinois Univ., Urbana. Dept. of Civil Engineering. Mar 70, 15 p
- STRENGTH AND DURABILITY OF STABILIZED LAYERS UNDER EXISTING PAVEMENTS

The report summarizes the results of a field and laboratory study to evaluate the strength and durability of stabilized layers under existing pavements. Eight sites in different geographic and climatic regions of the country were tested, using lime and cement as the stabilizing agents. Tests performed on the subgrade were laboratory and field California Bearing Ratio, unconfined compression, moisture-density, classification, and x-ray diffraction analysis.

Aufmuth, Raymond E.
Army Construction Engineering Research Lab Champaign Ill Oct. 70
Final technical rept.

- SOIL STABILIZATION: A DURABILITY TEST FOR STABILIZED SOILS

The report describes and evaluates a new testing procedure for determining the surface durability of stabilized soils by measuring the change in tensile strength at the surface of test specimens (slabs) subjected to laboratory cycles of weathering. This test, called the Durability Tensile Test, is shown to be potentially a more direct and reproducible method than the standard ASTM Durability Test for evaluating stabilized soils. A prototype apparatus has been constructed to measure the surface tensile strength over approximately 4.0 sq cm circular areas of a 5-inch-square slab, one inch thick. Preliminary tests on three slabs show that the measured strength is related to the effective cohesion of the soils system. For example, increases in curing or dry density which results in an increase in effective cohesion also produce and increase in measured tensile strength. Weathering cycles which have been shown elsewhere to cause a loss in effective cohesion, also result in a loss in tensile strength. Therefore the Durability Tensile Test appears to be a rational method of evaluating durability characteristics. Based on the experience obtained with the prototype apparatus, a modified version is recommended to improve reproducibility and to simplify the testing procedure.

Wissa, Anwar E.Z., Paniaqua, Jose Guillermo
Massachusetts Inst of Tech Cambridge Soil Mechanics Div
Phase rept. no. 7 June 69, 169p
- SYNTHETIC AGGREGATE FROM SOIL CEMENT

The report presents the results of an investigation on the feasibility of preparing a synthetic aggregate by crushing soil-cement. The synthetic soil-cement aggregate was to be blended with existing soils and used for soil-aggregate base in Southeast Alabama where natural aggregates are not available. Two soils, the Cogdell and the Mitylene, were selected for study. The Cogdell was mixed with 8, 10, 12, 14 and 16 percent cement and tested in compression to determine the optimum cement content required to produce as satisfactory soil-cement synthetic aggregate. The synthetic aggregate was mixed with the Mitylene soil in various percentages and tested for CBR to determine the effectiveness of the synthetic aggregate as a stabilizer. The resulting soil aggregate mixes were found to be satisfactory for use as bases in primary roads.

Bransford, Thomas L.
Auburn Univ., Ala. Dept. of Civil Engineering
March 72  72p

- STABILIZATION STUDIES OF SOUTHEAST ASIAN SOILS: VIETNAM

The report summarizes the results of an investigation to determine physical, chemical and selected engineering properties of six Southeast Asian soils encountered in pavement facility construction, lime and cement manufactured in the United States were used to stabilize or otherwise improve the engineering characteristics (plasticity, moisture-density, and California Bearing Ratio) of the soils.

Aufmuth, Raymond E.
Army Construction Engineering Research Lab Champaign Ill
Final technical rept. June 72  18p

- STABILIZATION OF CONTAMINATED CLAYS

Three basic clay minerals -- kaolinite, illite and montomorillonite -- were investigated to determine the feasibility of stabilizing or otherwise improving selected engineering properties using lime or cement. Treatment with lime developed greater unconfined compressive strengths, lower densities with increased moisture, and greater resistance to moisture and ice penetration, than with the natural clay minerals. Treating kaolinite and illite with cement produced improved strengths and resistance to wet-dry and freeze-thaw cycling. However cement was not effective in improving these properties in montmorillonite because of the clay's fineness, crystallinity and large surface area.

Aufmuth, Raymond E.
Army Construction Engineering Research Lab Champaign Ill
Final technical rept. June 72  16p
- SOIL STABILIZATION - THE EFFECTS OF MIXING CONDITIONS, METHOD OF COMPACTION, AND CURING CONDITIONS ON THE EFFECTIVE STRESS-STRENGTH BEHAVIOR OF A STABILIZED SOIL

The effects of mixing conditions, method of compaction, and curing conditions on the strength behavior of a cement-stabilized clayey silt were investigated using consolidated-undrained triaxial compression tests with pore pressure measurements. The results were analyzed using the Mohr-Coulomb criterion of failure in terms of effective stresses. The results of the testing program showed that the consistency of the soil prior to the addition of cement is the most important factor controlling the mixing quality. The use of a mechanical device for mixing was not found to be inherently inferior to the standard laboratory mixing procedure.

Wissa, Anwar E.Z., McGillivray, Ross T., Paniaqua, Jose Guillermo
Massachusetts Inst of Tech Cambridge Soil Mechanics Div
A50927J3 PLD: 9M, 64L USRD7220
Aug 71 75p

- BEHAVIOR OF STABILIZED SOILS UNDER REPEATED LOADING. REPORT 5.
PERFORMANCE EVALUATION OF CEMENT-STABILIZED SOIL LAYERS AND ITS RELATIONSHIP TO PAVEMENT DESIGN

Properties of cement-stabilized soils were interrelated, and the performance of field sections previously tested (1963-1964) at the Waterways Experiment Station (WES), Vicksburg, Mississippi, was evaluated for the purpose of determining the validity of existing theory for prediction of pavement behavior and developing criteria and procedure for designing pavements containing soil layers stabilized with small amounts of cement. Field test sections of three different thicknesses were constructed of Vicksburg silty clay stabilized with 3%, 6%, and 10% cement contents on a heavy clay subgrade prepared to CBR values of 4 and 10, and tested under 10,000, 25,000, and 50,000-pound single-wheel loads. A failure criterion was defined according to rut depth, and the equivalency of different wheel loads (in terms of damage caused to the pavement) was determined.

Mitchell, J.K., Ueng, T.S., Monismith, C.L.
California Univ Berkeley Dept. of Civil Engineering
Aug 72
- COUNTERACTION OF DETRIMENTAL EFFECTS OF DELAYED COMPACTION

In previous studies it was shown that allowing an extended delay between mixing and compaction will reduce the strength, density, and durability of soil-cement. In the subject study, the author sought to counteract some of the undesirable effects of delayed compaction by the addition of an admixture in trace amounts. The purpose of the admixture was to retard the initial setting of the soil-cement for such periods as might be required to manipulate and compact the materials in the field. He conducted 1800 laboratory tests to evaluate the variables of soil type, admixture type and quantity, compaction moisture, compaction effort and curing period in terms of compressive strength, density, and durability. He found that the admixture Tri Methylol Propane is effective in partially counteracting the detrimental effects of delayed compaction of soil-cement mixes with the exception of soils of extremely low plasticity such as sandy loam.

Arman, Ara
Louisiana State Univ., Baton Rouge. Div. of Engineering Research
Jul 72 210p

- SOIL STABILIZATION

Many aspects of stabilization of sand with cationic shrinkage cracking in soil-cement bases to stabilization of sand with cationic bitumen emulsion are discussed in papers presented at a conference on cracking of soil-cement held at the 52nd Annual Meeting of the Highway Research Board. Also presented are methods of improving the tensile strength of soil-cement, factors that effect the creep behavior of cement-stabilized soils, a method for predicting the freeze-thaw durability of stabilized materials, proposal of realistic cutoff dates for contraction with lime-fly ash and lime-cement-fly ash mixtures, development of different indexes of lime reactivity for different soil groups especially in tropical and subtropical areas, and effects of factors such as temperature and specimen age on the shear strength of sands stabilized with cationic bitumen emulsion.

George, K.P.
1973 132p
STABILIZATION OF OKLAHOMA SHALES

Eight Oklahoma Shales representing regional characteristics but differing texturally and mineralogically were selected for stabilization studies. Of the various stabilizing agents used, it was found that 6% hydrated lime, 14% Portland cement, and 25% flyash give optimum conditions by imparting acceptable strength levels to the shales. The degree of strength attained varies inversely with the plasticity of shales. On the basis of compressive strength, cyclic loading, and weatherability criteria cement is the most effective additive, flyash the least, and lime moderately effective. The addition of small amounts (less than 2%) of NaCl, CaCl₂, NaOH, and Na₂CO₃ to the shales which have already been mixed with one of the main stabilizing agents, further enhances the stabilizing benification. With the exception of flyash stabilized shales, delayed compaction appears to produce an overall decrease in the compressive strength properties. Electron microscopic studies indicate that the voids of the stabilizing shales are reduced substantially compared to the raw shales and there is a direct relationship between void domain characteristics and stabilization effectiveness. Shales having higher void cross sectional areas show lower compressive strengths.

Laguros, J.G., Jha, K.
- SOIL STABILIZATION METHODS FOR MINIMIZING THE DETRIMENTAL EFFECTS OF FROST ACTION ON PAVED AND UNPAVED ROADS IN NORTH CAROLINA

The report concerns the description and evaluation of 12 experimental projects featuring base course stabilization for the prevention of frost damage. The stabilizing additives used included: portland cement, lime, lime-fly ash, NaCl and CaCl2. The Phoenix Creek project featured a 5" bituminous concrete or "Black Base", while the Orchard Loop and State Farm projects featured mechanical stabilization of the base course. Report contains a considerable amount of climatological data for the area in which the projects are located. Several of the major conclusions and observations include: an 8" untreated base course performed as well as or better than a 5" layer treated with CaCl2, NaCl, lime, lime-fly ash or portland cement; bituminous concrete base course performed better than any of the other (treated or untreated) base courses; CaCl and CaCl2 treatments lose effectiveness with time and a cold quantity of 250 degree days and average precipitation will produce appreciable damage to unstabilized roads. (Degree days= Ta-32 degree, where Ta= average daily temp., and cold quantity= summation of all negative degree days).

McCollough, Charles R.
North Carolina State Univ., Raleigh. Highway Research Program
Final rept
Oct 66 128p
APPENDIX B

Selected Bibliography With Abstracts On Asphalt Emulsions Stabilization
MIX DESIGN CRITERIA FOR CEMENT MODIFIED EMULSION TREATED MATERIAL

This paper is the second part of a comprehensive investigation of the stabilization of sands and sand-clay aggregates with asphalt emulsion. The objective here is to develop mix design criteria for emulsion treated soil aggregates. Previous investigations by author and others suggest that cement in trace quantities is indispensible in order to enhance the durability of sand-emulsion mixtures; accordingly Cement-modified Emulsions Treated Material (CETM) only is studied herein. With due consideration to the prevailing distress mechanisms in cold mix bases, several tests are proposed to evaluate CETM. Marshall stability and shear strength tend to exhibit an optimum, respectively, with emulsion content and fines content. It appears feasible to predict the Marshall stability of CETM from a simple soil property such as particle size distribution. Using the test results on five sands and sandy soils is proposed. Minimum Marshall stability of 4.23 kN (950 lbs.) insures the CETM will not undergo shear failure under heavy truck tire pressure. Another criterion to detect and avoid moisture susceptible mixtures is that Marshall cylinders during vacuum soaking should not absorb more than 8.5% moisture.

This paper appeared in TRB Research Record No. 702, Low Volume Roads: Second International Conference. (Proceedings of a conference conducted by the Transportation Research Board, August 20-23, 1979.)

Fang, NY (Lehigh University) Transportation Research Record No. 702, 1979, pp 147-154, 8 Fig., 2 Tab., 25 Ref.
A GUIDE TO SHORT-CUT PROCEDURES FOR SOIL STABILIZATION WITH ASPHALT

A Guide to short-cut procedures for soil stabilization with asphalt has been prepared primarily for Naval Mobile Construction Battalion forces in areas where time and the exigencies of field operations preclude the use of the more elaborate procedures and equipment normally employed. For those with considerable experience in asphalt construction, who may feel that simple steps are covered in more than enough detail, we point out the the Guide is designed also for use by individuals to whom these procedures may be less familiar. The Navy uses both asphalt and portland cement for soil stabilizing purposes. Use of the latter is covered in Technical NoteN845, 'Short-Cut Procedures for Soil Cement Construction in Sandy Soil', October 1966.

Materials Research and Development Inc. Oakland, Calif.

Vallerga, B.A.
Dec. 18, 1967 March 29, 1968

BITUMINOUS STABILIZATION LABORATORY STUDY

The report concerns the bituminous stabilization of three soils. A loam, a fine sand and a dirty gravel were treated with asphalt cement, cutback asphalt, and road tar, soil-bituminous mixtures were tested by Hveem Stabilometer, cohesiometer, unconfined compressive strength, also for water absorption, volumetric well, and freeze-thaw durability. The principal product of the work is the development of a procedure for designing soil-bituminous mixtures in the laboratory.

Minnesota Dept. of Highways. Office of Materials

Final rept. for 1969
Korfhage, G.R.
MIX DESIGN CRITERIA FOR CEMENT MODIFIED EMULSION TREATED
MATERIAL

This paper is the second part of a comprehensive investigation of the
stabilization of sands and sand-clay aggregates with asphalt emulsion.
The objective here is to develop mix design criteria for emulsion
treated soil aggregates. Previous investigation by author and others
suggest the cement in trace quantities is indispensable in order to
enhance the durability of sand-emulsion mixture; accordingly Cement-
modified Emulsion Treated Material (CETM) only is studied herein. With
due consideration to the prevailing distress mechanisms in cold mix
bases, severable tests are proposed to evaluate CETM. Marshall stability
and emulsion content and fines content. It appears feasible to predict
the Marshall stability of CETM from a simple soil property such as
particle size distribution. Using the test results on five naturally
occurring soils and one synthetic aggregate mix design criteria for sands
and sandy soils is proposed. Minimum Marshall stability of 4.23 kN (950
lbs) insures that CETM will not undergo shear failure under heavy truck
tire pressure. Another criterion to detect and avoid moisture susceptible
mixtures is that Marshall cylinders during vacuum soaking should not
absorb more than 8.5% moisture. A third criterion to safeguard against
stiff moisture is that the seven day "dry bearing strength" shall not
exceed 2760 kPa (400 psi). The recommended design values and test
method are presented and discussed in the paper.

This paper appeared in TRB Research Record No. 702, Low Volume Roads:
Second International Conference. (Proceedings of a conference conducted
by the Transportation Research Board, August 20-23, 1979.)

George, K.P.
Transportation Research Board
Mississippi University
Transportation Research Record N702 1979 pp182-190 7 Fig. 3 Tab. 20 Reg.

PERFORMANCE OF OPEN GRADED EMULSION MIXES

This paper describes a survey of open graded asphalt emulsion mix projects
in the Pacific Northwest. The survey documents performance, distress,
material characteristics, traffic history, and construction history of
the projects. The paper describes a performance rating system used to
evaluate the performance of the projects. The factors which influence
projects performance and material characteristics are discussed and
methods of accounting for them in a thickness design method for open
graded emulsion mixes are enumerated. 17 refs.

Hatch, D.R., Hicks, R.G.
Oregon State Univ. Corvallis
Proc Paving Conf for 14th Meet, Univ. of NM, Alburquirque, 1977
p 184-182 CODEN: PPCODL
DEVELOPMENT OF EMULSIFIED ASPHALT-AGGREGATE COLD MIX DESIGN PROCEDURE

The development of emulsified asphalt-aggregate cold mixture (EAM) design procedure is described. The procedure is based on extensive laboratory and field testing, and uses the Marshall stability equipment and a capillary soak test. The procedure consists of conducting aggregate and emulsion quality tests, determining the compatibility of emulsion and aggregate (coating), optimum moisture content at mixing and at compaction, optimum residual asphalt content, and adequacy of structural and durability properties of the mixture. The mix design procedure is intended to be practical and easily implementable by governmental agencies and others. Several mix designs for actual projects were conducted to aid in verification. Results show the procedure to be practical and reasonable. The study has shown that emulsified asphalt-aggregate cold mixtures are complex, and good engineering design is essential to achieve consistently satisfactory results.

Feb 78 155p

MIX DESIGN METHODS FOR BASE AND SURFACE COURSES USING EMULSIFIED ASPHALT

A state-of-the-Art Report

A comprehensive literature search was conducted to determine the state-of-the-art in mixture designs for pavements using emulsified asphalts. The widely used Marshall or Hveem mix design method using hot asphalt cement generally serve as their basis. Preparation and fabrication of specimens are similar in each method with difference existing primarily in the curing and testing schemes. Although several methods exist, no single method has been adopted by the highway community. A common method, used on a nationwide basis, needs to be established so that performance data can be readily exchanged among user agencies.

Gong, G.K.

BITUMINOUS STABILIZATION FIELD PROJECT: WADEMA COUNTY


The report contains results of a field study featuring stabilization of sandy subgrade soils with emulsified asphalt, cut back asphalt, and road tar, to upgrade them to serve as an adequate base course for low traffic density roads. Although construction difficulties and the absence of failures precluded evaluation of design procedure used by observing the relative performance of the various sections, some general conclusions were developed.

Minnesota Dept. of Highways, Office of Materials


EXPONENTIAL FIELD PROJECT ON BITUMINOUS STABILIZATION OF SILTY SOILS

An experimental field project was constructed in southeastern Minnesota in 1965 to evaluate the effectiveness of stabilizing the upper portion of a silty subgrade with two different bituminous materials, MT-6 and MC-2. The project contained six sections in which the upper six inches of the subgrade was stabilized with bituminous material and capped with three or five inches of gravel. Two unstabilized control sections had a 7-inch gravel base. The best performing stabilized section was on a par with the control sections, but was much more costly. The relative performance of the stabilized sections could be related to results from laboratory tests conducted on similar soil-bituminous mixtures.

Korfhage, G.R.

Minnesota Dept. of Highways, Office of Research Coordination
Final Report. 1972
APPENDIX C

Selected Bibliography With
Abstract On Chemical Soil Stabilization
STABILIZATION

Some factors affecting the durability of lime-fly ash-aggregate mixtures; Effect of lime treatment on the resilient behavior of fine-grained soils; Curing and tensile strength characteristics of aggregate-lime-pozzolan; The Waco Ponding Project; A study of soil cement with chemical additives; Using additives to improve cold weather compaction. Variation in laboratory and field strengths of soil cement mixtures; A method for quantitative determination of soil minerals by x-ray diffraction. Library of Congress catalog card no, 76-10689

Andres, R.J. Transportation Research Board, Washington, D.C.
1975 88p

METHOD OF SOIL STABILIZATION

The general purpose of this invention is to provide a method of soil stabilization that has all the advantages of similarly employed techniques and has none of the above described disadvantages. To attain this, the present invention provides a unique series of solutions for alternate application to the soil. The first water solution comprises one-two percent by weight of polyethylene oxide, and is applied to the soil at approximately 0.1 lb/sq yd and is followed by a second application of a 10-20 percent water solution of polyacrylic acid loaded to about 0.5 lb/sq yd.

Department of the Navy, Washington, D.C.

Government-owned invention available for licensing. Copy of patent available Commissioner of Patents, Washington, D.C. 20231
Beneficiation of Low Grade Soils. Part III. Stabilization Procedures for Puerto Rico Low Grade Soils

The report summarizes the procedure used in Puerto Rico for stabilization of low-grade soils. The procedures are divided into two broad categories--densification and chemical stabilization. Compaction, dewatering and preloading are discussed as techniques for densification. Chemical stabilization by the addition of asphalt, cement, lime and a combination of lime and cement is also discussed. The report lists projects where various stabilization techniques have been used for construction.

Puerto Rico Dept. of Public Works Research Div.

Final Report
March 73 83p

EFFECT OF METHYL BROMIDE TREATMENT ON RESPONSE OF A SOIL TO STABILIZATION WITH CEMENT AND LIME

The purpose of this study was to examine the influence of methyl bromide treatment of Vicksburg clayey silt (losses) on the responsiveness of the soil to stabilization with portland cement and hydrated lime.

Stougger, J.D.

Army Engineer Waterways Experiment Station Vicksburg, Miss

MODIFICATION OF FROST-HAVING OF SOILS WITH ADDITIVES, INVESTIGATIONS 1953 THRU 1955

A 3-year search for additives to reduce the frost susceptibility of soil is described. Fifteen soils and about forty additives have been tested. A discussion of the theoretical considerations for the choice of additives is presented. The additives are divided into four groups: (1) void pluggers and cements, (2) aggregants, (3) dispersants, and (4) 'water-proofers' - according to their action in soil.

Lambe, T. William

Massachusetts Inst of Tech Cambridge Soil Stabilization Lab
EXPERIMENTAL STABILIZATION EXPANSIVE SHALE CLAY PROJECT P 039-1(1) LYNAN COUNTY, SOUTH DAKOTA

The report presents the results of a field study on the stabilization of Pierre shale by lime, lime-asphalt, phosphoric acid plus ferric sulfate and Products Development Company stabilizer (PDC). The objective of stabilization was to prevent warping of road surfaces by treatment of highly expansive in-place soils and to determine if chemical treatment was more effective and more economical for reducing warping than replacing with non-expansive soils. To evaluate the permanency of treatment, stability and effectiveness of warping control and maintenance cost, annual comparative liquid limit, PI, CaCO3, modified field and laboratory CBR, moisture-density, volume change, pH and plate load tests were performed. Precise level data and High Speed Roughometer results were correlated to determine warping effects on ridability. Frost penetration, patching and crack studies were made to provide relative maintenance cost. Based on serviceability index ratings, all of the stabilized sections, except phosphoric acid, are superior to the standard design with respect to reducing surface warping. Overall, it appears that lime-treated soil is more economical than using non-expansive soils by reducing the long-range maintenance costs.

McDonald, E.B.

South Dakota Dept. of Highways
Final rept