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HEMICAL COMPACTION AIDS
OR FINE-GRAINED SOILS

Vol. I
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Final Report

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FOREWORD

This report presents the results of a comprehensive study of soil compaction and enhancing the compactability of fine-grained soils by chemical treatment. After an extensive literature search, yielding a theoretical analysis of the compaction process and identification of feasible materials, appropriate laboratory and field experiments were developed to evaluate the effectiveness of chemical compaction aids. These experiments included over 25 different soil series and over 20 chemicals. Many more chemicals were identified during the literature search and screening tests, but were not further evaluated because they demonstrated questionable effectiveness. Effects of chemical treatment on moisture-density relationships, shear strength, and stability were evaluated. The results of this comprehensive study indicate that, although chemicals may be cost effective aids for improving the compaction, strength, and stability characteristics of fine-grained soils in roadway structures, relatively subtle differences in the soil physico-chemical makeup may create large differences in chemical compaction aid effectiveness. This suggests that a laboratory evaluation program must be conducted for each soil-chemical combination proposed.

The results were developed by Iowa State University under Contract DOT-FH-11-8135.

The authors specially acknowledge Drs. Lindo J. Bartelli and Donald E. McCormack, the assistance of Soil Survey Interpretations Division, Soil Conservation Service, USDA, and personnel of the Technical Service Centers, State Soil Scientists, State Conservationists, District Conservationists, local Soil Scientists, Survey Parties, and technicians for invaluable assistance in obtaining the approximate one ton samples of each soil series needed in the testing programs.

Copies of the report are being distributed by the Materials Division, Office of Research, to appropriate members of the FCP Project 4D team.

Charles F. Scheffey
Charles F. Scheffey
Director, Office of Research

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16. Abstract

Soil is man's cheapest and most abundant construction material, and compaction is the most widely used method of strengthening soils and making them suitable for construction uses. The technology of compaction, while improving, remains largely in a trial and error state, emphasizing the basic moisture-density relationships discovered by R. R. Proctor. In recent years, the trial-and-error approach has led to the introduction of proprietary trace chemical additives that are said to increase soil densification and ease of compaction, and that improve strength and stability qualities, particularly of fine-grained soils.

The report contained herein (Volume I of a two-volume report) includes the principal objectives of Phase I of the total project, i.e., an extensive review of appropriate subject literature and a pilot laboratory moisture-density-strength study of twenty chemicals with eight soils of varying origin and mineralogy. Also included in this report are a theoretical discussion of possible mechanisms of chemical compaction aids, properties of the twenty-six soils used in the total investigation (Phase I and Phase II), and data from supplemental tests designed to improve our understanding of the influences of the chemicals on fine-grained soils. Six of the chemicals were then selected for the more extensive laboratory evaluations (project Phase II), described in report Volume II.

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Alan J. Lutenegger - Compaction and Iowa K-tests, bearing capacity and shear strength analyses, field tests and evaluations.

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The many student laboratory technicians of the Soil Research Laboratory, Engineering Research Institute, Iowa State University, who measured, molded, and tested the thousands of specimens produced for this project.

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
Angstroms	0.0000001 (10^{-7})	millimetres
inches	2.54	centimetres
feet	0.3048	metres
miles (U. S. statute)	1.609344	kilometres
square inches	0.00064516	square metres
square feet	0.09290304	square metres
cubic feet	0.02831685	cubic metres
cubic yards	0.7645549	cubic metres
grams	0.001	kilograms
pounds (mass)	0.4535924	kilograms
tons (2000 pounds)	907.1847	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
pounds (mass) per cubic yard	0.59327631	kilograms per cubic metre
pounds (force)	4.448222	newtons
pounds (force) per square inch	6894.757	pascals
pounds (force) per square foot	4.882428	kilograms per square metre
miles per hour	1.609344	kilometres per hour
degrees (angle)	0.01745329	radians
Fahrenheit degrees	5/9	Celsius degrees or Kelvins*

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* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

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LIST OF ABBREVIATIONS AND SYMBOLS

BHST	Bore Hole Shear Test
CBR	California Bearing Ratio
CTB	Cement-treated base
DI	Dispersion Index
FHWA	Federal Highway Administration
M-D	Moisture-density; relation between compacted density and moisture content
OMC	Optimum Moisture Content
RRP	Reynolds Road Packer
SBV	Spherical Bearing Value
SEM	Scanning Electron Microscope

A	cross-sectional area
C	capacitance
c	soil cohesion (psi), also: fractional concentration of chemicaly in additive
D	diameter of sphere (inches)
D_f	surcharge or depth of foundation below soil surface
d	specimen length
E	dielectric dispersion
H	initial or air-dry hygroscopic moisture content (percent)
h	penetration of sphere into compacted soil (inches)
L	load (pounds)
M	final moisture content (percent)
P	percent chemical on a dry-soil-weight basis, probability
q_d	ultimate bearing capacity
R	resistance
T	surface tension
w/c	water content
z	depth

γ	soil unit weight
ε	dielectric constant
ε_o	dielectric constant of a vacuum (8.85×10^{-14} farads/cm)
τ	shear strength, stress (psi)
σ	stress, normal pressure (psi)
ϕ	internal friction angle

INTRODUCTION

Objectives

Soil is man's cheapest and most abundant construction material, and compaction is the most widely used method to stabilize or strengthen soils, a method dating from antiquity. As time, man, and equipment have progressed, soil compaction has increased in importance, complexity, and cost, and billions of cubic yards of earthen materials are now compacted annually. Still, the technology of compaction, while improving, remains for the most part in the trial-and-error stage, with most practitioners of compaction utilizing only the basic concepts of Proctor.[1,2] An extension of the trial-and-error approach has been the introduction of many proprietary "compaction aids", or chemical additives to soils, which have been promoted for increasing densification and/or for ease of compaction, and thereby improving desirable engineering qualities of soils. Generally, however, no desirable effects have been noted during standardized laboratory testing of soils treated by prescribed amounts of such chemical additives. Two interrelated questions therefore arise:

1. Do chemical compaction aids actually improve moisture-density and the strength and stability qualities of fine-grained soils?
2. Are present laboratory test techniques adequate to fairly evaluate effectiveness of such aids?

These in turn give rise to a third question:

3. Do our present technology and testing methods fully and fairly represent the mechanisms of field compaction?

The research herein delves into the above questions, in line with the following objectives:

1. To determine the feasibility of improving compaction characteristics of fine-grained soils by chemical treatment.
2. To measure the effects of promising chemical compaction aids generated for Objective 1 on moisture-density relationships and other engineering properties of soils, such as strength, plasticity, and stability characterisitics.

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[1] R. R. Proctor, "Fundamental Principles of Soil Compaction," Engr. News-Record, 111, (1933), p. 286.

[2] H. E. Wahls, et al., "The Compaction of Soil and Rock Materials for Highway Purposes," Final Report No. FHWA-RD-73-8, Federal Highway Administration, Offices of Research and Development (Washington, D. C.; Aug. 1966).

Three phases were established for this investigation as follows:

Phase 1 - Literature review (Task A) and pilot laboratory study (Task B)
Phase 2 - Laboratory study
Phase 3 - Field evaluation

Through the above objectives and investigative phases, the study herein has developed a fuller understanding of the mechanics of compaction and suggests several pertinent and meaningful measurements for evaluation of compaction aids. For example, it has been demonstrated that no laboratory compaction test fully duplicates actions occurring in the field.[2] Therefore, it has been argued that a particular chemical compaction aid which shows no benefit in the laboratory does show benefit in the field, even though there often is no control section (without the extra ingredient) put under the same conditions. Even within control sections, there are many intractable variables, and it would be economically prohibitive to attempt to evaluate each potential aid by means of field test sections. Furthermore, it has been suggested that when the swelling potential of clays must be controlled by compacting on the wet side of optimum moisture, chemical stabilization additives and techniques should be employed.[2] Therefore, because of this need for knowledge of chemical stabilization additives and techniques, this study was conducted as a means of ascertaining what each chemical additive was doing, and, if it appeared to be of no benefit, it was rejected.

Theory of Compaction

The following is a brief survey of mechanisms believed to be involved in compaction, with discussions of possible contributive effects of chemical additives. The inclusion of this material here is for two reasons: 1) to illustrate the need for and usefulness of a guiding theory, without which meaningful results could be lost or overlooked in the myriad of interrelated variables, and 2) as an indicator of the extent that potential mechanisms of chemical compaction aids may relate to conclusions obtained within the study.

Possible influences from chemical compaction aids will be discussed in the following sequence:

1. Reduction of surface tension, and therefore intergranular contact force and friction.
2. Reduction of resistence to intergranular shading through dispersive effects on the clay-water system.
3. Weakening of soil structure that must be broken down prior to compaction.

<u>Surface Tension in Unsaturated Soils</u>. Compaction involves compression of an unsaturated soil to squeeze the air out. As the air

is forced out and the soil therefore approaches water saturation (i.e., the remaining voids are mainly filled with water), and the permeability of the soil for air is greatly reduced, effectively preventing further compaction despite the application of further effort.[3] The requirement that an overly wet soil be dried before it can be compacted is well known and requires no further elaboration. The weakening effect of continued compactive effort on an overly wet soil also is well known, as demonstrated from California Bearing Ratio (CBR) tests[4] and triaxial compression tests.[5] It is doubtful that any chemical additive could overcome the deleterious effect on compaction of too much water in the soil, although an additive which reduces surface tension may contribute an indirect minor benefit by increasing the rate of drying.

Figure 1 shows the elements of a theory and derivation by Haines[6] modified by Fisher[1] in the 1920's. According to this theory, surface tension T causes a tensile force between adjacent soil grains due to coupling by an annular ring of water, the main contribution to the force not being surface tension but the negative pore water pressure from surface tension pulling outward on the water ring. The force (pressure times area), therefore, is a function not only of the surface tension but also of the ring geometry which in turn depends on the grain shape and moisture content. Because of increasing curvature of the annulus, tensile force increases as the soil becomes drier. A limiting value of the negative pressure is the vapor pressure of the water solution, which may be very high in clayey soils. In sands, the soil dries and the tensile force drops to zero, leaving a loose, unbonded sand.

The tensile force discussed above opposes compaction, since it is a normal force causing sliding friction between soil grains. This opposition to compaction should "peak out," giving an inverted peak or minimum density with constant compactive effort somewhere between the saturation and zero moisture contents. Such an influence, which is not widely recognized because compaction tests are seldom conducted at zero moisture, is shown by several curves in Fig. 2 taken from Forssblad.[6] This effect also was reported by Olson[3] for an illitic clay.

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[3] Roy E. Olson, "Effective Stress Theory of Soil Compaction," <u>ASCE Jour</u>., <u>89</u>:SM 2, (1963), pp. 27-45.

[4] C. R. Foster, "Reduction in Soil Strength with Increase in Density, <u>ASCE Trans</u>., <u>120</u>, (1955), pp. 803-22.

[5] H. B. Seed and C. K. Chan, "Structure and Strength Characteristics of Compacted Clays," <u>ASCE Jour</u>., <u>85</u>:SM 5, Pt. 1, (1959), pp. 87-128.

[6] Lars Forssblad, "New Method for Laboratory Soil Compaction by Vibration." <u>HRB Record</u>, <u>177</u>, (1967), pp. 219-24.

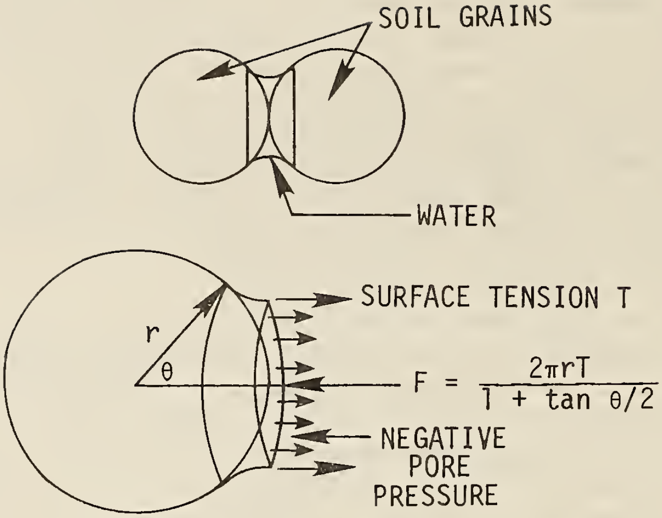

Fig. 1. Forces arising from capillary water at a grain contact (Fisher, 1926).

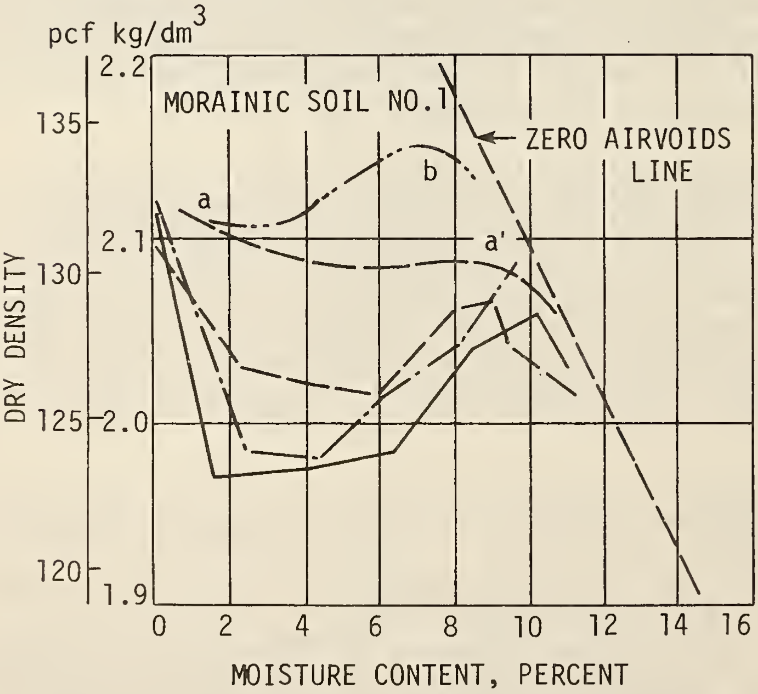

Fig. 2. Moisture-density curves for a silty sand compacted by modified AASHO method (dotted line) or by vibrating tamper; a - a', a - b: hypothetical curves with chemical compaction aids.

If, as suggested above, negative pore pressure increases intergranular friction and opposes compaction, a most important function of a compaction aid would be to reduce this negative effect by decreasing surface tension. For example, a reduction of 90% in surface tension might cause a soil to compact as shown by a-a' in Fig. 2, in effect reducing the critical nature of the optimum moisture content (OMC) and allowing suitable compaction at a lower-than-optimum moisture content. Laboratory tests conducted only by compaction at a previously-determined OMC probably would miss the potential benefits from such a compaction aid; this could be one factor contributing to the record of so-called failures of certain compaction aids in the laboratory vs. successes in the field. However, such chemically aided compaction at a lower moisture content might produce a deleterious long-term effect on strength because of reduced negative pore pressure.

Clay-Water Forces in Unsaturated Soils. Proctor's original explanation for the existence of an optimum moisture content was that more water gives better lubrication.[1] In clayey soils this, in a sense, is true since dilution reduces ionic attractions and negative pressure;[7] however, this amounts to a reduction in the normal force, not the coefficient of sliding friction. Tests of common non-clay minerals show that wetting tends to increase rather than reduce sliding friction. On the other hand, a reduction in sliding friction in clays could be implemented through modification of electrical double-layer interactions--the same interactions which contribute flocculation, as opposed to dispersion, of soil-clays. For example hydrated lime, $Ca(OH)_2$, added to clayey soil is an effective flocculent. $Ca(OH)_2$ - treated clay has high internal friction and compacts to a low density; yet it is stronger and volumetrically more stable than its untreated, higher density counterpart.

Since most soils in nature are at least weakly flocculated, it should not be difficult to define chemical dispersants that, by weakening the clay bonding, will improve compaction and decrease strength until the dispersing effect wears off, if indeed it does wear off. Since the zero air voids line of Fig. 2 cannot be crossed, the result would be a curve shifted up and to the left, a-b in Fig. 2.

Clay Structure. Field compaction involves breaking down and remolding existing soil clods, a process which requires energy and which, incidentally, is not simulated in conventional laboratory compaction tests for which clods are reduced beforehand. Thus, a chemical which weakens the clods could result in the same density with lower compactive effort, or higher density with the same effort, as curve a-b in Fig. 2. The mechanism by which clod strength is

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[7] R. E. Olson and L. J. Langfelder, "Pore Water Pressures in Unsaturated Soils," ASCE Jour., 91:SM 4, (1965), pp. 127-50.

reduced could be either or both of the two mechanisms discussed above -- reduced surface tension or increased dispersion.

In summary, for a chemical compaction aid to be effective, it would appear that it must reduce soil strength in one way or another. Such a reduction could only be temporary if the effect of the chemical is then lost through biological activity, oxidation, or further absorption into the clay. Consequently, the practical implications insofar as conduct of this research are as follows:

1. Soil probably should not be finely pulverized prior to laboratory compaction.
2. Soil probably should not be allowed to air-dry prior to laboratory compaction except as required to reduce the moisture content below optimum.
3. Soil should not be re-used for consecutive compaction specimens, since the structure is lost.
4. Evaluation of effectiveness of a chemical should include tests for effects on surface tension and clay dispersion as a function of time.
5. Ultimate potential benefits should be evaluated from the standpoint of strength, also as a function of time.

The first three hypotheses were tested early in the research program to determine their relevance. For example, comparative tests were made with and without preliminary pulverization, and the results were used to standardize the research procedures. This was believed far preferable to blindly accepting existing standard methods, which, as it turned out, would have seriously obscured or modified the findings. In most cases, the unrealistic aspects of current standard procedures appear to have been developed for expediency (as in re-using soil samples) and better reproducibility (as in air-drying and pre-pulverization) rather than a close simulation of field priorities.

Mechanics of Confined Compaction. Confined compaction, as in a steel mold, does not normally occur in the field where the confining member is soil with a much lower elastic modulus than steel. It is therefore instructive to consider the mechanics of completely confined compaction, as would occur for example in a consolidometer, as a clue to what may or may not occur in the laboratory and/or field compaction. The following hypothesis was developed by Spangler and Handy:[8]

> "...consolidation must involve at least minor shear displacements in order that lateral pressure can develop as a consequence of axial loading. Furthermore, the ratio of lateral-

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[8] M. G. Spangler and R. L. Handy, Soil Engineering, 3rd ed. (Scranton, Pa: International Textbook Company, 1973).

to-vertical stress during uniaxial consolidation was found to equal a constant, K_o, because of resistance from sliding friction between mineral grains in the soil. The stress path during consolidation follows a straight line called the $\underline{K_o \text{ line}}$. The K_o line passes through the origin and has a slope tan α with the value as shown in Equation (1)."

The authors then show that

$$\tan \alpha = \sin \phi_s = \frac{1 - K_o}{1 + K_o} \tag{1}$$

where ϕ_s is the angle of sliding friction. The lowest common value measured for K_o is 0.4 for sands, which gives $\phi_s = 25^o$, coincidentally the angle of sliding friction for quartz. The highest common value for K_o is 0.7 for clay, which gives $\phi_s = 10^o$, the angle of sliding friction for mica, both values providing a slender confirmation of the above hypothesis. Solution of Eq. (1) for K_o gives

$$\frac{\sigma_3}{\sigma_1} = K_o = \frac{1 - \sin \phi_s}{1 + \sin \phi_s} \tag{2}$$

where σ_3 and σ_1 may be taken to represent horizontal and vertical stress, respectively, during consolidation or confined compaction.

It should be noted that Eq. (2) is similar to the Rankine equation for the active earth pressure coefficient K_a, except that the latter uses sin ϕ rather than sin ϕ_s, and thus incorporates dilatant effects in angle ϕ. Since the above represents an essentially zero lateral expansion case, the predicted ratio of σ_3/σ_1 should be an upper limit resulting from compaction. The effect of a yielding lateral restraint, as occurs in the field or in a triaxial test, should next be considered.

Reduced Confinement in Compaction. The importance of lateral confinement in compaction was hypothesized by Handy[9] from constant σ_3 triaxial test data on compacted base course samples. In Fig. 3, the axial stress increases to the right until after failure, so σ_3/σ_1 generally decreases to the right. The value of σ_3/σ_1 is shown at each minimum volume point, and, excluding one value at a lateral stress of 10 psi, averages 0.21 which is a much lower value than that which develops with complete confinement. Most significant, however, is that below this lower value of σ_3/σ_1 the volume increases

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[9] R. L. Handy, "From Practice to Theory in Soil Compaction." (presented at 13th Annual Convention National Asphalt Pavement Association, Los Angeles, Cal., Feb. 1968).

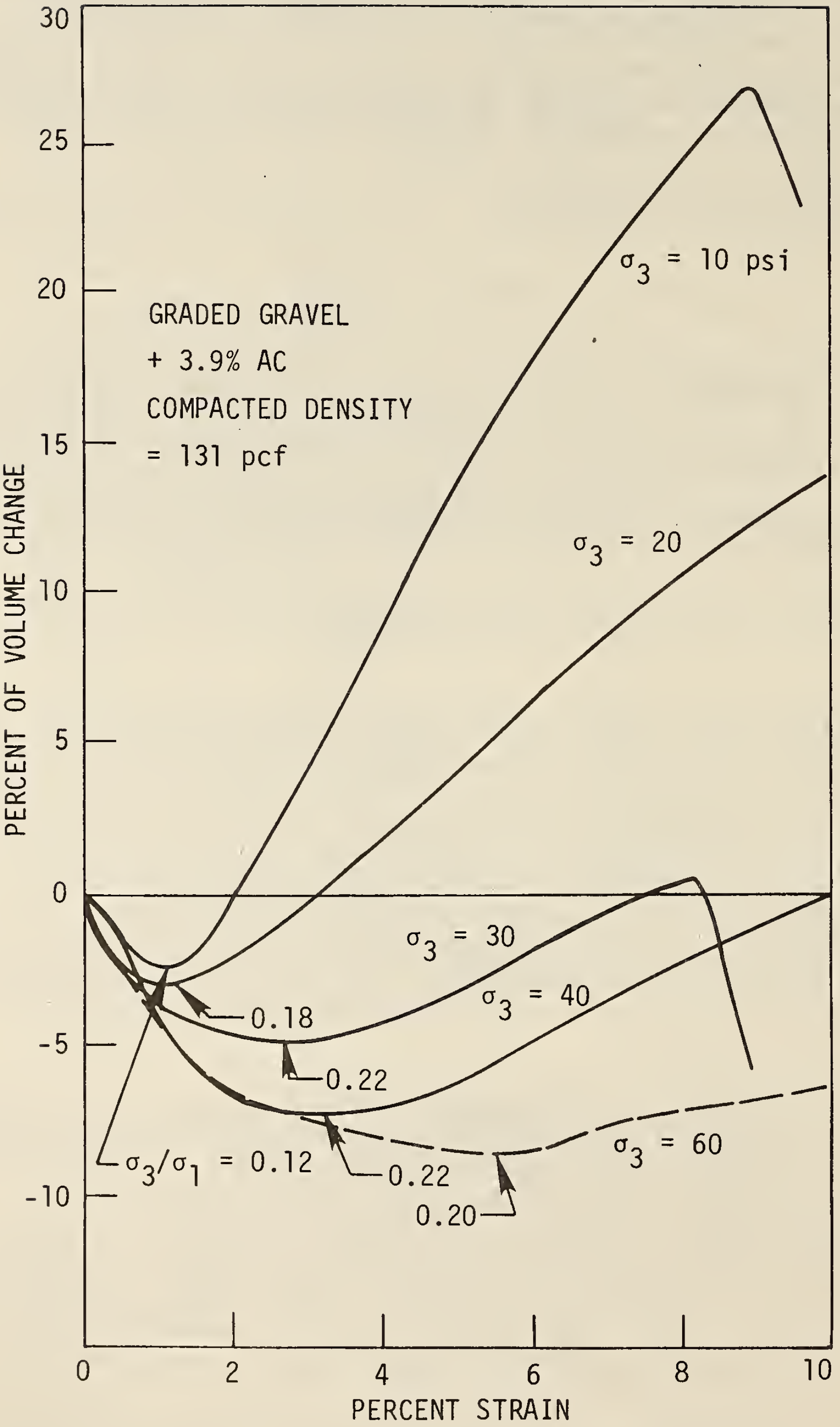

Fig. 3. Compaction in a conventional-triaxial test with constant σ_3.

rather than reduces, i.e., the soil dilates or "de-compacts". Lateral confinement is thus essential for compaction, the minimum σ_3/σ_1 ratio probably depending on ϕ rather than ϕ_s. Substitution of 0.21 for K in Eq. (1) gives $\phi = 40.8^\circ$, which is the friction angle with the minimum-volume failure criterion.[10]

Handy[9] showed a relation of lateral confinement to existence of a firm base for compaction as indicated by Boussinesq and Burmister elastic theories, Fig. 4. Compaction of a thicker layer would give a σ_3/σ_1 ratio of less than 0.2, i.e., too low for compaction near the middle of the layer if 0.2 is the minimum allowable ratio. The importance of a firm, rough underlayer to provide lateral restraint can be illustrated by pressing loose soil against a sheet of sandpaper, vs. pressing it against a smooth surface such as glass; in the latter case the soil squeezes out and fails plastically at much lower compaction.

Although the principles revealed by the above analysis appear valid, the analysis assumes elastic soil behavior, i.e., strain proportional to stress. This obviously is not the case in a shearing or failing soil, where strain increases out of proportion to stress. Elastic theory may, however, be fairly valid for a compacting soil so long as it is recognized that the elastic modulus will be higher on the second loading than the first, at least up to the stresses attained under the first loading, whereupon compaction will resume and the lower "compacting elastic modulus" will prevail. Thus, the repetition of passes could be analyzed as a complex three-layer problem, while the same principles apply.

In terms of the influence of a compaction aid, anything which decreases intergranular friction, either by reducing the coefficient of sliding friction or the negative pore water pressure, will have the effect of increasing σ_3/σ_1 (Eq. [5]). This suggests that the ratio σ_3/σ_1 be monitored during laboratory compaction as an indication of intergranular sliding friction (Eq. [1]). The higher σ_3 could improve compaction so long as it did not overcome lateral restraint. Therefore, from this standpoint, an aid might look promising in the laboratory and perform badly in the field.

Destructive Rebound. After a compactive effort is applied and released, the lateral restraining stress tends to remain, but the vertical stress is removed and now equals only the pressure from overlying soil. To relieve the lateral stress the soil therefore will tend to shear and dilate or rebound to an equilibrium value dictated by the soil properties and overburden stress, Fig. 5. The condition is analogous to a triaxial (plane-strain) test specimen laid on its side with $\sigma_3 = \sigma_v = \gamma z$ and $\sigma_1 = \sigma_h =$ the previous σ_3

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[10] J. M. Hoover, "Granular Base Materials for Flexible Pavements," Final Report, Proj. HR-131/704S, (1970).

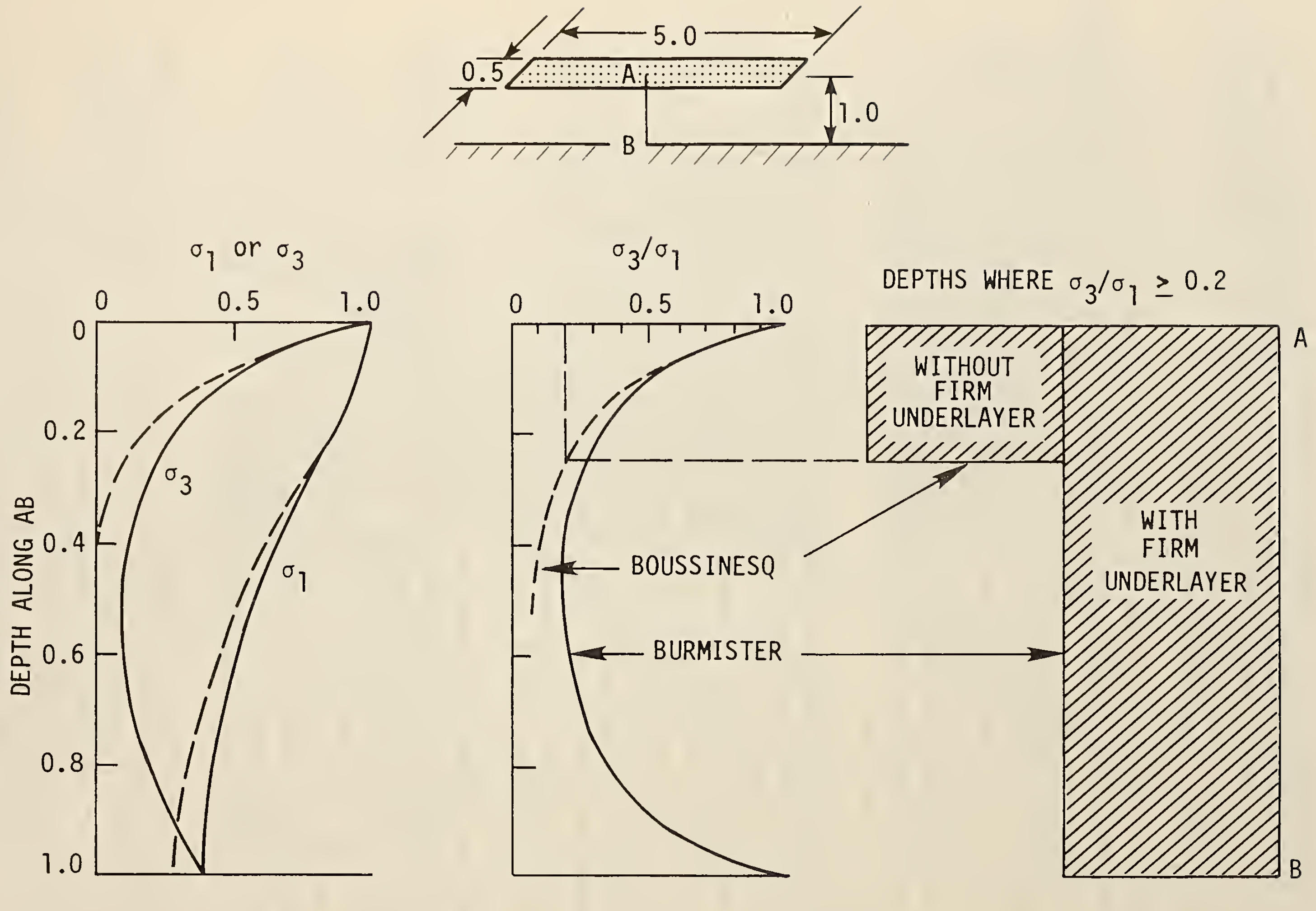

Fig. 4. Increase in confining stress σ_3 due to a firm underlayer.

while under load, where σ_v and σ_h are vertical and horizontal stress, γ is the soil unit weight, and z is the depth. Destructive rebound will occur where z is insufficient to retain the inherited σ_h.

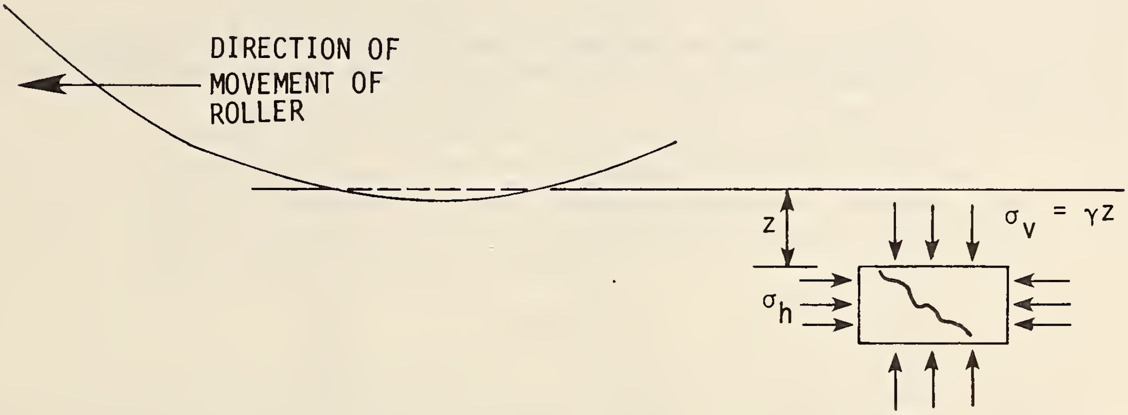

Fig. 5. Conditions for destructive rebound.

From the Mohr circle at failure,

$$\sin \phi = \frac{\sigma_1 - \sigma_3}{\sigma_1 + \sigma_3 + 2\ c \cot \phi} \tag{3}$$

where c is the soil cohesion (which was ignored or assumed to be negligible in uncompacted soil). Substituting for σ_1 and σ_3,

$$\sin \phi = \frac{\sigma_h - \gamma z}{\sigma_h + \gamma z + 2\ c \cot \phi} \tag{4}$$

Solving for the destructive rebound depth z,

$$z = \frac{\sigma_h\ (1 - \sin \phi) - 2\ c \cos \phi}{\gamma (1 + \sin \phi)} \tag{5}$$

This equation gives some rather interesting implications. From Eq. (5), for z to be zero,

$$c \geq \frac{\sigma_h}{2}\left(\frac{1 - \sin \phi}{\cos \phi}\right) = \frac{\sigma_h}{2}(\sec \phi - \tan \phi) \tag{6}$$

Solution of Eqs. (5) or (6) requires an estimation of the residual horizontal stress σ_h, which depends on compactor weight, etc. Since the purpose here is to evaluate the influence of soil properties, and changes in these properties from chemical additives, let us arbitrarily assume $\sigma_h = 2$ psi. If $\gamma = 100$ pcf, then

ϕ, °	Minimum c, psi, for z = 0	z, in., if c = 0
0	1.0	35
10	0.8	24
20	0.7	17
30	0.6	12
40	0.5	6

Thus, a modest cohesion will prevent destructive rebound. However, dry sand, for example, should rebound and loosen in the upper foot or so. If ϕ is low, and also c is very low, as in micaceous soils, the predicted destructive rebound goes much deeper. This is borne out by their separate A-5 category in the AASHTO classification, despite relative scarcity of these soils.

The pertinence of these arguments for the present problem is that chemicals which reduce ϕ or c should increase the tendency for destructive rebound, and these chemicals are also undesirable from a strength standpoint.

Volume Change Characteristics. Dispersed clays are far more susceptible to volume change than are their flocculated counterparts, since individual clay particles are not directly linked, but are rather tenuously separated from one another by filters of water. Drying soil clays reduces the film thickness and wetting increases it, causing deleterious volume change. Therefore, chemicals that tend to permanently disperse soil clays may be deleterious to strength as well as volume change; if the dispersive effect is temporary, it could result in higher density, and stronger soils, with less compactive effort. If, for lack of better information, we again assume $\sigma_h = 200$ psf, then

$$c \geq 83.9 \text{ psf} = 0.58 \text{ psi} \tag{7}$$

Thus, a relatively low value of cohesion should prevent destructive rebound. If we assume $\sigma_h = 0.7\ (1000) = 700$ psf, the value for 0.7

representing the maximum, fully confined, K_o value,

$$c \geq 0.42\ (700) = 294 \text{ psf} = 2.0 \text{ psi}, \qquad (8)$$

still a relatively nominal value of cohesion to prevent destructive rebound.

From the standpoint of compaction aids, the practical implications of these volume change characteristics are as follows:

1. A higher σ_h, which may be caused by use of a chemical compaction aid, could mean deeper destructive rebound.
2. A nominal cohesion can prevent destructive rebound. Thus, improving cohesion should prevent rebound, and reducing cohesion may increase rebound.

Summary

1. It is conjectured that tensile forces arising from negative pore pressures, due either to surface tension or clay-water effects, cause intergranular friction which varies with the moisture content, resists compaction, and therefore produces lower compacted densities to the left of maximum density of a typical moisture content curve. Chemicals which reduce surface tension of water or interrupt the continuity of clay-water bonding should reduce this effect, and therefore reduce the criticality of optimum moisture content for compaction. As a practical outcome from this conjecture, evaluations of potential compaction aids should involve compaction at several moisture contents below the optimum determined without the additive.

2. Evidence indicates that lateral confining pressure is essential for compaction and is a factor determining maximum field lift thickness. The minimum σ_3/σ_1 ratio is measurable for a particular soil by means of triaxial tests with monitored volume changes. A compaction aid which decreases sliding friction may allow an increased lateral pressure but also may increase the minimum σ_3/σ_1 ratio required for compaction. Regardless of density, a reduction in sliding friction should mean a weaker soil and perhaps shear failure during field compaction, severely damaging the soil strength.[5,11] Such shear failure is at least in part prevented in conventional laboratory compaction by rigid steel molds because of the higher elastic constant of steel compared to that of soil, and hence the higher confining pressure and frictional restraint against vertical movement. This suggests that the mold should be split, and a wall composition and thickness be developed such that the mold expansion force simulates representative values of elastic modulus (a lateral modulus of subgrade reaction) of compact-

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[11] L. J. Langfelder and V. R. Nivargikar, "Some Factors Influencing Shear Strength and Compressibility of Compacted Soils," HRB Record, 177, (1967), pp. 4-21.

ed soils. Lateral pressures resulting from compaction could then be readily monitored from expansion of the mold, and may be indicative of intergranular sliding friction.

3. Destructive rebound occurs as a result of lateral pressures causing shear failure of the surface soil after the compaction load is removed. The maximum depth of resulting de-compaction is predictable from soil mechanics, which indicate that depth can be reduced by increasing the internal friction angle ϕ, or prevented altogether by a relatively small soil cohesion. Thus, a compaction aid could have an effect on this action through modification of friction or cohesion.

PRODUCT LITERATURE REVIEW

Publications pertinent to the mechanics of compaction and the use of chemical compaction aids were reviewed from two aspects:

1. Improvement of compactability with soil additives as evidenced by an increase in density, reduction of water content for achievement of maximum density, and potential for reduction of compaction effort to achieve densification.
2. Nature and potential mechanism of chemical compaction aids.

To some degree, the literature review is incomplete due to two primary factors:

1. Manufacturer's or distributor's trade literature consists principally of testimonials, coupled with (a) extremely limited evaluations of "field tests", most of which have no comparative control, (b) less than substantive wording on the chemical make-up/or mechanism of the soil-additive combination, (c) an occasional "laboratory" study, (d) specifications on application rates, mix design, and/or construction procedures that are so extremely broad as to be useless.
2. Many agencies or firms are reluctant to publish data dealing with any proprietory product, particularly if laboratory and/or field evaluations produced negative results. Discussions with organizations known to have conducted limited lab and/or field evaluations yielded a general response of "let's not talk about it."

Non-proprietary Literature

Tables 1 through 6 are summaries of data gleaned from the literature, showing increase or decrease in actual maximum density and optimum moisture content with various types of chemical treatments as compared with the untreated soils. The treatments are categorized as Cementing Agents - Table 1, Binding Agents - Table 2, Chlorides - Table 3, Waterproofers Table 4, Trace Chemicals - Table 5, and Combinations - Table 6.

Cementing Agents. From Table 1, it may be noted that most cementing agents tend to decrease density, often by significant amounts, and are accompanied by increases in optimum moisture content with most fine-grained soils. When utilized with a dune sand, however, Davidson et al.[12] noted that portland cement significantly increased

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[12] D. T. Davidson et al. "Moisture-Density, Moisture-Strength and Compaction Characteristics of Cement-Treated Soil Mixtures," HRB Bulletin, 353, (1962), pp. 42-63.

Table 1. Summary of increase or decrease in maximum density and optimum moisture content with various types of chemical cementing agent treatments.

Legend: * Trade Name, - no data given

Soil Type, Soil Series, or Sample Location	Textural Class.	Engr. Class.	Additive	Concentration or % Dry Soil Weight	Inc. or Dec. in Max. Dry Density, pcf	Inc. or Dec. in OMC, % Dry Weight	Source of Data
-	Clay	A-7-5(20)	Portland Cement	12%	-1.8	+0.5%	Davidson, D.T., et al.[12]
-	Clay	A-7-5(20)	"	16%	-2.0	0	"
-	Clay	A-7-6(18)	"	12%	-2.0	+2.8	"
-	Clay	A-7-6(18)	"	16%	-3.0	+3.2	"
Dune Sand	Sand	A-3 (0)	"	12%	+5.5	+0.6	"
"	Sand	A-3 (0)	"	16%	+7.5	0	"
Massachusetts	Clayey Silt	A-4 (2)	Lime	2%	-9.0	+2.1	Ladd, C.C., et al.[60]
"	"	A-4 (2)	"	6%	-10.0	+4.0	"
"	"	A-4 (2)	"	10%	-17.0	+5.1	"
Port Hueneme	Clay	A-7-5(18)	"	2%	-4.1	+2.0	"
"	"	A-7-5(18)	"	6%	-8.2	+4.1	"
Port Hueneme	Clay	A-7-5(18)	Lime	10%	-11.0	+8.0	Ladd, C.C., et al.[60]
Hamburg	Silt	A-4 (8)	Lime	6%	-10.4	-1.1	Davidson, D.T., et al.[12]
"	Silt	A-4 (8)	Lime	4.5%	-12.5	-0.1	"
Marshall	Clay	A-7-6(18)	Lime	6%	-8.2	-7.0	"
"	Clay	A-7-6(18)	Lime	4.5%	-7.7	+0.3	"
In-Place roadway	Clay	A-6 (5)	Lime	2%	-5.9	+1.0	Squier, L.D.[18]
"	Clay	A-6 (5)	Lime	4%	-8.2	+1.2	"
"	Clay	A-6 (5)	Lime	6%	-10.7	+2.3	"
"	Clay	A-6 (4)	Lime + Flyash	5% 8%	-5.1	+1.6	"
"	Clay	A-6 (4)	Lime + Flyash	4% 12%	-6.4	+2.0	"
"	Clay	A-6 (4)	Lime + Flyash	3% 16%	-6.2	+1.9	"
Mahaska	Clay	A-7-6(18)	Phosphoric Acid	1%	+2.0	-	Demirel, T., et al.[13]
"	Clay	A-7-6(18)	"	6.5%	+3.0	-	"
"	Clay	A-7-6(18)	"	20%	+8.0	-	"
Shelby	Clay	A-7-6(12)	Phosphoric Acid	2%	+1.5	-	Demirel, T., et al.[13]
"	Clay	A-7-6(12)	"	5.5%	+5.0	-	"
Alluvial	Clay	A-7-6(20)	"	2%	+1.0	-	"
"	Clay	A-7-6(20)	"	10%	+6.0	-	"
Virginia	Clay	A-7-6(12)	"	2%	+0.5	-	"
"	Clay	A-7-6(12)	"	10%	+4.0	-	"
Hamburg	Silty Clay	A-4 (8)	Aniline Furfural	2%	-4.0	-0.5	Sheeler, J.B., et al.[61]

(continued)

Table 1. Continued.

Soil Type, Soil Series, or Sample Location	Textural Class.	Engr. Class.	Additive	Concentration or % Dry Soil Weight	Inc. or Dec. in Max. Dry Density, pcf	Inc. or Dec. in OMC, % Dry Weight	Source of Data
Hamburg	Silty Clay	A-4 (8)	Aniline Furfural	5%	-4.7	-1.7	Sheeler, J.B., et al.[61]
"	"	A-4 (8)	"	2%	-6.6	+0.7	"
"	"	A-4 (8)	"	5%	-6.9	-1.2	"
Monona	"	A-6 (8)	"	2%	-7.0	+1.0	"
"	"	A-6 (8)	"	5%	-9.2	-0.9	"
Marshall	"	A-6 (9)	"	2%	-6.5	+1.7	"
"	"	A-6 (9)	"	5%	-8.6	+0.1	"
"	"	A-7-6(18)	"	2%	-6.4	+0.9	"
"	"	A-7-6(18)	"	5%	-9.4	-1.2	"
Sharpsburg	Clay	A-7-6(19)	"	2%	-7.6	+0.9	"
"	"	A-7-6(19)	"	5%	-9.2	-3.0	"

dry density, probably due to more complete filling of the voids with the heavy specific gravity cement. Phosphoric acid increased the dry density of several clayey soils (Demirel et al.[13]) with increased concentrations of the acid, but no data were available relative to changes in optimum moisture content. Since most of the products in Table 1 reduced maximum dry density and since phosphoric acid and aniline-furfural are extremely toxic for field usage, none of these products were considered for evaluation in the present project.

Binding Agents. Binding agents such as lignin, Table 2, have been used as soil stabilizers for many years. Replenishment by periodic treatment has been necessary since lignosulfonates dissolve and leach out of a soil. Several types of lignosulfonates have been tested in both powder and solution forms[14] and produced similar results, though powder was easier to use. Lignosulfonates increased the soil's plasticity index which was greatest for soils having the highest clay and organic matter contents. In the study by Sinha et al.,[14] optimum lignin content was generally found to be about 6% by dry soil weight, a situation which is economically unjustified as a compaction aid only since most lignins are sold in 50% water concentrations at $0.25 per gallon and up.

Lignins have been noted to act as dispersing agents[15,16] and as binders,[16] decreasing needed moisture for maximum standard density; i.e., causing a shift of the M-D curve to the left of optimum. Fox and Hoover[17] noted an increase of about 2 pcf density and decrease of optimum moisture of about 2% dry soil weight, with 2% lignin solids with a sandy loam soil. Improved insulating properties were also noted,[17] though use for roadway treatments in Iowa have been limited by costs.

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[13] T. Demirel et al., "Use of Phosphoric Acid in Soil Stabilization," HRB Bulletin, 282 (1961), pp. 38-58.

[14] S. P. Sinha et al., "Lignins as Stabilizing Agents for Northeastern Iowa Loess, Iowa Academy of Science Proceedings, 64 (1957).

[15] M. Ekse, Investigation of Use of Lignin Sulphonate as a Soil and Mineral Aggregate Binder, Report to Scott Paper Co., Western Division (Everett, Washington: June 25, 1958).

[16] D. T. Davidson and R. L. Handy, "Soil Stabilization with Chlorides and Lignin Derivatives," Highway Engineering Handbook (New York: McGraw-Hill, Inc., 1960).

[17] D. E. Fox and J. M. Hoover, "Ammonium Lignosulfonates as Dust Palliatives and Surface Improvement Agents for Unpaved Secondary Roads," Final Report, Surface Improvement and Dust Palliation of Unpaved Secondary Roads and Streets, Iowa Highway Research Board Project HR-151 (Engineering Research Institute, Iowa State University: July 1973).

Table 2. Summary of increase or decrease in maximum density and optimum moisture content with various types of chemical binder treatments.

Legend: * Trade Name, - no data given

Soil Type, Soil Series, or Sample Location	Textural Class.	Engr. Class.	Additive	Concentration or % Dry Soil Weight	Inc. or Dec. in Max. Dry Density, pcf	Inc. or Dec. in OMC, % Dry Weight	Source of Data
In-Place Roadway	Sandy Silt	A-2-4 (0)	Lignin	1 gal/yd^2	-1.0	+0.5	Squier L.D.[18]
"	"	A-2-4 (0)	Lignin	1 1/2 gal. yd.^{2}	-1.3	+0.2	"
"	"	A-2-4 (0)	Lignin	2 gal/yd^2	0	+0.2	"
"	"	A-2-4 (0)	Lignin + 20 gal/acre	1 gal/yd^2 Pramitol E-25*	-1.5	+0.3	"
"	"	A-2-4 (0)	Lignin + 20 gal/acre	1 1/2 gal. yd.^{2} Pramitol E-25*	-1.0	+0.8	"
"	"	A-2-4 (0)	Lignin + 25 gal/acre	1 gal/yd^2 Pramitol E-25*	-0.2	+0.2	"
"	"	A-2-6 (1)	Asphalt emulsions	3.0 residual	-3.8	+0.3	"
"	"	A-2-6 (1)	"	4.0 "	-6.5	+0.2	"
"	"	A-2-6 (1)	"	5.0 "	-5.0	-0.2	"
"	Clay	A-6 (2)	"	3.0 "	-6.1	+0.9	"
"	Clay	A-6 (2)	"	4.0 "	-7.0	0.0	"
Fayette	Silty Clay	A-7-6 (12)	Spent Sulphite Liquor	3.0	+4.6	-2.0	Sinha, S.D. et al.[14]
"	"	A-7-6 (12)	"	6.0	+5.1	-2.7	"
"	"	A-7-6 (12)	"	9.0	+4.0	-4.4	"
"	"	A-7-6 (12)	Sulphite Lignin Grade A*	3.0	+3.3	-2.0	Sinha, S.D. et al.[14]
"	"	A-7-6 (12)	"	6.0	+4.2	-2.7	"
"	"	A-7-6 (12)	"	9.0	+4.8	-3.2	"
"	"	A-7-6 (12)	Sulphite Lignin Grade D*	3.0	+3.9	-1.3	"
"	"	A-7-6 (12)	"	6.0	+4.2	-2.1	"
"	"	A-7-6 (12)	"	9.0	+4.2	-2.1	"
"	"	A-7-6 (12)	Bindarene flour*	3.0	+4.2	-1.0	"
"	"	A-7-6 (12)	"	6.0	+4.3	-1.8	"
"	"	A-7-6 (12)	"	9.0	+4.2	-2.1	"
"	"	A-7-6 (12)	Clarian extract*	3.0	+2.7	-1.1	"
"	"	A-7-6 (12)	"	6.0	+2.9	-2.3	"
"	"	A-7-6 (12)	"	9.0	+2.3	-2.5	"
Fayette	Silty Clay Loam	A-6 (8)	Spent Sulphite Liquor	3.0	+2.9	-4.0	"
"	"	A-6 (8)	"	6.0	+5.6	-6.4	"
"	"	A-6 (8)	"	9.0	+7.5	-6.9	"
"	"	A-6 (8)	Bindarene flour*	3.0	+3.4	-3.3	"
"	"	A-6 (8)	"	6.0	+5.1	-4.4	"
"	"	A-6 (8)	"	9.0	+5.8	-6.2	"
Tama	Silty Clay	A-6 (9)	Spent Sulphite Liquor	3.0	+5.8	-1.7	"
"	"	A-6 (9)	"	6.0	+7.0	-3.4	"
"	"	A-6 (9)	"	9.0	+7.1	-3.8	"

(continued)

Table 2. Continued.

Soil Type, Soil Series, or Sample Location	Textural Class.	Engr. Class.	Additive	Concentration or % Dry Soil Weight	Inc. or Dec. in Max. Dry Density, pcf	Inc. or Dec. in OMC, % Dry Weight	Source of Data
Tama	Silty Clay	A-6 (9)	Sulphite Lignin Grade A*	3.0	+4.2	-2.1	Sinha, S.D., et al.[14]
"	"	A-6 (9)	"	6.0	+5.2	-2.2	"
"	"	A-6 (9)	"	9.0	+6.2	-3.8	"
"	"	A-6 (9)	Sulphite Lignin Grade D*	3.0	+5.7	-2.1	"
"	"	A-6 (9)	"	6.0	+6.1	-1.7	"
"	"	A-6 (9)	"	9.0	+6.1	-1.7	"
"	"	A-6 (9)	Bindarene flour*	3.0	+5.2	-3.1	"
"	"	A-6 (9)	"	6.0	+7.5	-3.6	"
"	"	A-6 (9)	"	9.0	+7.8	-4.7	"
"	"	A-6 (9)	Clarian extract*	3.0	+4.7	-2.3	"
"	"	A-6 (9)	"	6.0	+5.7	-2.4	"
"	"	A-6 (9)	"	9.0	+5.8	-2.8	"
"	"	A-6 (9)	Lignin	2.0	+3.3	-1.0	Gow, A.J., et al.[62]
"	"	A-6 (9)	Tornil A*	2.0	+2.5	-1.1	"
"	"	A-6 (9)	Molasses	2.0	+2.6	-1.2	"
Hamburg	Silty Clay Loam	A-4 (8)	Al-Sulfate	1.0	+0.3	+0.4	Demirel, T., et al.[63]
"	"	A-4 (8)	"	3.0	-1.7	+1.8	"
"	"	A-4 (8)	"	5.0	-2.7	+1.6	"
"	"	A-4 (8)	Ca-Lignosulfonate	2.0	-1.8	-0.7	"
"	"	A-4 (8)	Ca-Lignosulfonate + Al-Sulfate	2.0 1.0	0	0	"
"	"	A-4 (8)	Ca-Lignosulfonate + Al-Sulfate	2.0 3.0	-3.7	+1.4	"
"	"	A-4 (8)	Ca-Lignosulfonate + Al-Sulfate	2.0 5.0	-4.7	+2.3	"
"	"	A-4 (8)	Ca-Lignosulfonate + Al-Sulfate	4.0 5.0	-5.5	+2.0	"
"	"	A-4 (8)	Ca-Lignosulfonate	6.0	-4.1	-2.6	"
"	"	A-4 (8)	"	8.0	-4.4	-3.5	"
"	"	A-4 (8)	Ca-Lignosulfonate + Al-Sulfate	8.0 6.0	-5.5	+1.1	"
Bedford Limestone	Sandy Gravel	A-3 (0)	NH_4-Lignosulfonate	1.0	+3.0	-3.5	Fox, D.E., et al.[17]
"	"	A-3 (0)	"	2.0	+2.3	-2.5	"
"	"	A-3 (0)	"	5.0	+1.5	-2.0	"
Clarion	Silty Clay	A-3 (0)	"	5.0	+0.4	-0.5	"

(continued)

Table 2. Continued.

Soil Type, Soil Series, or Sample Location	Textural Class.	Engr. Class.	Additive	Concentration or % Dry Soil Weight	Inc. or Dec. in Max. Dry Density, pcf	Inc. or Dec. in OMC, % Dry Weight	Source of Data
Clarion	Silty Clay	A-3 (0)	NH_4-Lignosulfonate	1.0	+0.7	-0.8	Fox, D.E., et al.[17]
"	"	A-3 (0)	"	2.0	+2.6	-1.8	"
In-Place Roadway	Gravelly Loam	A-2-6 (0)	NH_4-Lignosulfonate	1.0	+2.0	+0.4	"
"	"	"	"	2.0	-0.2	-0.5	"
"	"	"	Sodium Silicate	0.5	-0.1	-0.4	"
"	"	"	"	1.0	-0.7	+0.6	"
"	"	"	"	1.5	-0.5	0	"
"	"	"	Polymer J B	0.5	+1.5	+0.3	"
"	"	"	"	1.0	0	+0.1	"
"	"	"	"	1.5	-2.6	+0.5	"
"	"	"	"	2.0	-6.1	+0.2	"
"	"	"	NH_4-Lignosulfonate + Sodium Silicate	1.0 1.0	-0.9	+0.7	"
"	"	"	"	1.0 0.5	-0.7	+0.9	"
"	"	"	NH_4-Lignosulfonate + Sodium Silicate	2.0 0.5	-0.5	-0.1	"
"	"	"	"	2.0 1.0	-0.9	-0.2	"
"	"	"	"	2.0 1.5	-1.4	+0.2	"
"	"	"	"	2.0 2.0	-2.4	+0.8	"
"	"	"	NH_4-Lignosulfonate + Polymer J B	1.0 0.5	-0.4	+0.7	"
"	"	"	"	1.0 1.0	-0.8	+0.2	"
"	"	"	"	1.0 1.5	-4.1	+0.8	"
"	"	"	"	2.0 0.5	-2.0	+0.5	"
"	"	"	"	2.0 1.0	-3.0	+0.1	"

(continued)

Table 2. Continued.

Soil Type, Soil Series, or Sample Location	Textural Class.	Engr. Class.	Additive	Concentration or % Dry Soil Weight	Inc. or Dec. in Max. Dry Density, pcf	Inc. or Dec. in OMC, % Dry Weight	Source of Data
In-Place Roadway	Gravelly Loam	A-2-6 (0)	NH_4-Lignosulfonate + Polymer J B	2.0 1.5	-4.0	-0.2	Fox, D.E., et al.[17]
-	Silty Clay	A-6	Soils Organic Binder* (Lignin)	1 to 4 in. water, by volume	+1.4	-0.5	Louisiana Dept. of Highways[64]

Addition of secondary additives to soil-lignin mixtures, Table 2, shows a general reduction in maximum density and increase in optimum moisture content. Either proprietary organic herbicide Pramitol E-25, or aluminum sulfate, when combined with lignin, retarded leaching and slightly improved strength characteristics, though no improvement in density or moisture content was noted.[17,18] Addition of a proprietary product termed Polymer JB (a guar derivative), sodium silicate, or combinations of each with an ammonium lignosulfonate also produced deleterious M-D* results on a gravelly loam soil.[17]

Yamanouchi[19] utilized a spent sulphite liquor with added potassium dichromate, aluminum sulfate, and ferric chloride as auxiliary agents in an organo-volcanic ash soil in Japan. He noted a definite increase in density with accompanying decrease in optimum moisture due to increasing percentages of additives.

Due primarily to the fairly large quantity of lignins required for beneficial M-D results, economics dictated removal of lignin from further evaluation as a compaction aid.

Binding agents, such as the asphalt emulsion noted in Table 2, generally produce only decreases in maximum density of fine-grained soils with slight increases in optimum water content. Small quantities of an MC-800 cutback asphalt used in a gravelly sandy loam by Bergeson and Hoover[20] showed no basic change in maximum dry density. However, two proprietary products called Peneprime and Semi-Pave, used in small quantities in the same soil showed slight increase in density but significantly decreased strength properties due to their oils.

Thus, no form of asphalt or oil was considered for evaluation in the present study, as an aid to the compaction of fine-grained soils.

Chlorides. Table 3 illustrates that sodium and calcium chlorides may significantly improve moisture-density characteristics of reasonably well-graded soils, but are only slightly effective in fine-grained soils, and deleterious in a poorly-graded silty sand. In a uniform

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* M-D: Moisture-density; relation between compacted density and moisture content.

[18] L. D. Squier, "Evaluation of Chemically Stabilized Secondary Roads; Linn County, Iowa," Unpublished Master of Science Thesis, Iowa State University, 1974.

[19] T. Yamanouchi, "A New Stabilization of Soils by Means of Lignin Materials," Trans. Japan Soc. Civ. Eng., 64 (Sept. 1959), pp. 66-72.

[20] K. H. Bergeson and J. M. Hoover, "Asphaltic Products and Elastomers as Dust Palliatives and Surface Improvement Agents for Unpaved Secondary Roads," Final Report, Surface Improvement and Dust Palliation of Unpaved Secondary Roads and Streets, Iowa Highway Research Board Project HR-151 (ERI, Iowa State University: July 1973).

Table 3. Summary of increase in maximum density and optimum moisture content with various types of chloride treatments.

Legend: * Trade name, - no data given

Soil Type, Soil Series, or Sample Location	Textural Class.	Engr. Class.	Additive	Concentration or % Dry Soil Weight	Inc. or Dec. in Max. Dry Density, pcf	Inc. or Dec. in OMC, % Dry Weight	Source of Data
Crosby	Silty Clay	-	Calcium Chloride	0.25	+0.3	-	Yoder, E.J., et al.[65]
"	"	-	"	1.5	+0.1	-	"
Ruston	Sand Clay	-	"	1.0	+0.9	-	"
"	"	-	"	1.5	+0.6	-	"
Memphis	Silty Clay	-	"	1.0	+0.9	-	"
"	"	-	"	1.5	+0.3	-	"
In-Place Roadway	Clayey Sand	A-2-6 (1)	Sodium Chloride	2.0	+1.3	-0.6	Butzke, M.R.[36]
-	Gravelly Silty Clay	A-2-4 (0)	Calcium Chloride	1.0	+6.9	-1.8	Gow, A.J., et al.[62]
-	"	A-2-4 (0)	"	2.0	+4.8	-1.3	"
-	"	A-2-4 (0)	Sodium Chloride	2.0	+5.2	-0.9	"
In-Place Roadway	Silty Sand	A-2-5 (0)	Calcium Chloride	1/5 gal/yd^2	-1.4	+1.1	Squier, L.D.[18]
"	"	A-2-5 (0)	"	1/3 gal/yd^2	-1.3	+1.5	"
"	"	A-2-6 (0)	Ca Cl_2	1/2 gal/yd^2	-1.1	+0.8	"
"	Sand	A-3	Sodium Chloride	1.5	+2.8	+0.6	"
"	"	A-3	"	2.0	+1.6	+1.2	"
"	"	A-3	"	3.0	+2.8	+0.5	"
-	Sand-Clay Gravel	-	Sodium Chloride	1.25	+2.9	-1.2	Louisiana Department of Highways[66]
-	"	-	"	2.50	+2.4	-1.5	"

sand, density was improved but optimum moisture content also increased.

Sambhandharaksa and Moh[21] found that 2% sodium chloride in Bangkok clay produced a definite increase in dry unit weight on the dry side of optimum moisture content. An insignificant change in dry density was noted on the wet side of optimum moisture. The soil had a high liquid limit and plasticity index, and was of mixed clay mineralogy with illite and montmorillonite predominating.

The Maine State Highway Commission[22] noted that dissolved chlorides improved compaction by improving lubrication between particles. Calcium chloride was found to be a better lubricant than sodium chloride. The improvement in compaction varied from 1 to 7% density gain while the effort required to achieve this increase was often reduced by as much as two-thirds.

The observed quantities of either chloride needed to achieve significant improvement in the compaction and/or compactibility of fine-grained soils, and the consideration that chlorides already are fairly well known for improving densification of many soils, precluded a further consideration of these products in this present study.

Surfactant Waterproofers. Cationic, anionic, and non-ionic waterproofing agents (surfactants), used in soil stabilization, are generally organic derivatives. Most of the products presented in Table 4 are cationic, i.e., surfactants which have long carbon chains and attach themselves rather readily to a negative clay surface through an exchange process replacing inorganic cations already on the clay.

In general, such chemical agents are fair to excellent in producing a hydrophobic effect in most fine-grained soils. However, as may be noted in Table 4, these chemicals generally create a definite reduction in dry density, most with an accompanying reduction in optimum moisture content. The latter reduction is due to the very rapid ion exchange of the inorganic for the larger organic ion, and results in at least a partial instantaneous hydrophobic, or water-hating effect.

On the basis of M-D analysis of the products noted in Table 4, it was not contemplated to use surfactant waterproofing agents in the present study. However, some of the proprietary products ultimately considered for use in both Phase I and II were suspected of containing small quantities of unknown surfactant and/or waterproofing compounds.

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[21] S. Sambhandharaksa and Z. C. Moh, "Effect of Salt Content on Thixotropic Behaviors of a Compacted Clay." Proc. of the Australia-New Zealand Geomechanics Conf., Vol. 1, Melbourne: (Aug. 1971), pp. 16-23.

[22] Maine State Highway Commission, Soil Stabilization for Highway Subgrades, Materials and Research Division Technical Paper 72-IR (April 1972).

Table 4. Summary of increase or decrease in maximum density and optimum moisture content with various types of chemical waterproofer treatments.

Legend: * Trade name, - no data given

Soil Type, Soil Series, or Sample Location	Textural Class.	Engr. Class.	Additive	Concentration or % Dry Soil Weight	Inc. or Dec. in Max. Dry Density, pcf	Inc. or Dec. in OMC, % Dry Weight	Source of Data
Sassafrass	Gr. Loam	A-2-6 (0)	Armac T*	2.0	-3.5	-0.9	Davidson, D.T., et al.[67]
"	"	A-2-6 (0)	"	2.0	-2.2	-0.4	"
Hamburg	Silty Clay	A-4 (8)	Arquad 2HT*	0.08	-8.0	+0.8	Hoover, J.M., et al.[68]
"	"	A-4 (8)	Arquad 2S*	0.16	-8.5	+1.2	"
"	"	A-4 (8)	Armeen*	0.38	-5.0	+0.8	"
"	"	A-4 (8)	Armac T*	0.24	-6.4	-1.3	"
"	"	A-4 (8)	Crude Amine	0.30	-7.3	+0.7	"
"	"	A-4 (8)	Armine Residue Arquad*	0.50	-7.9	-0.5	"
Marshall	"	A-7-6 (18)	Arquad 2HT*	0.45	-6.9	-0.9	"
"	"	A-7-6 (18)	Arquad 2HT*	0.45	-6.5	-0.7	"
"	"	A-7-6 (18)	Armine Residue Arquad*	0.60	-11.6	-1.4	"
"	"	A-7-6 (18)	Armac T*	0.76	-6.9	-1.9	"
"	"	A-7-6 (18)	Crude Amine	0.60	-5.1	-1.4	"
"	"	A-7-6 (18)	Armeen Residue Arquad*	0.45	-3.7	-0.5	"
"	"	A-7-6 (18)	Arquad 2HT*	0.5	-2.5	-1.7	"
Hamburg	"	A-4 (8)	Arquad 2HT*	0.3	-3.3	+0.8	"
In-Place Roadway	Clayey Sand	A-2-6 (1)	Arquad 2HT*	0.5	-3.7	+2.3	Butzke, M.R.[36]
"	"	"	Armac T*	0.5	-4.0	+1.0	"
-	Silty Clay	-	4-tert Butylpyrocatechol (TBC)*	0.42	+0.9	+0.7	Hemwall, J.B., et al.[69]
-	"	-	"	0.085	+0.3	-0.7	"
-	"	-	"	0.212	+0.6	+0.4	"
-	"	-	"	0.850	+2.0	-0.3	"
-	"	-	"	0.042	-0.8	-1.1	"
-	"	-	"	0.085	-0.4	-0.5	"
-	"	-	"	0.212	-1.3	-0.3	"
-	"	-	"	0.850	-1.0	-0.5	"
Edina	Silty Loam	A-7-6 (20)	Armac T*	1.2	-1.5	+1.3	Whitsell, C.H.[70]
"	"	"	Armac T*	3.22	-3.4	+0.1	"
"	"	"	Armac T*	6.44	-2.6	-1.1	"
"	"	"	Armac T*	9.66	-3.1	-1.3	"
"	"	"	Armac T 180*	1.3	+1.0	-0.1	"
"	"	"	"	3.26	+0.5	-2.6	"
"	"	"	"	6.52	-3.0	-1.7	"
"	"	"	"	9.78	-2.4	-3.7	"

Trace Chemicals. Table 5 presents a summation of changes in moisture-density requirements of various soils using trace chemicals. Most of the products noted are proprietary, and some will be further reported in the section under Trade and Patent Literature. The Central Chemical Company Products (i.e. SA-1, Clapak, Claset and Kelpak), when compared to the untreated soils without regard to classification of the soils, showed diversities in M-D, ranging from less to more density, with similar effects on optimum moisture content.

Recent observations on the SA-1 base test sections reported by Squier[18] indicate superior performance when compared with untreated control sections or with Clapak/Claset treated sections, after about 1 1/2 years of service under predominantly truck traffic and in spite of the lack of significant improvement in either lab moisture or density studies.

In a study by Kozan and Stouffer,[23] the product SA-1 was investigated for effectiveness in pre-treating soil to improve penetration of dust-control materials (an asphaltic penetrative soil binder, APSB) and as a soil stabilizer for military purposes. It was concluded after field testing under moving loads having contact pressures of 84.4 psi and 97.7 psi that the field treated and untreated fine-grained soil sections showed no significant differences with respect to strength and traffic support ability under either wet or dry conditions. Lab tests on samples from the field test sections showed no significant alteration of water content or Atterburg limits, and only a minor decrease of pH in the treated sections as compared with the untreated sections.

In addition to the lab test results shown in Table 5, the Louisiana Department of Highways conducted a field evaluation of SA-1 on an existing gravel-sand-clay base.[24] No significant variations of physical properties were noted between the SA-1 treatments and the original untreated base materials. Less deflection was obtained in the SA-1 treated sections than in the untreated section, indicating better load-bearing characteristics. Results of density measurements during construction and after selected numbers of equipment passes indicated no attainment of desired densities any sooner for the treated than the untreated sections.

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[23] G. R. Kozan and J. D. Stouffer, "Investigation of a Proprietary Chemical Agent for Soil Stabilization," Miscellaneous Paper S-70-11 (U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss.: April 1970).

[24] Louisiana Department of Highways, Research and Development Section. Evaluation of SA-1 Chemical Agent, Report II - Field Tests (April 1966).

Table 5. Summary of increase or decrease in maximum density and optimum moisture content with various types of trace chemical treatments.

Legend: * Trade name, - no data given,

Soil Type, Soil Series, or Sample Location	Textural Class.	Engr. Class.	Additive	Concentration or % Dry Soil Weight	Inc. or Dec. in Max. Dry Density, pcf	Inc. or Dec. OMC, % Dry Soil Weight	Source of Data
In-Place Roadway	Silt	A-4-(3)	Clapak* + Claset*	0.031 0.021	+1.1	+0.3	Squier, L.D.[18]
"	"	"	Clapak* + Claset*	0.007 0.005	+0.2	-0.7	"
"	"	"	Clapak* + Claset*	0.064 0.042	+0.8	+0.5	"
"	"	A-4-(1)	SA-1*	0.004	-0.3	-0.3	"
"	"	"	"	0.004	+0.5	-0.1	"
"	"	"	"	0.039	+0.8	0.0	"
"	Stone Fragments	A-1-b	"	0.005	-0.4	+0.9	"
"	"	"	"	0.004	+2.3	+0.1	"
"	"	"	"	0.040	+1.3	-0.2	"
"	Sandy Silt	A-2-4(0)	Kelpak*	0.032	0.0	-0.8	"
"	"	"	"	0.024	+0.9	-0.5	"
"	"	"	"	0.144	-1.1	-0.2	"
"	Clay	A-6-(9)	Clapak* + Claset*	0.039 0.026	-0.3	+0.5	"
"	"	"	Clapak* + Claset*	0.011 0.007	-0.2	-0.1	"
"	"	"	Clapak* + Claset*	0.083 0.055	-1.3	1.1	"
"	"	A-6-(1)	Terra-Seal*	0.004	+1.5	+0.4	"
"	"	"	"	0.003	+1.0	+0.1	"
"	"	"	"	0.017	+1.3	+0.2	"
Nevada	Clayey Silt	"	Enzymes SA*	-	+5.2	-	Engr. News Record Magazine[71]
Georgia	Silt	A-4(0)	Alkanol OJ*	0.50	+0.5	-	Shirley, H.G.[26]
"	"	"	"	3.0	+1.0	-	"
"	"	"	"	9.0	+1.5	-	"
Virginia	Clay	A-7-5(7)	"	0.50	+2.0	-	"
"	"	"	"	3.0	+2.0	-	"
"	"	"	"	9.0	+1.5	-	"
Georgia	Silt	A-4-(0)	Polytergent B-300*	0.25	+0.5	-	"
"	"	"	"	0.75	+1.0	-	"
"	"	"	"	3.0	+1.0	-	"
Virginia	Clay	A-7-5(7)	"	0.25	+9.0	-	"

(continued)

Table 5. Continued.

Soil Type, Soil Series, or Sample Location	Textural Class.	Engr. Class.	Additive	Concentration or % Dry Soil Weight	Inc. or Dec. in Max. Dry Density, pcf	Inc. or Dec. OMC, % Dry Soil Weight	Source of Data
Virginia	Clay	A-7-5(7)	Aerosol OT-75%*	0.75	+10.0	-	Shirley, H.G.[26]
"	"	"	"	3.0	+10.0	-	"
Georgia	Silt	A-4-(0)	Akanol 189-S*	0.5	-0.8	-	"
"	"	"	"	5.0	+0.2	-	"
"	"	"	"	9.0	+1.2	-	"
Virginia	Clay	A-7-5(7)	"	0.5	+8.0	-	"
"	"	"	"	5.0	+7.0	-	"
"	"	"	"	9.0	+8.5	-	"
Georgia	Silt	A-4-(0)	Akanol B*	0.25	+2.0	-	"
"	"	"	"	0.75	+1.5	-	"
"	"	"	"	3.0	+3.0	-	"
Virginia	Clay	A-7-5(7)	Alkanol B*	0.25	+5.0	-	"
"	"	"	"	0.75	+6.0	-	"
"	"	"	"	3.0	+6.0	-	"
In-Place Roadway	Sandy Loam	A-2-4(0)	Petro D Dust*	0.25	-0.1	-	Denny, C.K.[72]
"	"	"	"	0.1	-1.2	-	"
"	"	"	SA-1*	0.1	-0.5	-	"
"	"	"	"	0.2	-1.5	-	"
"	"	"	Kelpak*	0.01	-2.5	-	"
"	"	"	"	0.1	-1.5	-	"
"	"	"	"	0.2	-0.2	-	"
"	"	"	Clapak*	0.01	-1.5	-	"
"	"	"	"	0.02	-1.9	-	"
"	"	"	Claset*	0.01	-2.1	-	"
"	"	"	"	0.1	-0.8	-	"
"	"	"	"	0.2	-1.8	-	"
"	"	"	Elvanol 71-30*	0.1	-4.1	-	"
"	"	"	"	0.25	-7.7	-	"
"	"	"	"	0.1	-11.9	-	"
"	"	"	Elvanol 52-22*	0.1	-3.8	-	"
"	"	"	"	0.25	-6.8	-	"
"	"	"	"	1.0	-7.5	-	"
"	"	"	Stypol 40-5020*	0.25	-0.2	-	"
"	"	"	"	0.50	0.0	-	"
"	"	"	"	1.0	-1.0	-	"
"	"	"	Clapak* + Claset*	0.1 0.15	-1.4	-	"
"	Clay	A-7-6(20)	Pakzyme*	1 part to 1000 parts water	+0.8	-0.7	Allender, H.L.[27]
Virginia	Sandy Clay	A-7-5(7)	Sodium Tetraphosphate	0.1	+2.0	+0.3	Lambe, T.W.[31]
Virginia	"	A-7-5(7)	"	0.3	+4.4	-0.9	"
Massachusetts	Clayey Silt	-	"	0.1	+0.7	-0.1	"

(continued)

Table 5. Continued.

Soil Type, Soil Series, or Sample Location	Textural Class.	Engr. Class.	Additive	Concentration or % Dry Soil Weight	Inc. or Dec. in Max. Dry Density, pcf	Inc. or Dec. OMC, % Dry Soil Weight	Source of Data
Georgia	Silt	A-4-(0)	Nacconol NR*	0.25	+2.0	-	Shirley, H.G.[26]
"	"	"	"	0.75	+2.5	-	"
"	"	"	"	3.0	+3.0	-	"
Virginia	Clay	A-7-5(7)	"	0.25	+8.5	-	"
"	"	"	"	0.75	+8.0	-	"
"	"	"	"	3.0	+8.5	-	"
Georgia	Silt	A-4-(0)	Nacconol DR*	0.25	+0.5	-	"
"	"	"	"	0.75	+1.0	-	"
"	"	"	"	3.0	+1.0	-	"
Virginia	Clay	A-7-5(7)	"	0.25	+8.0	-	"
"	"	"	"	0.75	+7.0	-	"
"	"	"	"	3.0	+7.5	-	"
Georgia	Silt	A-4-(0)	Alkanol DW*	0.5	+0.2	-	"
"	"	"	"	5.0	+0.5	-	"
"	"	"	"	9.0	+1.0	-	"
Virginia	Clay	A-7-5(7)	"	0.5	+3.0	-	"
"	"	"	"	5.0	+4.0	-	"
"	"	"	"	9.0	+4.3	-	"
Georgia	Silt	A-4-(0)	Auitex SF*	0.25	0.0	-	"
"	"	"	"	0.75	0.0	-	"
"	"	"	"	3.0	+0.5	-	"
Virginia	Clay	A-7-5(7)	"	0.25	+6.0	-	"
"	"	"	"	0.75	+6.5	-	"
"	"	"	"	3.0	+6.0	-	"
Georgia	Silt	A-4-(0)	Duponal WA*	0.25	-1.0	-	"
"	"	"	"	0.75	-0.5	-	"
"	"	"	"	3.0	0.0	-	"
Virginia	Clay	A-7-5(7)	"	0.25	+9.0	-	"
"	"	"	"	0.75	+8.5	-	"
"	"	"	"	3.0	+8.5	-	"
Georgia	Silt	A-4-(0)	"	0.25	-1.0	-	"
"	"	"	"	0.75	-1.0	-	"
"	"	"	"	3.0	0.0	-	"
Virginia	Clay	A-7-5(7)	"	0.25	+5.5	-	"
"	"	"	"	0.75	+6.0	-	"
"	"	"	"	3.0	+6.5	-	"
Georgia	Silt	A-4-(0)	Product BCO*	0.5	-0.4	-	"
"	"	"	"	5.0	-1.3	-	"
"	"	"	"	9.0	-1.3	-	"
Virginia	Clay	A-7-5(7)	"	0.5	+8.0	-	"
"	"	"	"	5.0	+7.0	-	"
"	"	"	"	9.0	+5.0	-	"
Georgia	Silt	A-4-(0)	Aerosol OT-75%*	0.25	+1.5	-	"
"	"	"	"	0.75	+2.5	-	"
"	"	"	"	3.0	+2.5	-	"
Virginia	Clay	A-7-5(7)	"	0.25	+9.0	-	"

(continued)

Table 5. Continued.

Soil Type, Soil Series, or Sample Location	Textural Class.	Engr. Class.	Additive	Concentration or % Dry Soil Weight	Inc. or Dec. in Max. Dry Density, pcf	Inc. or Dec. OMC, % Dry Soil Weight	Source of Data
Virginia	Clay	A-7-5(7)	Nacconol 90F*	3.0	+9.0	-	Shirley, H.G.[26]
Georgia	Silt	A-4-(0)	Nacconol NRSF*	0.25	+0.5	-	"
"	"	"	"	0.75	+0.5	-	"
"	"	"	"	3.0	+0.5	-	"
Virginia	Clay	A-7-5(7)	"	0.25	+8.0	-	"
"	"	"	"	0.75	+8.0	-	"
"	"	"	"	3.0	+9.0	-	"
Georgia	Silt	A-4-(0)	Avitex Y*	0.50	-3.0	-	"
"	"	"	"	3.0	-3.5	-	"
"	"	"	"	9.0	-2.0	-	"
Virginia	Clay	A-7-5(7)	"	0.50	+8.5	-	"
"	"	"	"	3.0	+6.0	-	"
"	"	"	"	9.0	+5.0	-	"
Georgia	Silt	A-4-(0)	Nacconol 40F*	0.25	+0.5	-	"
"	"	"	"	0.75	+1.0	-	"
"	"	"	"	3.0	+1.0	-	"
Virginia	Clay	A-7-5(7)	"	0.25	+8.0	-	"
"	"	"	"	0.75	+7.5	-	"
"	"	"	"	3.0	+9.0	-	"
Georgia	Silt	A-4-(0)	Nacconol 40 DBX*	0.25	+0.5	-	"
"	"	"	"	0.75	+1.0	-	"
"	"	"	"	3.0	+1.0	-	"
Virginia	Clay	A-7-5(7)	"	0.25	+7.5	-	"
"	"	"	"	0.75	+7.5	-	"
"	"	"	"	3.0	+8.5	-	"
Georgia	Silt	A-4-(0)	Nacconol Beads*	0.25	+1.0	-	"
"	"	"	"	0.75	+1.5	-	"
"	"	"	"	3.0	+2.0	-	"
Virginia	Clay	A-7-5(7)	"	0.25	+8.0	-	"
"	"	"	"	0.75	+8.5	-	"
"	"	"	"	3.0	+6.0	-	"
Georgia	Silt	A-4-(0)	Nacconol DBX*	0.25	+0.5	-	"
"	"	"	"	0.75	+1.0	-	"
"	"	"	"	3.0	+1.5	-	"
Virginia	Clay	A-7-5(7)	"	0.25	+8.0	-	"
"	"	"	"	0.75	+8.0	-	"
"	"	"	"	3.0	+8.5	-	"
Georgia	Silt	A-4-(0)	Nacconol 40 DB*	0.25	+2.0	-	"
"	"	"	"	0.75	+2.5	-	"
"	"	"	"	3.0	+3.5	-	"
"	"	"	Nacconol 40LB*	0.25	+2.5	-	"
"	"	"	"	0.75	+2.5	-	"
"	"	"	"	3.0	+3.0	-	"
Virginia	Clay	A-7-5(7)	"	0.25	+6.5	-	"
"	"	"	"	0.75	+5.0	-	"
"	"	"	"	3.0	+7.0	-	"

(continued)

Table 5. Continued.

Soil Type, Soil Series, or Sample Location	Textural Class.	Engr. Class.	Additive	Concentration or % Dry Soil Weight	Inc. or Dec. in Max. Dry Density, pcf	Inc. or Dec. OMC, % Dry Soil Weight	Source of Data
Virginia	Clay	A-7-5(7)	Polytergent B-300*	0.75	+10.0	-	Shirley, H.G.[26]
"	"	"	"	3.0	+9.5	-	"
Georgia	Silt	A-4-(0)	Polytergent L-405*	0.25	+0.5	-	"
"	"	"	"	0.75	+1.0	-	"
"	"	"	"	3.0	+1.0	-	"
Virginia	Clay	A-7-5(7)	"	0.25	+8.0	-	"
"	"	"	"	0.75	+8.0	-	"
"	"	"	"	3.0	+8.5	-	"
Georgia	Silt	A-4-(0)	Tergitol NPX*	0.25	+0.5	-	"
"	"	"	"	0.75	+1.0	-	"
"	"	"	"	3.0	+0.5	-	"
Virginia	Clay	A-7-5(7)	"	0.25	+6.0	-	"
"	"	"	"	0.75	+6.5	-	"
"	"	"	"	3.0	+8.0	-	"
Georgia	Silt	A-4-(0)	Tergitol TP-9*	0.25	+0.5	-	"
"	"	"	"	0.75	+0.5	-	"
"	"	"	"	3.0	0.0	-	"
Virginia	Clay	A-7-5(7)	"	0.25	+9.0	-	"
"	"	"	"	0.75	+9.0	-	"
"	"	"	"	3.0	+7.5	-	"
Georgia	Silt	A-4-(0)	Ivory Liquid*	0.50	+2.5	-	"
"	"	"	"	3.0	0.0	-	"
"	"	"	"	9.0	-1.5	-	"
Virginia	Clay	A-7-5(7)	"	0.50	+8.0	-	"
"	"	"	"	3.0	+6.5	-	"
"	"	"	"	9.0	+8.5	-	"
Georgia	Silt	A-4-(0)	Hydroxyacetic Acid	0.25	-0.5	-	"
"	"	"	"	0.75	-0.5	-	"
"	"	"	"	3.0	0.0	-	"
Virginia	Clay	A-7-5(7)	"	0.25	+7.5	-	"
"	"	"	"	0.75	+7.0	-	"
"	"	"	"	3.0	+8.5	-	"
Georgia	Silt	A-4-(0)	Nacconol Z*	0.25	+0.5	-	"
"	"	"	"	0.75	+1.0	-	"
"	"	"	"	3.0	+1.0	-	"
Virginia	Clay	A-7-5(7)	"	0.25	+7.0	-	"
"	"	"	"	0.75	+7.0	-	"
"	"	"	"	3.0	+7.5	-	"
Georgia	Silt	A-4-(0)	Nacconol 90F*	0.25	+0.5	-	"
"	"	"	"	0.75	+1.0	-	"
"	"	"	"	3.0	+1.0	-	"
Virginia	Clay	A-7-5(7)	"	0.25	+8.0	-	"
"	"	"	"	0.75	+8.0	-	"

(continued)

Table 5. Continued.

Soil Type, Soil Series, or Sample Location	Textural Class.	Engr. Class.	Additive	Concentration or % Dry Soil Weight	Inc. or Dec. in Max. Dry Density, pcf	Inc. or Dec. OMC, % Dry Soil Weight	Source of Data
Massachusetts	Clayey Silt	-	Sodium Tetraphosphate	0.5	+3.2	-1.3	Lambe, T.W.[31]
Maine	"	-	"	0.1	+4.9	-0.7	"
Pennsylvania	Sandy Silt	-	"	0.1	+3.4	-0.7	"
Pennsylvania	High P.I. Soil	-	SA-1	1:1000 Solution	-0.4	0.0	Louisiana Dept. of Highways [73]
Pennsylvania	Low P.I. Soil	-	"	1:1000 Solution	0.0	-0.1	"

According to Thomson,[25] the "Central System can stabilize any of the following when correctly applied: highly organic soils; clay and silts; alkaline clays and silts where lime and cement do not work; caliche, shell, or other lime source soils. And it offers a method of dispersal of new asphalt in granular soils, or old cured asphalt better than mechanical, breaking, crushing, or pulverizing methods." In addition, Thomson noted that for successful chemical stabilization, the chemical agent must reduce organic compounds within the soil through speeded oxidation and reduction, and should improve the characteristics of clays and silts by lessening the moisture present after a period of saturation.

Terra-Seal, a product of Del Chemical Co., evaluated by Squier,[18] showed some improvement in lab densities while optimum moisture content was very slightly increased. Recent observations on the Terra-Seal treated base test section reported by Squier indicate approximately equal performance to the untreated control section.

Products utilized in a study by Shirley,[26] Table 5, indicate a generalized improvement in densities for a Virginia clay and a Georgia Silt, some of the products producing very significant increases in density with small additions of chemical. However, the moisture contents, at which each of the treated soils was molded, were identical for each tested soil/product and were noted to be somewhat less than that of the untreated soil. Therefore, it is impossible to ascertain if density could be maintained or improved by significant decreases in either moisture content or by compactive effort with these products. A selected few of these products were studied during Phase II of this project.

Statistical M-D lab studies conducted by Allender,[27] Table 5, on an A-7-6(20) soil using one part Paczyme to 1000 parts water indicated a mean increase in T-99 density of 0.80 pcf and 0.66% reduction in optimum water content as compared with the untreated soil. Five-day air-cured unconfined compressive strength was increased by 12.96 lb on 1/30 cu ft specimens.

In a study of Paczyme, the Louisiana Department of Highways[28] found only very slight increases in density and reduction of optimum moisture as compared to an untreated clay loam, A-6(8) soil.

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[25] P. Thomson, "Chemical Soil Treatment Makes Aggregate Base Unnecessary," Rural and Urban Roads (June 1970), pp. 44-46.

[26] H. G. Shirley, "The Effect of Chemical Wetting Agents on the Compaction of Clay and Silt Soils," Unpublished Master of Science Thesis, Georgia Institute of Technology, 1965.

[27] H. L. Allender, Personal Communication, Des Moines Testing Laboratory, Des Moines, Iowa (1968).

[28] Louisiana Department of Highways, Research and Development Section, A Study of Paczyme (Soil Stabilizer) (date not reported).

Utilizing the product at 1/10, 1/20, and 1/30 gal. Paczyme per cubic yard of soil, insignificant improvements in CBR values and unconfined compressive strengths were noted, whereas R-value tests showed the treated soil to be weaker than the untreated specimens.

Two proprietary enzymatic products, Paczyme and Grozyme, were field trafficked and laboratory tested by Kozan, Ables, and Stouffer.[29] M-D was nearly identical for untreated versus Paczyme-treated clayey silt. Unconfined compressive strength was slightly less for Paczyme-treated silt at lower than optimum moisture content, and nearly identical to the untreated at higher than OMC. No significant difference in water retention versus time was noted with the untreated soil as compared with the Paczyme-treated soil. On the basis of lab tests, the authors concluded that neither Paczyme nor Grozyme showed any potential for requirements as a dust palliative for military purposes. They also concluded that Paczyme was of no value in construction of a test roadway in terms of compacted density, strength, or quantity of water required for construction. However, we conducted a statistical analysis of the authors' composite data, the median and standard deviation of which are presented in the following table; the ± entries signify standard deviations on the means:

	Section A, Treated			Section B. Untreated		
Description	Water Content, %	Dry Density, pcf.	CBR	Water Content, %	Dry Density, pcf.	CBR
Before traffic on center line	14.8 ± 1.5	104.0 ± 2.9	17.7 ± 3.2	14.3 ± 1.8	100.1 ± 2.0	18.0 ± 2.2
After 200 passes on dry surface in traffic path	13.8 ± 2.6	100.8 ± 3.6	25.3 ± 9.6	12.8 ± 1.4	100.4 ± 1.9	20.7 ± 9.1
Outside traffic path	13.2 ± 1.2	104.1 ± 3.6	24.3 ± 6.9	14.0 ± 2.5	100.5 ± 2.0	19.7 ± 6.6
In-situ soil prior to treatment and construction	14.1 ± 4.9	107.0 ± 3.4	-	15.4 ± 4.3	106.5 ± 3.4	-

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[29] G. R. Kozan et al., "Investigation of Enzymatic Materials for Soil Stabilization," Miscellaneous Paper S-69-9 (U.S. Army Waterways Experiment Station, Vicksburg, Miss.: (Feb. 1969).

From this table, composite density of the Paczyme-treated section prior to traffic may have been several pounds per cu ft greater than the untreated section, while the moisture content was approximately the same. Two hundred passes of a standard M54, 5-ton military truck loaded to a gross weight of 40,000 lb, with tires at 70 psi, reduced the treated density to nearly equivalent to the untreated either before or after traffic. However, the CBR value improved significantly in the treated section and only slightly in the untreated section following traffic. Outside of the traffic path, densities remained approximately the same as prior to traffic, but the CBR had improved significantly in the treated section and only slightly in the untreated section. Due to construction, neither section achieved densities equal to the in-situ soil prior to treatment and construction.

Paczyme and Reynolds Road Packer were extensively evaluated in a laboratory study developed by the Federal Highway Administration (FHWA) and endorsed by the manufacturers prior to its initiation.[30] Tests were conducted on four fine-grained soils with three clay mineralogies typical of the mid-Atlantic states, and consisted of Atterberg Limits, M-D by both AASHTO T-99 and T-180, unconfined compression and triaxial shear, CBR, and R-Values and expansion pressure. Statistical analyses were applied to much of the data. Results indicated that neither product significantly improved the engineering characteristics of the four soils. The following conclusions are quoted directly from the study report:

1. Neither Paczyme nor Road Packer had any significant effect on the optimum moisture content or maximum dry density as determined by AASHTO Methods T-99 and T-130.

2. Paczyme treatment did not cause attainment of maximum T-99 density by using less than the standard compactive effort.

3. Although statistical analyses demonstrated that Paczyme and Road Packer increased the unconfined compressive strength for some of the soils under certain conditions of density and curing, the magnitude of the strength increase is deemed too small to be of any practical utility.

4. The increases in strength detected in the unconfined compressive strength test were not confirmed by triaxial tests, i.e. the strength envelopes for the raw soils and Paczyme- and Road Packer-treated soils were almost colinear.

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[30] D. G. Fohs, A Laboratory Evaluation of Two Proprietary Materials as Compaction Aids and Soil Stabilizers, Final Report, (Federal Highway Administration, Offices of Research and Development, Washington, D.C.: March 1975).

5. Neither Paczyme nor Road Packer had any effect on the slope of the stress-strain curve or on the percent of strain recorded at failure.

6. Paczyme had no effect on the CBR value for the four soils. Road Packer, however, significantly increased the CBR of the Keyport and Readington soils when compacted to AASHTO T-180 density.

7. Neither of the products had any effect on the ability of the soils to resist the detrimental effects of water, i.e., soaked CBR values were much lower than for unsoaked values regardless of whether the soil was treated or untreated.

8. Treatment with either of the products had little effect on the R-value or expansion pressure of the four experimental soils.

As shown in Table 5, Lambe[31] found beneficial density improvements upon treating a sandy clay and two clayey silts with small quantities of sodium tetraphosphate, known to be a dispersing agent for clays.

In 1973, the Transportation Research Board Committee on Chemical Stabilization of Soil and Rock submitted a questionnaire to 110 agencies regarding usage of chemical additives (other than cement, lime and asphalt) in soil stabilization.[32] Results of the 102 responses, published in 1977, indicated that the most used chemical additives were lignosulfonates, phosphoric acid, and Paczyme. Lignosulfonates were indicated to be effective dust control agents and, in some instances, increased soil strength and decreased susceptibility to frost action and swelling. Phosphoric acid increased strength of certain clays, while Paczyme "was most often found not to increase soil strength." Most agencies using SA-1 indicated mixed results. Tetrasodium phosphate, sodium hydroxide, and sodium sulfite decreased frost heave and permeability of a silty soil. Clapak and Claset were noted to have stabilized an A-7-6 soil. Terbec C-7 was effective in waterproofing a silty clay loam embankment. A number of products were noted as preventing wind and/or water erosion, including Aerospray 70, a styrene-butadiene latex, Petroset SB, Coherex, Polyco 2460 and 2605, DCA-7, and a resin-in-water emulsion. Considerable variation in treatment levels and costs were reported for the products due to the varying usage purposes and soil types. Strength, stability, changes

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[31] T. W. Lambe, "Improvements of Soil Properties with Dispersants," J. Boston Soc. Civ. Eng. 41: 2 (1954), pp. 186-207.

[32] Transportation Research Board, National Academy of Science, "Chemical Stabilization of Soils," Questionnaire Summary prepared by TRB Committee on Chemical Stabilization of Soil and Rock, Information Series No. 8 (April 1977).

in Atterberg Limits, and benefits versus time were reported as ranging from excellent to detrimental with nearly all of the products. Responses regarding improvement of compaction characteristics were extremely limited to non-existent.

A product termed Hi-Spec from Diversified Chemical Products of Lynwood, Washington, was lab and field tested by the Louisiana Department of Highways.[33] No increase in compaction, compactibility, or maximum density was noted with Hi-Spec treated materials. Also, after treatment, no improvement was noted in compressive strengths, Atterberg Limits, or R-values of soil specimens.

In laboratory tests on Reynolds Road-Packer, the Louisiana Department of Highways concluded that maximum dry unit weights and optimum moisture contents showed no difference between treated and untreated soil.[34]

Combinations. Table 6 presents a summation of density and moisture content changes, as observed in the literature, for combinations of waterproofer/binder, waterproofer/chloride, and binder/cementing agents with various soils. With the exception of the chemicals used by Michaels[35] on a Massachusetts clayey silt, and of the sodium chloride/Armac T and Sodium chloride/Duomac T used by Butzke[36] on a A-2-6(1) soil from a roadway, none of the combined products exhibit improvement in M-D relationships as compared with the untreated soils. Since significant quantities of sodium chloride were required to achieve improvement of M-D, its combination with either organic cationic compound was considered uneconomical. Phosphoric acid is a difficult product to work with due to the many construction safeguards and specialized equipment required, and was therefore eliminated from further consideration within this study.

Patent Literature

A search of patents dealing with chemical soil stabilization agents yielded only limited results. It was hoped that this review would provide some information on the make-up of marketed proprietory agents. Those of interest to this project were categorized, and a summary is presented below.

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[33] Louisiana Department of Highways, Research and Development Section, Evaluation of Chemical Agent Hi-Spec (Sept. 1968).

[34] Louisiana Department of Highways, Research and Development Section, Laboratory Evaluation of Reynolds Road-Packer (Sept. 1966).

[35] A. S. Michaels and F. W. Tausch, "Effects of Fluorides, Waterproofing Agents and Polyphosphoric Acids on Soil Stabilization with Acid Phosphorous Compounds," HRB Bulletin, 318 (1961), pp. 57-63.

[36] M. R. Butzke, "Organic Cationic and Sodium Chloride Soil Stabilization," Unpublished Master of Science Thesis, Iowa State University, 1974.

Table 6. Summary of increase or decrease in maximum density and optimum moisture content with various types of chemical combination treatments, including waterproofer/binder, waterproofer/chloride, and binder/cementing agents.

Legend: * Trade name, - no data given

Soil Type, Soil Series, or Sample Location	Textural Class.	Engr. Class.	Additive	Concentration or % Dry Soil Weight	Inc. or Dec. in Max. Dry Density, pcf.	Inc. or Dec. in OMC % Dry Weight	Source of Data
Carrington & Fayette	Silty Sand "	A-3 (0)	Arquad 2HT* + Lignin B	0.1 1.0	+0.8	-	Hoover, J. M., et al.[74]
"	"	"	"	0.1 0.2	+1.3	-	"
"	"	"	"	0.1 0.0	-2.3	-	"
"	"	"	"	0.2 1.0	-0.2	-	"
"	"	"	"	0.2 2.0	-0.5	-	"
"	"	"	"	0.2 0.0	-2.3	-	"
"	"	"	"	0.3 1.0	-0.6	-	"
"	"	"	"	0.3 2.0	-1.7	-	"
"	"	"	"	0.3 0.0	-1.4	-	"
"	"	"	"	0.4 1.0	-1.1	-	"
"	"	"	"	0.4 2.0	-1.4	-	"

Table 6. Continued.

Soil Type, Soil Series, or Sample Location	Textural Class.	Engr. Class.	Additive	Concentration or % Dry Soil Weight	Inc. or Dec. in Max. Dry Density, pcf.	Inc. or Dec. in OMC % Dry Weight	Source of Data
Shelby	Silty Clay	A-6 (11)	Arquad 2HT* + Lignin B	0.1 1.0	-4.0	-	Hoover, J. M., et al.[74]
"	"	"	"	0.1 2.0	-5.9	-	"
"	"	"	"	0.1 0.0	-0.7	-	"
"	"	"	"	0.2 1.0	-5.0	-	"
"	"	"	"	0.2 2.0	-6.8	-	"
"	"	"	"	0.2 0.0	-2.8	-	"
"	"	"	"	0.3 1.0	-5.7	-	"
"	"	"	"	0.3 2.0	-6.1	-	"
"	"	"	"	0.3 0.0	-2.0	-	"
"	"	"	"	0.5 1.0	-4.4	-	"
"	"	"	"	0.5 2.0	-6.4	-	"
"	"	"	"	0.5 0.0	-5.4	-	"

(Continued)

Table 6. Continued

Soil Type, Soil Series, or Sample Location	Textural Class.	Engr. Class.	Additive	Concentration or % Dry Soil Weight	Inc. or Dec. in Max. Dry Density, pcf.	Inc. or Dec. in OMC % Dry Weight	Source of Data
Shelby	Silty Clay	A-6 (11)	Arquad 2HT* + Lignin B	0.6 1.0	-4.6	-	Hoover, J. M., et al.[74]
"	"	"	"	0.6 2.0	-6.0	-	"
"	Clay	A-7-5 (20)	"	0.1 1.0	-1.6	-	"
"	"	"	"	0.1 2.0	-2.2	-	"
"	"	"	"	0.1 0.0	+0.4	-	"
"	"	"	"	0.2 1.0	-0.6	-	"
"	"	"	"	0.2 2.0	-3.7	-	"
"	"	"	"	0.2 0.0	+0.5	-	"
"	"	"	"	0.3 1.0	-1.6	-	"
"	"	"	"	0.3 2.0	-3.6	-	"
"	"	"	"	0.3 0.0	-0.1	-	"
"	"	"	"	0.5 1.0	-3.5	-	"

(Continued)

Table 6. Continued.

Soil Type, Soil Series, or Sample Location	Textural Class.	Engr. Class.	Additive	Concentration or % Dry Soil Weight	Inc. or Dec. in Max. Dry Density, pcf.	Inc. or Dec. in OMC % Dry Weight	Source of Data
Shelby	Clay	A-7-5 (20)	Arquad 2HT* + Lignin B	0.5 2.0	-5.5	-	Hoover, J. M., et al.[74]
"	"	"	"	0.5 0.0	+0.8	-	"
"	"	"	"	0.7 0.0	-3.4	-	"
"	"	"	"	0.7 2.0	-3.8	-	"
"	"	"	"	0.7 0.0	-0.4	-	"
"	"	"	"	0.9 1.0	-3.4	-	"
"	"	"	"	0.9 2.0	-4.3	-	"
Massachusetts	Clayey Silt	A-4 (2)	Na_2SiF_6	0.5	+9.8	+3.5	Michaels, A. S., et al.[35]
"	"	"	$O-P_2O_5$	0.05	+11.6	-3.4	"
"	"	"	C_8Amine + $O-P_2O_5$	0.05 0.05	+12.5	-4.2	"
"	"	"	Na_2SiF_6 + C_qAmine	0.5 0.05	+6.5	-4.2	"
"	"	"	H_3PO_4	1.0	+6.5	-3.0	"
"	"	"	H_3PO_4	2.0	+9.8	-3.5	"

(Continued)

Table 6. Continued.

Soil Type, Soil Series, or Sample Location	Textural Class.	Engr. Class.	Additive	Concentration or % Dry Soil Weight	Inc. or Dec. in Max. Dry Density, pcf.	Inc. or Dec. in OMC % Dry Weight	Source of Data
Hamburg	Silty Clay	A-4 (8)	Arquad 2HT* + Lignin B	0.1 1.0	-0.2	-	Hoover, J. M., et al.[74]
"	"	"	"	0.1 2.0	+0.8	-	"
"	"	"	"	0.1 0.0	-1.3	-	"
"	"	"	"	0.2 1.0	+0.8	-	"
"	"	"	"	0.2 2.0	+1.7	-	"
"	"	"	"	0.2 0.0	-1.1	-	"
"	"	"	"	0.3 1.0	-0.2	-	"
"	"	"	"	0.3 2.0	+0.2	-	"
"	"	"	"	0.3 0.0	-1.8	-	"
"	"	"	"	0.5 1.0	-0.3	-	"
"	"	"	"	0.5 2.0	+1.9	-	"

(Continued)

Table 6. Continued.

Soil Type, Soil Series, or Sample Location	Textural Class.	Engr. Class.	Additive	Concentration or % Dry Soil Weight	Inc. or Dec. in Max. Dry Density, pcf.	Inc. or Dec. in OMC % Dry Weight	Source of Data
Vicksburg	Clay	A-7-6 (14)	H_3PO_4 + C_q Amine	2.76 1.0	-0.7	-0.4	Michaels, A. S., et al.[35]
"	"	"	H_3PO_4 + Na_2SiF_6	4.0 1.0	+2.2	-1.0	"
"	"	"	P_2O_5 + C_q Amine	1.75 1.0	-0.4	+0.1	"
"	"	"	P_2O_5 + $FeCl_3$	3.1 1.6	+1.6	-0.6	"
"	"	"	Duomac*	0.5	-2.4	+2.0	"
In-Place Roadway	Clayey Sand	A-2-6 (1)	NaCl + Armac T*	2.0 0.3	+2.2	-0.1	Butzke, M. R.[36]
"	"	"	NaCl + Duomac T*	2.0 0.1	+2.8	+0.7	'
"	Clay	A-7-6 (12)	Lignin + Lime	1/2 Gal/yd^2 4.0	-2.9	-1.3	Squier, L. D.[18]
"	"	"	Lignin + Lime	1 Gal/yd^2 2.0	-2.9	+0.3	"
"	"	"	Lime	6.0	-6.6	+2.7	"
"	"	"	Lignin	1 1/2 Gal/yd^2	-0.6	+0.1	"

Earth Mass and Stabilization of Landslides. U.S. Patent No. 3,732,698[37] claimed invention of the stabilization of soil masses and active slides by applying aqueous solutions, slurries, or powders of chemical agents to the soil either through surface application techniques or into bored holes. Chemical agents were selected from ammonium and mono-, di-, and trivalent metal salts of carboxylic acids of from two to six carbon atoms. Also selected were: ammonium and mono-, di-, and trivalent metal fluorides and polyfluorides; ammonium and mono-, di-, and trivalent metal fluoborates, fluosilicates, and fluorophosphates; ammonium and alkali metal salts of phosphoric and polyphosphoric acids; sulfate salts of mono-, di-, and trivalent metals; cupric chloride; stannic (IV) chloride; and borate salts of metals. Most of these chemicals were illustrated to increase strength of various soils after mixing therewith, as tested by vane shear.

Injection. U.S. Patent No., 3,719,050[38] comprises stabilization by injection of a polyurethane prepolymer having terminal isocyanate groups, alone or mixed with water. Being a gel, gelling time of the prepolymer is shortened by addition of a basic material and prolonged by acidic materials or a chelate compound. The method claims to provide a simultaneous water cutoff and stabilization effect.

U.S. Patent No. 3,696,622[39] describes a resinous compound composed of a water soluble strongly alkaline liquid phenol formaldehyde resin, having a molar ratio of phenol to formaldehyde between 1:1.5 and 1:3, and a lactone added in a proportion of 1-30% of the liquid resin, in which a compound such as urea, a urea derivative, or neutral salt, is used as a gelation control agent. The product is recommended for injection into soils, into crevices and cracks of rock, into construction joints of concrete dams, etc. The product is claimed to harden in either acid or alkaline soils, resulting in soil compressive strength to more than 10 kg/sq cm.

Erosion and Permeability Control. U.S. Patent No. 3,705,467[40] "comprises coating soil particles with a reactive, cationically

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[37] U.S. Patent No. 3,732, 698. "Method for Stabilizing Soils and Abating Active Slides," Inventor: H. S. Arora, Assignee: E. D. Graf (May 15, 1973).

[38] U.S. Patent No. 3,719,050. "Soil Stabilization Method," Inventors: Hiroshi Asao et al., Assignee: Toho Chemical Industry Co., Ltd., Tokyo, Japan (March 6, 1973).

[39] U.S. Patent No. 3,696,622. "A Method of Soil Stabilization and Leakage Prevention," Inventors: Wataru Tohina et al., Assignees: Sumitomo Durez Co., Ltd., Tokyo, and Sumitomo Chemical Co., Ltd., Osaka, Japan (Oct. 10, 1972).

[40] U.S. Patent No. 3,705,467. "Soil Bed Preparation, Soil Stabilizing, Soil Conditioning, and Soil Improving Process," Inventor: J. T. McKnight (Dec. 12, 1972).

charged binding material in order to form coated, positively charged soil particles and reacting the coated, charged soil particles with an anionic alkali-treated lignin binder to provide a film or network on the soil of sufficient wet strength to provide adequate resistance to rainfall and water runoff." The cationic binding materials must be above 500,000 molecular weight and must coagulate with alkali-treated lignin. Specific examples of suitable cationic latexes, dispersions, and polymer solutions were described. The preferred ratio of cationic to anionic materials was noted within the range of 0.75:1 to 1.25:1, with an effective application rate of at least 5 lb/acre of both materials, but less than 150 lb/acre. A two to three-fold reduction in soil erosion was taken as a minimum criterion for soil stabilization.

The invention presented in U.S. Patent No. 3,708,319[41] comprises soil application by spraying or by other techniques, of a drying oil for prevention of wind or water erosion. The oil may contain a drying or oxidizing agent and one or more water-swellable polymers. Suggested natural oils, partial synthetic oils, and wholly synthetic oils included caster oil, corn oil, sardine oil, safflower oil, tung oil, neats-foot oil, etc. Oil-in-water emulsions were suggested, using known emulsifying agents. Drying agents comprised of soaps were suggested for accelerating the rate of drying of the drying oils. Preferred composition of the invention, on a percent by weight basis, was: drying oil, 5-50%; polymer, up to 40%; drying oil solvent, 40-95%; and drier, 0.01-1.0%. The material was surface-applied.

<u>Penetrants for Soil Stabilization and Improvement of Bearing Capacity</u>. U.S. Patent No. 3,208,226[42] relates to a process for stabilizing water-permeable soil, rendering the soil impermeable, by applying an aqueous dispersion of an acid-catalyzed thermosetting urea-formaldehyde resin and curing at ambient temperatures. A further objective of this invention was the use of the product as a grout under soil embankments, foundations, within oil wells, and as a water cut-off to basement walls. Solids' contents of the resins were noted in one example of surface application to range from 15 to 45%, with depth of penetration from 1/2 to 10 - 1/4 in., and unconfined compressive strength from zero to 690 psi.

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[41] U.S. Patent No. 3,708,319. "Stabilizing Soils and Accumulations of Fine Particulate Material," Inventors: K. H. Nimerick and L. H. Eilers. Assigned to: The Dow Chemical Co., Midland, Mich. (Jan. 2, 1973).

[42] U.S. Patent NO. 3,208,226. "Process for Stabilizing Soil," Inventor: J. J. Falvey, Assigned to: American Cyanamid Co., Stamford, Connecticut (Sept. 28, 1965).

Two water-soluble polymer solutions are alternately sprayed on soil in U.S. Patent No. 3,696,621.[43] The first is a water solution of approximately 1-2% by weight of polyethylene oxide deposited to a loading of about 0.1 lb/sq yd. The second is a water solution containing approximately 10-20% polyacrylic acid deposited to about 0.5 lb/sq yd. Continued alternate spraying builds up a thicker surface. The invention was also described for mixing the two products, in powder form, at a rate of approximately 10 lb of each per 2.5 cu yd of soil, adding water, and mixing.

Under U.S. Patent No. 3,651,649,[44] a vinyl ester resin, readily extended with water or other aqueous solutions to become a water-in-resin emulsion, may be applied in innumerable ways to various types of soils and aggregate to provide resistance to corrosion, seepage, and loading. Densities of the emulsion were shown to vary from 63 to 64.5 pcf, depending on quantity of water included. Viscosities were noted as ranging from 3100-9700 cps. Examples of sand-resin emulsion combinations exposed to air and chloride brine noted high compressive and tensile strengths.

Compaction. While the previously noted patents may or may not contain products relative to adaptation to chemical compaction aids, U.S. Patent No. 3,404,068[45] was specifically issued to improve soil compaction. The product in this patent is the compaction aid termed Paczyme. Preferred proportions of the product, in parts by weight, are noted as: seaweed 1.5-2, magnesium sulphate 1.5-2, manganese sulphate 1.5-2, dry yeast 0.5-2, malt 5-20, black strap molasses 45-130, sugar 25-100, and water 375-1500. The malt and dry yeast are considered active enzymatic agents, while the seaweed and sulphates furnish minerals to the solution. The ingredients are mixed at a temperature above 59 °F, and, within 72 hours, the solution begins to ferment, the molasses and sugar accelerating the fermentation process. A second solution is then added consisting of a surfactant at 200-600 parts by weight, and an antibiotic at 2-6 parts by weight. The surfactants selected were one or more polyoxyethylene partial fatty acid esters, a polyoxyethylene fatty alcohol ether, a sodium tetradecyl sulfate (Tergitol), and a polyethylene glycol. The antibiotics were either Terramycin or Aureomycin. A formulation of the product, when

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[43] U.S. Patent No. 3,696,621. "Method of Soil Stabilization," Inventors: B. B. Simms et al., Assignee: United States of America as represented by the Secretary of the Navy (Oct. 10, 1972).

[44] U.S. Patent No. 3,651,649. "Stabilization of Soil with Water-in-Vinyl Ester Resin Emulsions," Inventors: D. J. Najvar et al., Assignee: The Dow Chemical Co., Midland, Michigan (March 28, 1972).

[45] U.S. Patent No. 3,404,068. "Composition for Compacting Soil," Inventor: L. M. Batistoni, Assigned to Zymak Biochemical Corp., a Puerto Rican Corporation (Oct. 1, 1968).

diluted 1000 times with water, was claimed to have increased the compactability of high alkaline soil to above 95, whereas its normal compactability was about 90. "The precise nature of the action of this formulation is not known. In a general way, it is theorized that the enzymatic action 'works' on the soil, and causes some decomposition whereby the void spaces, within the interstices of the soil, are reduced."[45]

Trade Literature

Review of the trade literature is summarized below. The bulk of the literature contained herein deals primarily with those proprietary products utilized in the testing phases of the study.

Paczyme - Larutan of the South, Inc., Hiram, Georgia. According to the trade literature, the surfactants and wetting agents in Paczyme increase water penetration into the soil and reduce surface tension of the water allowing wet soils to more readily drain. Thus, soils with more than optimum water contents for compaction can be dried by the addition of Paczyme, "if there is some place for the water to drain." Paczyme reduces friction between soil particles and produces a "mild cementation" upon curing, thus improving bearing capacity. When examined under an electron microscope, a Paczyme-treated soil exhibited less abundant 250 Å cracks than an untreated soil, and also exhibited a "higher degree of alignment." M-D curves of Paczyme-treated soils show no decided differences from untreated soils due to the "high energy input used in these lab tests." Paczyme increases unconfined compressive strength of soils when the soil"...is in a semi-dried condition. Wet strengths are better defined by load bearing tests. In general, the bearing strength of a properly cured Paczyme compacted soil is higher than an untreated soil. Without curing, bearing strengths are not improved in all cases." Soils treated with Paczyme normally exhibit lowered permeability than untreated soils. Atterburg Limit tests are not applicable to Paczyme-treated soils since the "manipulation destroys the compaction, alignment, and cementatious properties."

This product also was available from Stabilization Chemicals, Inc., Orange, California, as product SC-500. No cost data were received from either supplier.

SS-13 - Stabilization Chemicals, Inc., Orange, California.* According to the supplier, SS-13 is an oil-in-water emulsion of polyacrylates and other resins and is effective for permeability control in soils, concrete, and some other materials. Depending on soil conditions, SS-13 can be used as a treatment at time of compaction or as a waterborne treatment after completion of construction. This product will reduce seepage losses and, when mixed with water at a rate of 1 part per 1000 parts water, acts on soils, reducing the

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*Approximately two-thirds of the way through this research project, Stabilization Chemicals, Inc., quit business.

size of openings between particles. Wet-dry cycles in some soils cause stress cracking which can destroy the benefits of SS-13 treatment, and retreatment may be needed. SS-13 is non-toxic; plants, humans, and animals are not affected by SS-13 in a diluted form. This product is also available through "authorized Larutan dealers."

In a lab report by the Hornkohl Laboratories, Inc., Bakersfield, California (contained as a section in the Stabilization Chemicals Literature), 2 gal. of SS-13 per 1000 gal. water increased maximum density of a soil up to 2.5 pcf, using an optimum water content of 25 to 50% less than required for a normal sample. SS-13 significantly decreased permeability and capillary rise and was illustrated to control embankment settlement of wet soils. Cost data on SS-13 were unavailable.

Aquablok - Stabilization Chemicals, Inc., Orange, California.* This "aqueous emulsion epoxy type polymer" was made from a vegetable oil. Intended as a soil/surface treatment, it provides abrasion and water resistance to the surface of a roadway where the subsurface soil is sufficiently stable for anticipated loads and has shown beneficiation to sands, silts, clays, loams and peat. Aquablok is mixed into the water, preventing foaming, at dilution rates of from 4 to 20 parts water per one part Aquablok, depending on soil type, soil moisture, and intended use. Ideally, it is applied as a surface sealer over soil stabilized with Terrafirm.

Terrafirm 1 and 1a - Stabilization Chemicals, Inc., Orange, California.* An emulsified polymer blend, effective at low treatment rates in difficult-to-stabilize soils and particularly fine silty soils. Typical treatment rates are between 0.81 and 1.16 gal/cu yd. Advantages of Terrafirm over other stabilizers include freedom from treatment-induced cracking, avoidance of soil rigidity and brittleness, and savings on labor and equipment-operating costs due to ease of use. Terrafirm 1 is also referred to in this company's literature as a "polymer soil cement."

Terrafirm 2 - Stabilization Chemicals, Inc., Orange, California.* Also an emulsified polymer product, but apparently differing from Terrafirm 1 and 1a in that it is mixed into the soil at a typical rate of 1.0 gal/cu yd for compaction. Cost data were not available on any of the Terrafirm products.

SC-518 - Stabilization Chemicals, Inc., Orange, California.* This is a wetting agent (surfactant) used primarily in agriculture for enhancing effectiveness of herbicides, insecticides, and defoliants. It may be used in combination with SC-450, an emulsified polymer product developed for use as an erosion control agent.

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*Approximately two-thirds of the way through this research project, Stabilization Chemicals, Inc., quit business.

SC-525 - Stabilization Chemicals, Inc., Orange, California.* This is a wetting agent for fire fighting for which it improves the wettability of combustibles to allow more water to soak in and less to run off. No cost data were available on any of the SC products.

Reynolds Road Packer 2-3-5, Liquid Soil Densifier - Zel Chemical Co., Portland, Oregon. Reynolds Road Packer (RRP) is "a complex chemical compound that makes a solution acting as a catalyst, that cleans the soil, preparing it for physical compaction." It induces ion-exchange and is "derived from combined organic sulfur, buffered acids, and is combined as bi-sulfates." It is a "true catalyst," which is "not consumed in its function, but continues and perpetuates its action so long as water is present." Also, RRP "...solution through its electrokinetic properties affects both positive and negative charges of the soil particles. This has three effects: Firstly, the layer of abosrbed water is greatly reduced or even completely broken up. Secondly, the soil particles tend to agglomerate. Thirdly, by the movement together the surface area is reduced, and therefore less absorbed water can be taken up, which again results in a reduced swelling capacity. Further, the compaction of the soil is facilitated by these three facts."

For treatment with RRP, double application is suggested, and total quantities are dependent on soil type as follows: Granular soils: 5 gal. per 4000 gal. water, covering 5000 to 6000 sq ft; Sandy clays or loam: 6 gal. per 4000 gal. water, covering 5000 to 6000 sq ft; heavy clay soils: 8 gal. per 4000 gal. water, covering 5000 to 6000 sq ft. Discing or mixing prior to application aids initial treatment penetration. Usage specifications state that after the total treatment has been applied, "...adjust to optimum moisture content if necessary, and compact ... with ... either a regular or vibratory sheepsfoot compactor." After blading, the soil is recompacted with a flat wheel vibratory and, as the final construction operation, with a pneumatic compactor. "After complete treatment, compaction will reduce the soil to virtually zero air voids, eliminate frost heave and damage from freezing. Reduces or eliminates the shrink and swell characteristics in high plastic, organic, colloidal clays."

The literature from Zel Chemical Company on RRP presents lab and field data from various consultants worldwide and indicates significant improvements in density, compactability, and CBR. Suggested retail price for RRP as of February 1, 1973, was $900.00 per 55 gal. drum ($16.36/gal.) in quantities less than 50 drums.

Coherex - Golden Bear Division, Witco Chemical, Bakersfield and Los Angeles, California. Coherex is said to be a concentrated, highly stable emulsion of petroleum oils and resins, consisting of

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* Approximately two-thirds of the way through this research project, Stabilization Chemicals, Inc., quit business.

about 60% resins and 40% wetting solution. The wetting solution keeps the petroleum resin dispersed and readily miscible with water, even salt water. Coherex is primarily a palliative, coating dust particles and forming cohesive membranes that attach adjacent particles resulting in large agglomerates. The size increase in particles thus immobilizes the dust and prevents it from remaining in air suspension. The resinous components of Coherex provide longer palliation than conventional dust oils, gradually forming on the dust a hardened coating which becomes more permanent with subsequent applications. Practical ratios for all applications of Coherex to water are 1:4, 1:7, and 1:10, depending on desired results. In 55 gal. steel non-returnable drums, the price for Coherex, as of about March 1973, was $0.49/gal.

Terra-Krete - Produced by Jennat Corp., a Union Carbide Subsidiary, marketed by Terra-Krete, Los Angeles, California. This product comes in two formulations, #1 for compaction, #2 for erosion control. "From a technical standpoint, Terra-Krete may be said to reduce the frictional resistance of soil particles, thereby enhancing compaction with minimum of effort. It is a slightly viscous solution of chemicals and employs a polymeric synthetic binder that renders permanent cementation and superior heave-thaw stability to soil-like materials. The admixture contains no germicides and is non-toxic, non-acidic, and non-inflammable." In a personal communication, Thomas H. James, Terra-Krete, Los Angles, stated that the products consisted "of various salts and an emulsion polymeric binder similar to that secreted by certain plant life."

Terra-Krete was noted to raise relative compaction of various soils from 4 to 9%, and, after 18 months on a slope, was still continuous and able to resist erosion. It improved compressive strengths in a cement treated base (CTB) material by 5.5 to 10% at cement contents from 4 to 6%, and reduced cure time in lime-treated soils. To increase compaction, Terra-Krete is diluted by water at a rate of 1 to 4 gal. per 1000 gal., depending on soil type. Clay soils require the higher dosage. As of April 18, 1973, price of Terra-Krete #2 was $2.25 to $3.00/gal., depending on quantity ordered.

Thinwater - Morgan International Products, Inc., Signal Hill, California, marketed by Newton Valve Service, Omaha, Nebraska. Thinwater "... works on most soils: hard pans, clays, silty loams, even adobe. One gallon treats 12,000 gallons of water..." Thinwater was stated to be a non-injurious penetrant, desireable for hard, stubborn soils and is used primarily as a soil conditioner. By reducing surface and inter-facial tensions of water, it is able to pierce the seal of soils normally impervious to water. When mixed with water, the water undergoes a physical change: molecular attraction between water molecules is neutralized, breaking surface tension and causing the water to become very thin and thus penetrative. Thinwater was also noted for improving soil compaction and reducing water runoff. In one testimonial, compaction costs were stated as being reduced as much as 50%. Surface tension tests indicated 33.4 dynes/cm to 35.7 dynes/cm for concentrations of 1:6000 to 1:12,000, respectively. As of August 2, 1976, Thinwater was quoted at $10.95/gal. in 5 gal. lots.

X-1000 and X-2100 - PVO International, Inc., Los Angeles, California. X-1000 is described as a liquid concentrate of polymers-in-water dispersion designed for substrate compaction. Compactability has been achieved in clays, silts, blow sand, loams, and soil combinations. When reduced with water, these non-ionic surfactants, emulsifiers, and plasticizers with basic polymers enact a cementitious effect in soils in a cured state. Curing occurs by air drying enhanced by drying agents in the compound, and by temperature and soil conditions. The product becomes inert and unsusceptible to change by soil chemicals, decomposition, or deterioration by fungi or living endospores. Thirty-day-cure compressive strengths of up to 880 psi were indicated. X-1000 is available in 55 gal. drums or 2000 gal. bulk minimum and is normally reduced at a ratio of 1 to 20 in water.

X-2100 is described as an aqueous conjugated epoxy ester emulsion, non-toxic, and non-flammable. It is "....50:50 weight percent epoxy ester prepared from a type 4 epoxy resin and a fatty acid with high linoleic content," plus nonionic emulsifiers on the approved list of the FDA, water, and a lead-free drying system of zirconium, cobalt, and calcium. It may be used as an admixture to oil and tar emulsions or as a stabilizing agent over loose gravel and foreign objects. Moreover, it provides cohesion of asphaltic components, reduces water erosion and oxidation by ultraviolet rays, and it is a dust control agent, lake bottom sealer, and cement block and wall sealer. Equipment cleanup is recommended with "copious amounts of water" flushing, followed by "lacquer thinner," and rinsing.

No cost data were available with the literature of either PVO product.

Petro-S - Petrochemical Co., Inc., Fort Worth, Texas. Petro-S was described by Mr. Tom Robertson, Technical Representative of the supplier, as a sodium alkyl ethylene sulfonate. However, literature received from the supplier described Petro-S as a 98% concentration of complex sulfonated monodimethyl naphthalene.[46] The product is a surfactant with excellent wetting characteristics. It is safe and "approved under paragraph 121.1198 of the Federal Register as an indirect food additive." Petro-S is usually described in the literature as a soil penetrant, providing retention of soil moisture, increasing aeration, and generally assisting in vegetative growth. It is available as a 50% aqueous solution or a 98% active dry powder, and

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[46] J. F. Osborn, J. Letey, and N. Valoris, "Surfactant Longevity and Wetting Characteristics," Calif. Turf. Cult. 19: 3 (July 1969).

as of January 8, 1974, was priced at $0.375 to $0.56/lb, depending on quantity. As of May 25, 1977 Petro-S was quoted at $0.2275 to $0.51/lb, depending upon quantity or solution/powder form. Normal agricultural application rates were described as 10-20 lb of active material per acre.

Pen-E-Pac - Holton International, Inc., Baton Rouge, Louisiana. Pen-E-Pac is described as being composed of long chain aliphatic and aromatic hydrocarbons, with a specific gravity of 1.04 to 1.06 at 25 °C, and having a pH of 6.0 to 8.1. Designed for soil stabilization and achievement of maximum density, Pen-E-Pac is stated to be "a concentrated, viscous, water dispersable, non-toxic, non-polluting, plastic, liquid." It reduces soil particle friction on contact, achieving maximum soil density with minimal effort. It permits use of in-place soils of all types up to a maximum plasticity index (P.I.) of 40 (with the exception of A-3 Materials), eliminates need for gravel, shell, or sand in achieving density, prevents base shrinkage cracking, can be used in high moisture content soils for year-round construction, reduces compactive effort up to 30%, and can be used to insure 100% compacted lab density. "When used in conjunction with soil cement the content can be reduced 50% to 60%."

As of November 4, 1973, the price of Pen-E-Pac concentrate in either 5 or 55 gal. drums was listed as $24.50/gal., FOB destination. "By using the Pen-E-Pac system materials costs for road base construction can be reduced as much as 80-90 percent. Labor and equipment costs can be reduced up to 50 percent." Dilution rates, calculated from tables presented in the literature, ranged from approximately 1:115 to 1:2300 gal. Pen-E-Pac to gallons water and were dependent on stabilization depth, optimum and in-situ moisture content, width of one mile length of stabilized material, and the amount of product to achieve a confined load bearing strength of 100 psi. Other required load-bearing strengths of up to 750 psi were noted. The literature did not specify quantity of Pen-E-Pac to achieve increased bearing strength though the following statement was noted: "Load bearing strengths for any traffic demand can be achieved by using Pen-E-Pac to obtain the highest possible soil density."

FR-20 - Halliburton Services, Duncan, Oklahoma. FR-20, an acrylamide co-polymer of in excess of one million molecular weight, is intended to reduce friction in oil-well cement. In small concentrations in almost all types of water, it will reduce friction by up to 75 or 80%. As compared to other friction reducers, it has less tendency to flocculate water-dispersed solids. Absorption by montmorillonite at a pH of 4 will generally produce an ordered type of polymer. However, disorder exists between clay crystals when the pH is 6.8 to 7.2. The polymer will desorb when washed with water, although it is dependent on the water contact efficiency with the polymer-clay complex, particularly if the soil-polymer mass is compacted. Dilution rates are at 1-2 lb per 1000 gal. water. Price was $1.21/lb as of about March 1974. This product is also thought to be available from Dow Chemical Company as "Separans," and from American Cyanamid as "Cypan."

The Central System of Soil Stabilization - marketed by Saunders Petroleum Co., Greeley, Colorado. This system includes four products labeled SA-1, Clapak, Claset, and Kelpak. Each product is water soluble, can be applied by water truck or asphalt distributor, and "makes possible the stabilization of soils to a considerable depth below the area worked," thus eliminating soft spots and frost damage in the treated soil.

SA-1 is described, not as a cementing or bonding material, but as a material whose function is the removal of organic residues and certain chemical combinations present in all soils through an accelerated process of reduction-oxidation, thus "increasing compactability, general stability and the internal drainage characteristics... the removal or alteration of these chemical combinations improve soil stability by increasing the coefficient of friction between soil particles..." This situation is coupled with a major improvement in the moisture equilibrium characteristics of the soil. SA-1 is recommended for soils that are predominantly sandy or granular and which have a P.I. of 5 or less. It is particularly recommended for soft carbonate materials such as caliche or shell. Materials "containing more than 10% of finely divided silts or clays or more than 20% of coarse silts should be treated with Clapak instead of SA-1." Recommended laboratory testing procedures indicate that highest compressive strengths of 1/30 cu ft specimens of SA-1 treated materials are attained after 5-7 days air curing, (specimens having been compacted in the Proctor mold under a compression of 80,000 lb and held for a period of 2 min).

Clapak is noted as the prime product of the Central System, increasing the bearing value of wet clays or silts and improving moisture equilibrium characteristics. Clapak provides a maximum increase in wet bearing strength of soils, reduces shrinkage and swelling of clays, and when used in combination with Claset in suitable proportions and quantities, reduces shrink-swell and P.I. It is noted as being especially effective in peat and bog soils. It is compatible with asphalt and tar, aiding their dispersion in clays and silts. When weather conditions are favorable, Clapak, like SA-1, breaks down and disperses existing asphaltic paving.

Combinations of Clapak and Claset are recommended for "wherever any type of clay problem is found in base or subbase," for clays with P.I. from 6 to over 30, and even for bentonites. Clapak is recommended for use in preventing soft spots and frost lensing in clayey or silty native soils where weather and traffic conditions are severe. While Clapak and Claset are cited for many soil applications when combined in water, Technical Bulletin 70S7 summarizes the combination as forming a "chemical interlock," with the prime function of each being maximum wet strength for Clapak and maximum reduction of shrink-swell for Claset. Recommended parts of Clapak to Claset per 1000 gal. water vary from 20:0 for P.I. = 10, to 65:35 for P.I. = 50.

Kelpak is a two-component stabilizer for use in sandy materials, loosely graded desert soils, and small particles of rock and gravel, forming cemented bonds between adjacent particles. The bonding material is a liquid packaged in 5 gal. containers, and the catalyst is a dry powder. Both are mixed with water to be applied to a soil but are not used separately. To improve results with Kelpak, the soil should first be treated with SA-1 at a rate of 1 gal. per 2500 gal. water. Application rates of Kelpak vary from 5 to 15 gal./foot-mile, depending on soil type and lift thickness.

It is noted in the Central System literature that the products do not respond in the laboratory as in the field. The following reasons for this discrepancy are direct quotations from Technical Bulletin 69S1:

1. Soil displaced from its natural location is no longer part of the great magnetic and electrical field that constitutes the mass of the earth.
2. The energy relationship that prevails at the earth's surface because of daily temperature changes is lost.
3. Daily and seasonal changes in the moisture content of soils appear to have a beneficial effect for a period of time after the initial chemical treatment. These benefits are lost in the laboratory.
4. Construction equipment is capable of far more vigorous and intensive mixing and blending than any laboratory method. The wheels of loaded water trucks and graders are of special benefit because of the pressure they exert on the wet soil.
5. Performance in the field is usually evaluated over a period of months or years, while laboratory tests are usually completed within a week from the time the soil is treated.
6. Changes in moisture equilibrium, the most important single improvement these products bring about, cannot as yet be accurately measured in the laboratory.

In Technical Bulletin 69S21, it is noted that deflection will be less in any treated area than in an untreated area, that moisture in the treated materials will be less than in the untreated after a period of hydration, that after a period of dehydration moisture will be higher in the treated areas, and that these clues can be used as verification that the method works.

Cost data of the Central System products are presented in Technical Bulletin 69S17 for SA-1: \$20.00/gal., Clapak: \$12.50/gal., and Claset: \$12.50/gal. No cost data were given for Kelpak. As of May 2, 1973, prices quoted for SA-1 at \$23.00/gal., and for Clapak or Claset at \$14.50/gal.

Poly-Tergent B-300 - Olin Chemicals, Stanford, Connecticut. The following information on this product was obtained from the 1967 and

1975 North American editions of McCutcheon's Detergents and Emulsifiers, published by M C Publishing Co., Olen Rock, New Jersey: A nonylphenoxy polyethoxyethanol, liquid, 99% concentration, nonionic. Used as a detergent, emulsifier, wetting agent, dispersant, and textile scouring agent. Soluble in water.

Tergitol 15-S-9. Union Carbide Co., New York, N.Y. No product information was provided by the producer. McCutcheon's Detergents and Emulsifiers lists the nearest chemical homologue, Tergitol TP-9, as a nonylphenyl polyethylene glycol ether, liquid 100% concentration, nonionic. Used as an emulsifier, wetting agent, dispersant, and detergent.

Terra-Seal. Del Chemical Corp., Menomonee Falls, Wisconsin and Reno, Nevada. Described by the manufacturer as "an ecological development consisting of a combination of biological enzymatic material which by catalytic action stimulates and activates certain natural actions in soil." Moreover, it improves compaction characteristics by a lowering of water surface tension and the "enzymatic action also lowers the moisture density curve at its peak, indicating a lessening of the sensitivity of the soil." In addition, Terra-Seal treatment of soil is described as reducing the plasticity index, minimizing problems of freeze-thaw, reducing swell and the coefficient of permeability, and increasing soil bearing capacities through "cementation of the soil" as evidenced from CBR tests. Recommended application rates are a concentration of 1 gal. per 1000 gal. of water, with 1 gal. of the solution applied to each 6 sq yd followed by a similar application the same day, and a 1/3000 solution daily for three days.

Aerosol OT-75%. American Cyanamid Co., Wayne, New Jersey. A 75% active solution of sodium dioctyl sulfosuccinate, the remainder being water plus "5% of a lower alcohol to provide fluidity." It is anionic, soluble in water up to 1.5 gal. per 100 ml at 30 °C, very soluble in organic solvents, and it produces a minimum surface tension in water of 26 dynes/cm. Its surface active properties improve "wetting, rewetting, increasing absorbency and penetration, emulsifying, dewatering, and reducing surface tension." Aerosol OT-75% is a clear, slightly viscous liquid having a molecular weight of 444 and a specific gravity of 1.09. "Except for eye exposures, Aerosol OT exhibits a low order of toxicity. In common with other anionic surface active agents, Aerosol OT is strongly irritating to the eyes. Persons handling this product must avoid eye contact." As of November 1975, this product was priced at $0.50/gal. in 55 gal. drums, or $0.57/ gal. in 15 gal. fiber drums.

Duponol WA Paste. E.I. DuPont DeNemours and Co., Inc., Wilmington, Delaware. As presented in McCutcheon's Detergents and Emulsifiers, this product is a sodium lauryl sulfate, liquid, and anionic and is used as a detergent and shampoo base and for textile scouring. The company literature indicates the product as an "improved cosmetic quality, alcohol sulfate product designed to meet the exacting requirements for liquid cream lotion and solid cream or paste shampoos." The manufacturer's literature primarily describes various "shampoo formulations." As of November 1975, this product was priced at \$0.2725/lb in 425 lb drums.

Alkanol 189-S. E.I. Dupont De Nemours and Co., Inc. Wilmington, Delaware. An anionic, reddish-brown liquid chemical of sodium alkyl sulfonate composition, Alkanol 189-S has a molecular weight of 354, and produces a surface tension of 30.0 dynes/cm at a 5% concentration in water. Alkanol 189-S "has excellent wetting and penetrating action as well as detergency. It is stable in acid, neutral and alkaline media. Suggested uses include metal cleaning and pickling, bottle washing, and general detergent applications." As of November 1975, this product was priced at \$0.42/lb in 425 lb drums.

Nacconol 40F and Bio Soft D-35X. Stepan Chemical Co., Northfield, Illinois. These two products were shipped as nearest chemical homologues in response to our initial request for Nacconol NR as used by Shirley.[26] Bio Soft D-35X is described as a biodegradeable, high-active sodium linear alkylate sulfonate, light straw-colored liquid, 35% active, stable over the entire pH range. It is a detergent "with good foaming, wetting and emulsifying properties," with a density of 8.9 lb/gal. at 25 °C. As of late November 1975, this product was priced at \$0.315/gal. in drum size quantities to \$0.285/gal. carload.

Nacconol 40F is "a drum dried biodegradeable sodium alkyl aryl sulfonate based upon a linear alkylate hving a tailored carbon distribution and moleclar weight ... of excellent surfactant performance." A free-flowing, white, medium-density flake, it contains "about 40% active organic sulfonate the balance being sodium sulfate 35% and sodium chloride 24%." It has a water solubility of 2 g per 100 ml at 25 °C and 4 g per 100 ml at 50 °C, coupled with a surface tension at 25 °C and 1.0% concentration of 27.0 dynes/cm. Suggested applications for this product include use as a cement air entrainment improvement by addition at low concentrations during clinker grinding (0.0125%), detergents, dyeing, antipitting agent in nickel plating solutions, metal cleaning, metal working, ore flotation, and various other wetting, foaming, dispersing and detergent uses in both soft and hard water. As of late November 1975, Nacconol 40F was quoted at \$0.335/lb in 150 lb fiber drums to \$0.29/lb in carload quantities.

RD-4480, RD-4481, RD-4482. Armak Co., McCook, Illinois. Each of these products are true surfactants composed of long hydrocarbon chains which alter the surface chemistry of soil particles. RD-4480 is weakly cationic. RD-4481 is anionic and is referred to as a quaykill sulfonate. RD-4482, a nonyl phenol, is nonionic. Recommended dilution rates in water were not provided.

Summary

Most of the emphasis and claims both in the non-proprietary and in the trade literature appear to be on the action of chemical compaction aids as surfactants, reducing surface tension of water and hence water's penetration into soil and allowing for ease of drying water from soil. Virtually none of the literature cites or explains the mechanics of the compaction process, except in belated explanations of why certain products do not show up well in the laboratory as compared to the field. Virtually no attention is given to the clay mineralogy of the soils or to possible soil clay - chemical or clay - water interactions. Possible dispersive effects for the most part are not mentioned.

The literature thus appears to reinforce the concept of reduced soil-water tension as an aid to compaction, although the actual mechanism is not stated. Many proprietary products also are claimed to have cementitious or strengthening effects, but the mechanisms are vague. The trade literature appears to range from authoritative to highly speculative, to pseudoscientific, but with more or less the same goal--to impress potential customers.

Since many of the proprietary products are, or have been actively promoted on the market, a primary responsibility of the present research was an impartial evaluation of as many of the commercially available products as time would permit. This objective should avoid or minimize previous criticisms. For example, if a product simultaneously increases maximum density and lowers optimum moisture content, it would clearly be unfair and incorrect to evaluate it only at the optimum moisture content for the untreated soil, as has occurred in some studies. Similarly, if a chemical is effective because of dispersion which permanently weakens the soil, it would be unfair and incorrect to evaluate it only in terms of its effect on density, since high density is only an intermediary to the true objective which is a more stable soil.

The present research did not overlook the potential of other products and chemicals noted within the non-proprietary literature as having shown potential for significantly increasing density, decreasing optimum moisture content, increasing ease of compactability, and possibly strengthening fine-grained soils of various clay mineralogies. As will become apparent in succeeding portions of this report, many of the proprietary products were slowly eliminated from further successive evaluations. Nevertheless, the literature reviewed and reported herein leads to one significant, though qualified, conclusion: Many chemical products have created improvements in laboratory densification, and some appear to have been a significant factor in improving strength, compressibility, and other physical and mechanical properties of fine-grained soils, for reasons that for the most part remain obscure and unknown.

SOILS

Physical, chemical, and mineralogical properties of the twenty-six soils used in this study are presented in Tables 7 and 8. Selection and sampling of soils was accomplished through the excellent cooperation and aid provided by soil scientists of the USDA-SCS.

In the Phase I investigation, six soils representing variable engineering properties and containing the three predominent clay mineralogies, montmorillonite, illite, and kaolinite, were to be tested. However, both of the montmorillonitic soils proved to be quite acidic. Because of the preponderance of basic montmorillonitic soils in nature, particularly in deep depositional profiles, two additional soils were obtained, i.e., Shelby and Monona series, and were used in the final stages of Phase I testing with those chemicals ascertained to be somewhat effective.

The eighteen soils for Phase II investigation were selected as representative of major soil types thoughout the United States, having a variety of engineering characteristics and clay mineralogies dependent on major soil-forming processes. Consideration was given to their geological origin, regional extent, and soil genesis. The following is a comparison of the ranges in physical and mineralogical properties, plus geological derivation of the soils utilized in this project.

1) 5 micron clay content, 20.0 to 79.9%.
2) pH values, 3.3 to 8.4.
3) Cation exchange capacity, 5.6 to 48.8 m.e. per 100 g.
4) Liquid Limit, 17.0 to 71.0%.
5) Plasticity index, 1.3 to 41.1%.
6) Specific gravity of minus No. 10 sieve size, 2.67 to 2.80.
7) AASHTO Classification, A-4(0) to A-7-6(20).
8) Mean moisture content as sampled, 11.8 to 42.7%.
9) Predominant clay mineralogy: montmorillonite, illite, kaolinite, vermiculite, mixed, and inter-layer biotite-vermiculite.
10) Other clay mineralogy: disordered kaolinite, muscovite, gibbsite, feldspar, quartz, dolomite, calcite, and gypsum.
11) Geological derivation: alluvium, colluvium, residuum, marine and lacustrine sediments, glacial till, and loess.

It is therefore apparent that the soils utilized within this study are broad and diverse representations of fine-grained soil types throughout the United States.

Table 7. Physical, chemical, and mineralogical properties of soils selected for study, Phase I.

Name or Series Location	AASHO Road Test Ottawa, Ill.	Grundite Morris, Ill.	Dundee Tensas Parish, La.	Shelby Knoxville, Ia.	Loring Jackson, Miss.	Decatur Knoxville, Tenn.	Cecil Newton, N.C.	Monona Sioux City, Ia.
Horizon Sampled	-	-	B/C	B/C	B/C	B/C	B/C	B/C
Textural Composition, %								
Gravel (> 4.76 mm)	2.2	0.6	0.0	0.0	0,0	0.3	0.0	0.0
Sand (4.76 - 0.074 mm)	16.2	22.7	21.3	2.6	1.2	12.5	32.9	0.6
Silt (0.074 - 0.005 mm)	29.1	37.7	49.0	57.4	71.8	29.2	20.1	78.4
Clay (< 0.005 mm)	52.5	39.0	29.7	40.0	27.0	58.0	47.0	21.0
Colloids (< 0.001 mm)	28.0	29.0	24.0	34.1	21.0	46.0	35.0	17.0
Chemical Properties:								
pH	7.4	2.4	4.8	6.5	4.7	5.4	4.1	8.4
Organic Matter, %	1.5	1.0	0.9	1.2	1.4	1.9	0.9	0.3
Carbonate Content, %	8.0	0	0	0	0	1.0	1.0	8.0
Cation Exchange Capacity, m.e./100 g.	11.3	23.6	22.4	29.6	16.4	13.4	13.4	15.5
Physical Properties:								
Liquid Limit, %	33	50	35	54	38	55	61	32
Plastic Limit, %	19	29	25	32	27	29	45	26
Plasticity Index, %	14	21	10	22	11	26	16	6
Specific Gravity	2.74	2.77	2.67	2.70	2.68	2.75	2.70	2.71
Std. Dry Density, pcf	114.5	105.4	102.1	100.0	102.3	95.3	97.0	103.8
Std. Opt. Moist. Cont., %	15.2	19.5	19.0	20.9	18.6	24.4	23.0	18.5
Classification:								
Textural	Clay	Clay Loam	Clay Loam	Silty Clay	Silt Loam	Clay	Clay	Silty Clay Loam
Engr. - AASHTO	A-6 (9)	A-7-6 (9)	A-4 (9)	A-7-5 (15)	A-6 (9)	A-7-6 (9)	A-7-5 (10)	A-4 (8)
Predominant Clay Mineral	Illite	Illite	Montmorillonite	Montmorillonite	Montmorillonite	Kaolinite	Kaolinite	Montmorillonite
Other Clay Minerals	Kaolinite* Montmorillonite*	disordered Kaolinite*	Illite* Kaolinite*	Illite*	Illite Muscovite*	Illite* Vermiculite*	Illite* Gibbsite*	Illite* Kaolinite*
Geological Description	-	-	Alluvium	Kansan Till, oxidized, leached	Loess	Old Alluvium	Residuum from felsic rock	Loess calcareous

* Indicated clay mineral present in small amounts only.

Notes:
1. AASHO soil sampled from embankment of AASHO Road Test.
2. Grundite soil sampled from clay pit stockpile.
3. Clay mineralogy determined by X-ray diffraction and differential thermal analysis.
4. Organic and carbonate contents determined by differential thermal and thermogravimetric analysis.

Table 8. Physical, chemical, and mineralogical properties of soils selected for study, Phase II

Series Location	Frederick Virginia	Fannin N. Carolina	Persanti S. Carolina	Bearden N. Dakota	Renohill Wyoming	Pierre S. Dakota
Horizon Sampled	B/C	B/C	B	C	B/C	B/C
Depth of Composite Sample	18 - 44 in.	6 - 36 in.	6 - 18 in.	15 - 48 in.	3 - 26 in.	6 - 24 in.
Textural Composition:						
Gravel (> 4.76 mm)	1.9	2.5	1.6	0.0	0.1	0.5
Sand (4.76 - 0.074 mm)	11.8	47.6	20.2	4.4	8.2	5.7
Silt (0.074 - 0.005 mm)	24.3	11.9	21.2	39.6	24.7	18.5
Clay (< 0.005 mm)	62.0	38.0	57.0	56.0	67.0	75.3
Colloids (< 0.001 mm)	51.0	30.0	46.0	35.0	53.0	59.0
Chemical Properties:						
Cation Exchange Capacity, m.e./100g	15.4	16.4	17.0	20.8	33.4	44.6
pH	3.9	5.0	4.5	7.9	7.1	7.0
Physical Properties:						
Liquid Limit, %	49	44	47	41	58	71
Plastic Limit, %	33	29	33	27	26	33
Plasticity Index, %	16	15	14	14	32	38
Shrinkage Limit, %	27	26	20	19	16	9
Specific Gravity	2.73	2.80	2.81	2.66	2.77	2.71
AASHTO T-99:						
Max. Density, pcf	92.8	102.6	95.3	108.1	103.1	89.5
Optimum Moisture, %	27.6	21.8	23.2	16.4	17.5	27.4
Classification:						
Engr - AASHTO	A-7-5 (12)	A-7-6 (11)	A-7-5 (11)	A-7-6 (10)	A-7-6 (20)	A-7-5 (20)
Moisture Content as Sampled, %*	28.6 ± 0.9	25.5 ± 0.5	31.8 ± 1.0	28.6 ± 0.8	30.2 ± 2.0	25.1 ± 2.9
Predominant Clay Mineral**	1 Kaolinite 2 Vermiculite	1 Interlayer Biotite-Vermiculite 2 Vermiculite 3 Gibbsite 4 Biotite	Kaolinite	1 Montmorillonite 2 Vermiculite	Montmorillonite	Montmorillonite
Other Minerals**	Feldspar	Quartz	1 Vermiculite 2 Illite	1 Illite 2 Dolomite 3 Calcite 4 Quartz	1 Illite 2 Gypsum 3 Disordered Kaolinite	Feldspar
Geological Description	residuum, dolomite limestone	residuum, micaceous schist and gneiss	alluvium, ancient coastal plain stream terrace	glacial lake sediment	residuum, shale and sedimentary rock	residuum, clay shales

(Continued)

* Mean moisture content of samples removed from four or more bags upon arrival in laboratory. ± indicates one standard deviation.

** Minerals listed in order of magnitude of x-ray peak.

Table 8. Continued.

Series Location	Altamont California	Rimrock Arizona	Houston Black Texas	Peavine Oregon	Melbourne Washington	Marias Montana
Horizon Sampled	A/C	C	A	B/C	B	A/C
Depth of Composite Sample	6 - 40 in.	3 - 34 in.	12 - 90 in.	12 - 60 in.	14 - 56 in.	4 - 35 in.
Textural Composition:						
Gravel (> 4.76 mm)	0	3.1	0	0	0.1	0.1
Sand (4.76 - 0.074 mm)	5.0	8.2	3.3	44.8	20.7	7.4
Silt (0.074 - 0.005 mm)	29.0	41.2	24.7	21.2	36.7	34.3
Clay (< 0.005 mm)	66.0	47.5	72.0	34.0	42.5	58.2
Colloids (< 0.001 mm)	54.5	40.2	56.2	20.4	28.4	46.4
Chemical Properties:						
Cation Exchange Capacity, m.e./100g	41.5	37.6	44.0	48.8	48.8	27.7
pH	6.3	8.0	7.7	3.3	4.6	7.5
Physical Properties:						
Liquid Limit, %	49	44	71	62	37	46
Plastic Limit, %	26	25	30	50	26	23
Plasticity Index, %	23	19	41	12	11	23
Shrinkage Limit, %	8	4	9	33	29	15
Specific Gravity	2.71	2.75	2.73	2.80	2.72	2.72
AASHTO T-99:						
Max. Density, pcf	100.4	99.5	99.5	74.8	88.1	99.9
Optimum Moisture, %	19.9	22.2	22.7	43.4	30.3	23.4
Classification:						
Engr - AASHTO	A-7-6 (15)	A-7-6 (12)	A-7-6 (20)	A-7-5 (7)	A-6 (8)	A-7-6 (14)
Moisture Content as Sampled, %*	14.7 ± 0.6	12.0 ± 0.4	33.3 ± 1.3	42.7 ± 1.3	27.7 ± 3.1	29.6 ± 1.4
Predominant Clay Mineral**	Montmorillonite	Montmorillonite	Montmorillonite	Montmorillonite	Vermiculite	Montmorillonite
Other Minerals**	1 Kaolinite 2 Feldspar	Feldspar	Feldspar	-	1 Feldspar 2 Illite	1 Feldspar 2 Calcite
Geological Description	residuum, fine-grained sandstone and shale	residuum, basalt, cinders, and volcanic ash	residuum, marls, calcareous clays	residuum and colluvium, siltstone and shale	residuum and colluvium, shale and sandstone	thick clay deposits

(Continued)

* Mean moisture content of samples removed from four or more bags upon arrival in laboratory. ± indicates one standard deviation.

** Minerals listed in order of magnitude of x-ray peak.

Table 8. Continued.

Series Location	Buxton Maine	Vergennes Vermont	Ontonagon Michigan	Onoway Michigan	Nappanee Michigan	Paulding Ohio
Horizon Sampled	A/B	B/C	A/C	B/C	B/C	B
Depth of Composite Sample	10 - 36 in.	12 - 62 in.	3 - 38 in.	1 - 38 in.	10 - 36 in.	7 - 38 in.
Textural Composition:						
Gravel (> 4.76 mm)	0.1	0.2	0	7.4	0.2	0
Sand (4.76 - 0.074 mm)	7.5	4.5	2.9	44.6	16.5	4.7
Silt (0.074 - 0.005 mm)	35.3	31.1	17.2	28.0	23.3	24.2
Clay (< 0.005 mm)	57.1	64.2	79.9	20.0	60.0	71.1
Colloids (< 0.001 mm)	31.9	35.1	54.0	8.0	41.0	47.6
Chemical Properties:						
Cation Exchange Capacity, m.e./100g	15.4	12.9	31.1	5.6	22.2	27.4
pH	4.4	7.0	5.3	6.8	5.3	5.4
Physical Properties:						
Liquid Limit, %	33	33	61	17	44	60
Plastic Limit, %	24	22	32	16	25	31
Plasticity Index, %	9	11	29	1	19	29
Shrinkage Limit, %	23	10	17	13	16	14
Specific Gravity	2.76	2.77	2.73	2.69	2.74	2.73
AASHTO T-99:						
Max. Density, pcf	99.4	99.9	90.5	127.5	105.7	85.9
Optimum Moisture, %	23.0	22.2	27.8	9.7	20.0	22.3
Classification:						
Engr - AASHTO	A-4 (8)	A-6 (8)	A-7-5 (20)	A-4 (0)	A-7-6 (15)	A-7-5 (20)
Moisture Content as Sampled, %*	20.7 ± 1.1	18.4 ± 1.9	32.4 ± 6.8	11.8 ± 0.6	17.7 ± 0.4	34.6 ± 0.9
Predominant Clay Mineral**	1 Vermiculite 2 Illite 3 Mixed Layer	1 Vermiculite 2 Illite	Montmorillonite	Mixed	1 Vermiculite 2 Illite	1 Vermiculite 2 Illite
Other Minerals**	1 Feldspar 2 Calcite	1 Kaolinite 2 Feldspar 3 Calcite 4 Dolomite	1 Feldspar 2 Quartz	1 Calcite 2 Dolomite 3 Feldspar	1 Feldspar 2 Kaolinite	Feldspar
Geological Description	marine and lacustrine sediment	glaciolacustrine and estaurine sediment	lacustrine, glacial lake plain	Wisconsin till	glacial till	lacustrine, lake plain

* Mean moisture content of samples removed from four or more bags upon arrival in laboratory. ± indicates one standard deviation.

** Minerals listed in order of magnitude of x-ray peak.

PILOT LABORATORY STUDY - PHASE I

The purpose of the Phase I - Pilot Laboratory Study was to conduct a series of tests on fine-grained soils of variable engineering characteristics but representative of the three dominant clay mineralogies, in order to determine effectiveness of chemicals which showed improvement of soil compactability as indicated by the literature. From this study, a few of the more promising chemical compaction aids were to be selected for further and more comprehensive evaluation with a broader range of fine-grained soils for the Phase II Laboratory Study.

Physical, chemical, and mineralogical properties of the eight soils selected for use in this study have been previously presented in Table 7.

Compaction and Spherical Bearing Value Tests

Moisture-density and spherical bearing value (SBV) tests were conducted to evaluate compaction and bearing capacity characteristics of the compacted soils. Chemically treated and untreated soils were tested, and comparisons were made by means of tables and graphs. Due to space limitations in this report, all moisture-density and SBV graphs could not be presented. However, examples of graphical formats used are shown as moisture-density curves and spherical bearing data for a treated and untreated soil (Fig. 6) and dry density versus chemical concentration at various moisture contents (Fig. 7). These figures are presented to illustrate: 1) how moisture-density and spherical bearing data were prepared for analysis in this investigation; 2) how an effective compaction aid shifts the moisture-density curve upward and to the left, thus increasing maximum dry density and reducing optimum moiture content; 3) how SBV varies with moisture content; 4) how dry density varies with different chemical concentrations; and 5) how dry density can be affected on the dry side of optimum moisture when compared to the untreated soil.

Such graphs showed that, as anticipated, many increases in dry density occur not at optimum moisture content of the untreated soil, but on the dry side of the untreated optimum. This would be advantageous in a dry climate since a treated soil could be compacted at a lower moisture content than the untreated while still achieving 100% untreated maximum dry density (i.e., the compaction moisture content would be less critical).

In the example illustrated in Fig. 6, OMC of the untreated Cecil is about 23%, producing a γ_d of about 97 pcf. As seen in Fig. 7, the 1/1000 concentration of Clapak is generally more effective in providing improved density than either of the larger concentrations, and at a moisture content of at least 3% less than optimun for the untreated. Consideration of the potential bearing characteristics

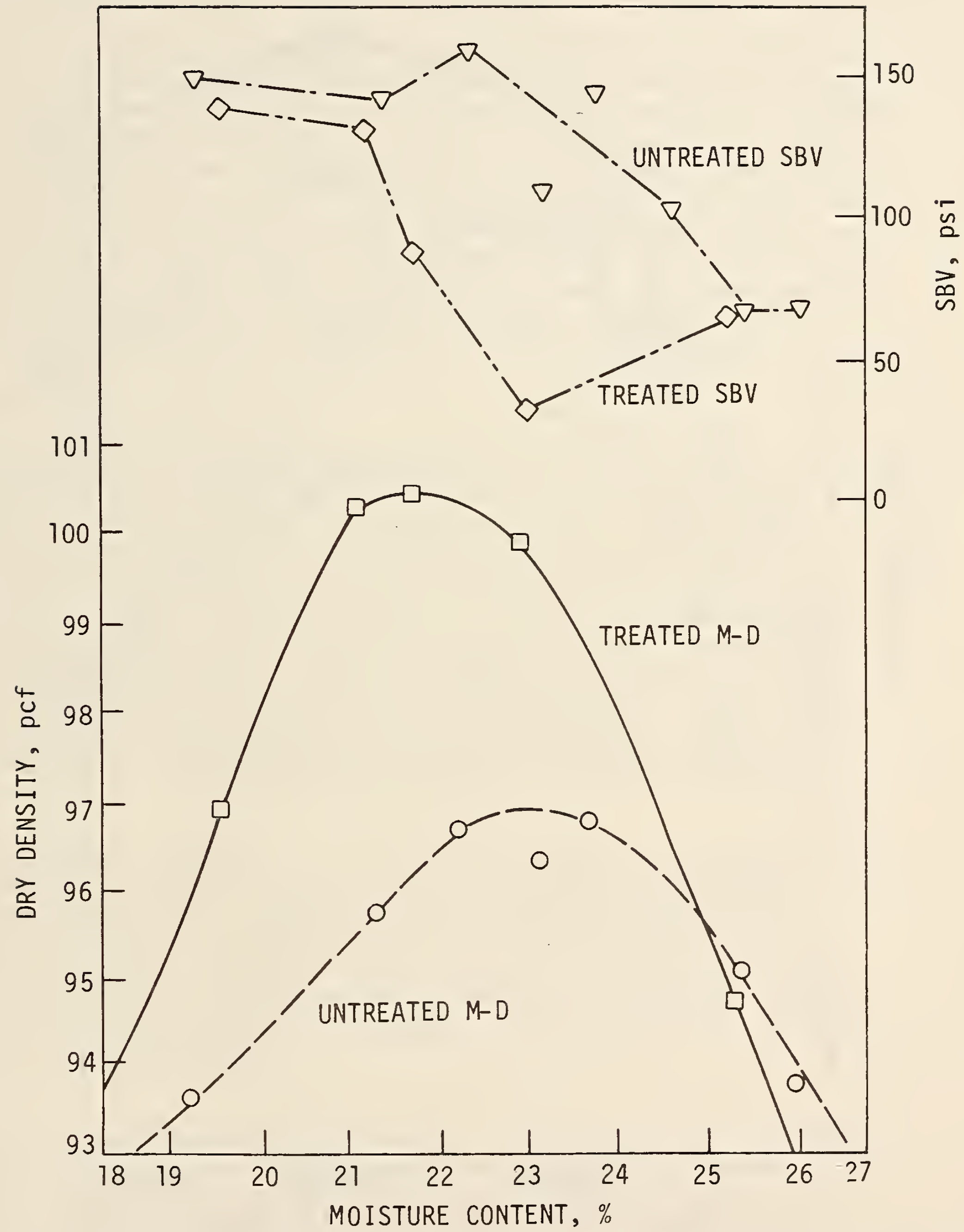

Fig. 6. Example of moisture-density curve and spherical bearing data, Cecil series soil, untreated and treated with Clapak at 10/1000 concentration.

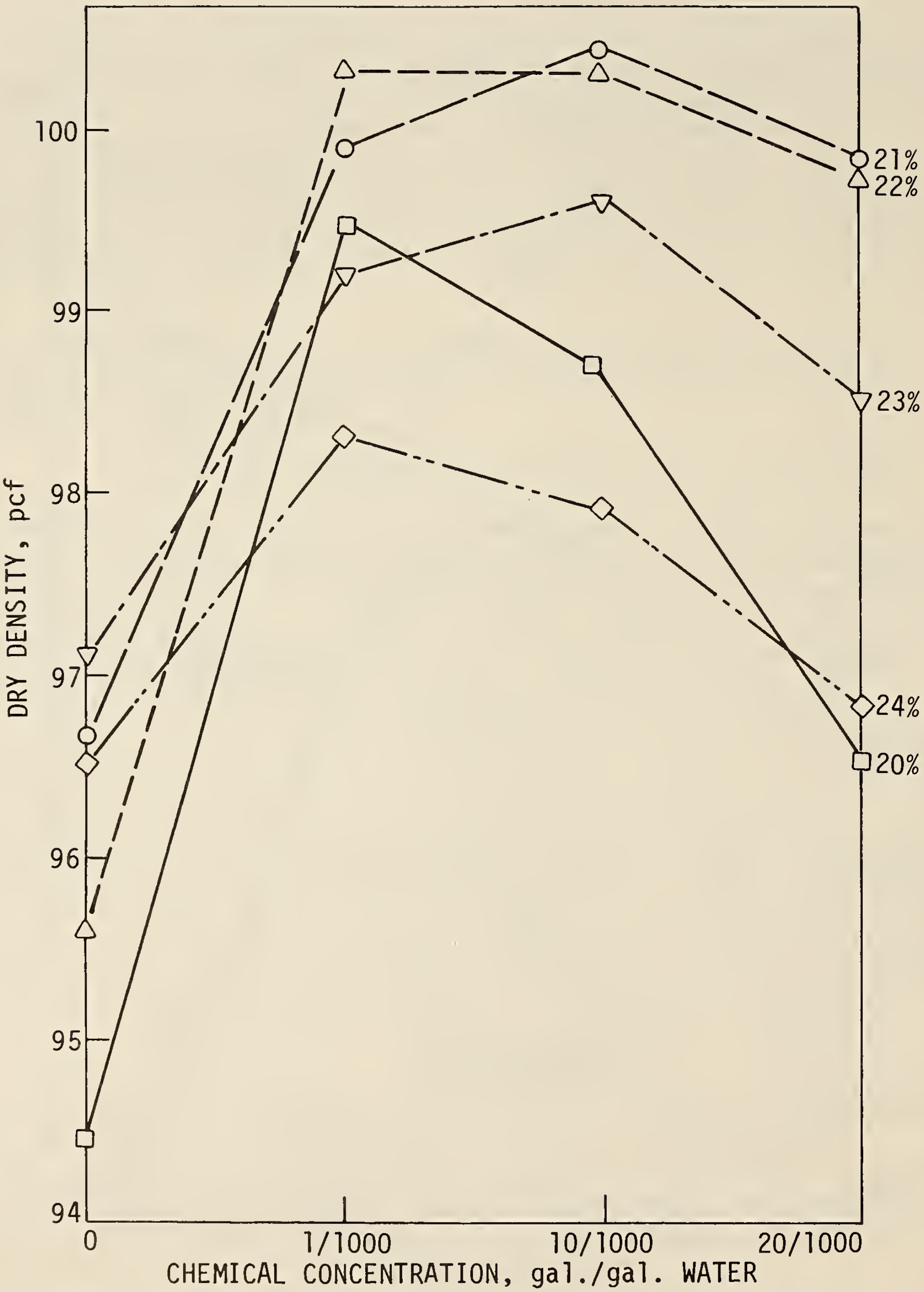

Fig. 7. Example of dry density versus chemical concentration at various moisture contents, Cecil series soil, treated with Clapak at 10/1000 concentration.

(Fig. 6) then suggests that the compacted moisture content of the treated soil should be somewhat less than OMC of the Clapak treatment of about 21%, to maintain a bearing value roughly equivalent to the untreated.

Not all products and concentrations were tested with all soils. After reviewing particular products and their performance on soils tested early in the investigation, a number of concentrations and products were later eliminated from the testing program. For example, all three concentrations of Terra Krete #2 proved ineffective with AASHO and Grundite soils; thus, only one concentration of Terra Krete #2 was tested on the Cecil, Decatur, Dundee, and Loring series. No improvement was noted on these soils so no further testing was done with this product on the Shelby and Monona series. It was felt that this approach made better use of available products and materials and provided more relevant data for each man-hour of testing.

Compaction Tests

Preparation of Additives. Products were diluted with tap water to appropriate concentrations or treatment levels as recommended by the manufacturer/supplier. If specific dilution rates were not given, careful review of pertinent literature was made, and concentrations were assumed. To find the effects of low and high concentrations, three dilution rates were tested for each product; if a manufacturer recommended using 5 parts chemicals to 1000 parts water for fine-grained soil, then 1 to 1000, 5 to 1000, and 10 to 1000 treatment levels were utilized in the testing program. The same dilution rates were then used on all eight soils. Therefore, in most instances, the middle concentration indicates quantity of chemical most often noted in the literature.

Soil-Chemical Mixing. A predetermined amount of diluted chemical product was mixed with 2500 g of soil for 4 min in a three-speed Hobart mechanical mixer. Actual amount of additive required was dependent on initial moisture content of the air-dry soil and the final moisture content desired. Each sample was separately mixed, and different amounts of chemical concentration were added to each sample so that varying moisture contents would be obtained, resulting in a moisture-density curve.

After each sample was mixed, it was stored in a sealed container for at least 45 min prior to compaction. It was believed that this "curing" time would 1) more closely resemble an actual field compaction procedure, 2) allow adequate time for the additive to be more evenly distributed throughout the soil, and 3) allow adequate time for any physico-chemical reactions to occur.

Compaction Procedure. Compaction was done in accordance with AASHTO Specification T99-70, standard density test procedure.[47] Compactive effort was supplied by a Testlab Model F590 automatic, programmable, rammer-type compactor. A minimum of five 1/30 cu ft specimens were compacted for each moisture-density relationship to accurately define the M-D curve. Periodic compactor calibration checks were made to ensure continuity of compactive effort.

It was noted early in the investigation that reuse of soil to make new specimens would affect the moisture-density curves. An example is shown with the AASHO soil, Fig. 8. In this case, fresh soil specimens treated with Clapak had a higher maximum density than those made from re-used soil. Also, both chemically treated and untreated re-used specimens had almost identical moisture-density curves. The effect of re-use of soil on successive compacted specimens was anticipated and may be readily explained: Re-used soil has a weaker structure due to prior compaction, and as a result, less compactive energy is expended in breaking up an aggregation of particles. It is precisely this energy that might plausibly be reduced by use of a chemical compaction aid. Thus, to more closely discern the effect of chemical additives on compaction and to more closely simulate field compaction procedures, fresh soil was used to mold each specimen. Such relationships are further illustrated in a later section of this report on variations in M-D Test Procedures.

Due to the manner of soil-chemical mixing, the actual amount of chemical in each specimen was dependent on 1) dilution rate of chemical, 2) amount of concentration added per specimen, and 3) compacted density of specimen. Amount of chemical as percent dry soil weight may be evaluated by the following expression:

$$P = C(M-H)$$

where: P = percent chemical on a dry-soil-weight basis
C = fractional concentration of chemical in the additive
M = final moisture content, in percent
H = initial or air-dry hygroscopic moisture content, in percent

As an example, determination of amount of chemical present in the SC-518 treated AASHO soil at maximum dry density is shown below:

$$P = C(M-H)$$

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[47] American Association of State Highway and Transportation Officials, (1970). Standard Specifications for Highway Materials and Methods of Sampling and Testing, Part II.

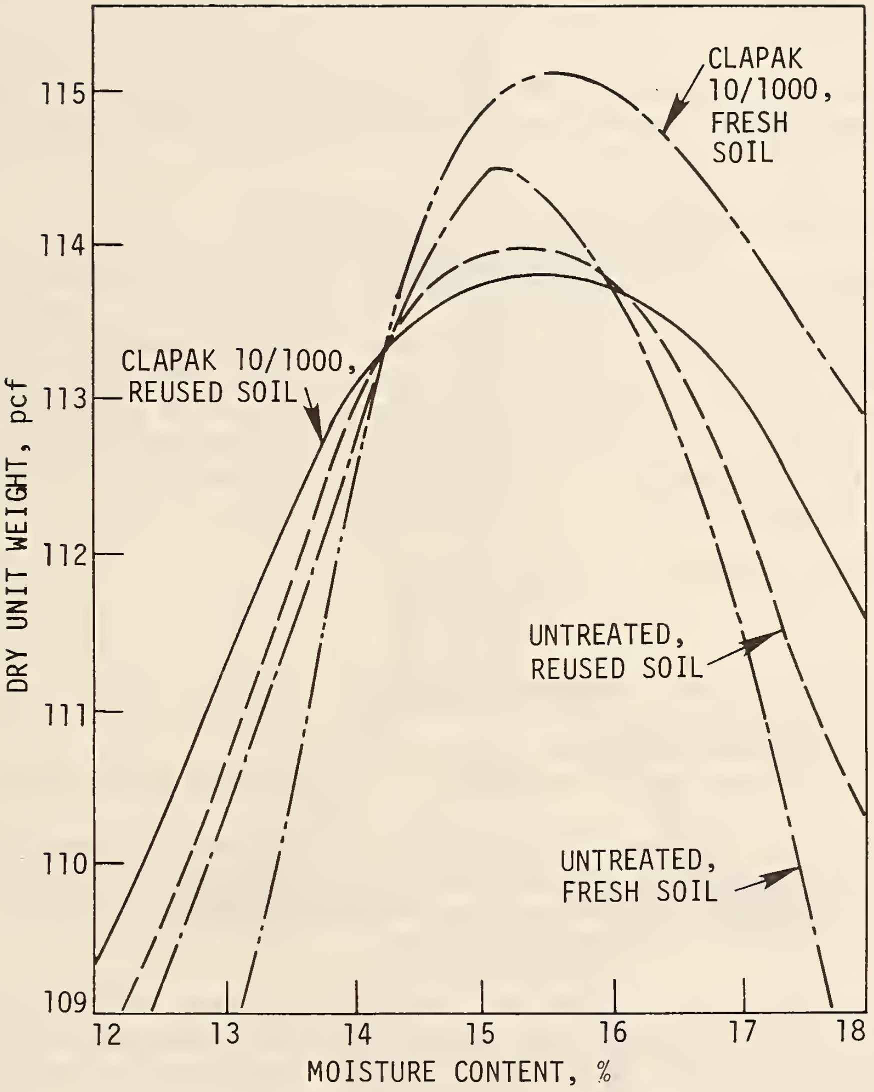

Fig. 8. Example of moisture-density curves compacted with fresh and reused AASHO soil.

C = 1/1000 gal./gal. water
M = 15.1%
H = 2.0%
P = (1/1000)(15.1 - 2.0)
P = 0.0131%

SC-518 treatment levels of AASHO soil varied from 1/1000 to 10/1000; thus, the percent of chemical on a dry-soil-weight basis ranged from 0.013% to 0.131% at maximum dry density.

Spherical Bearing Test

Procedure and Calculations. Relative soil bearing strength was evaluated through a spherical penetration device, Fig. 9. The spherical bearing value (SβV) is the result from a laboratory stress-strain test in which a 10 lb load is applied to a 1 in. diameter sphere resting on the soil specimen surface. Depth of penetration is recorded after 1 min and the contact area of the sphere penetrating the soil is calculated. Load divided by the area is SBV, in pounds per square inch:

$$SBV = \frac{L}{\pi Dh}$$

where: SBV = spherical bearing value, psi
L = load, pounds
D = diameter of sphere, inches
h = penetration of sphere into the compacted soil, inches

Butt et al.[48] present a discussion of the spherical bearing test and its correlation with CBR and plate bearing tests. However, the laboratory procedure used herein was for the purpose of a quick, relative evaluation of bearing strength.

Immediately after compaction, two SBV tests were run at different locations on the surface of each moisture-density specimen while still in the mold. SBVs were then averaged, resulting in one SBV for each molded specimen.

Compaction and Spherical Bearing Test Results

Moisture-density and SBV test results are presented in tabular form, categorized by soil type, in Tables 9 through 16. These eight tables show: 1) additive and dilution rates, 2) maximum dry density, 3) optimum moisture content, 4) percent increase or decrease in maximum dry density, 5) increase or decrease in optimum moisture content, and 6) adjusted average SBV.

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[48] G. S. Butt, T. Demirel, and R. L. Handy, "Soil Bearing Test Using a Spherical Penetration Device" HRB Record, 243 (1968).

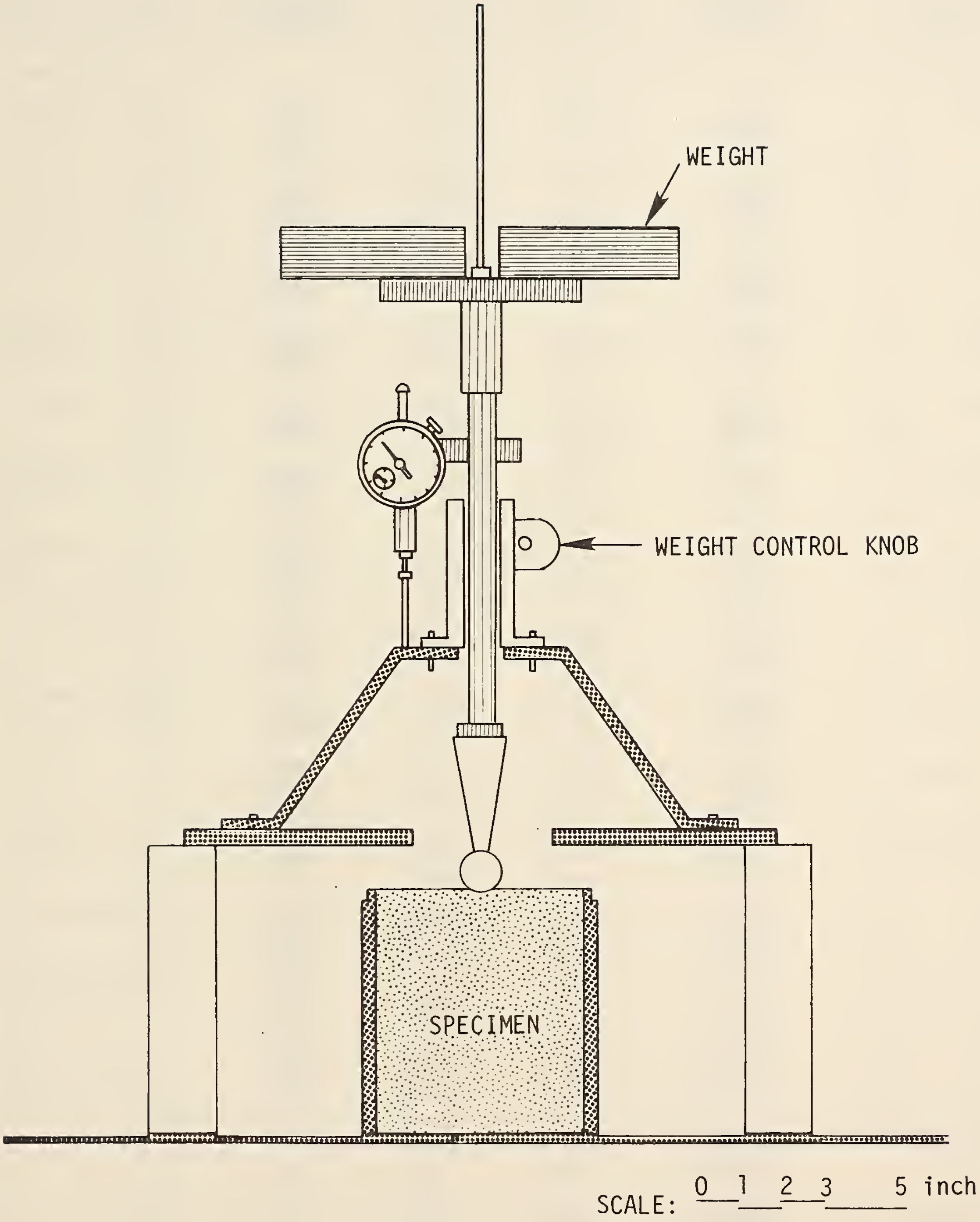

Fig. 9. Schematic of Spherical Bearing Value Test (SBV).

Table 9. Moisture-density and spherical bearing value results, AASHO soil.

Chemical Product	Concentration gal./gal. Water	Max. Dry Density, pcf	OMC, %	% Inc. or Dec. in Max. Dry Density	Inc. or Dec. in OMC	Adjusted Average SBV, %
Untreated		114.5	15.2	--	--	100
Clapak	1/1000	115.5	15.2	+0.8	0.0	94
	10/1000	115.5	15.3	+0.8	+0.1	121
	20/1000	115.2	15.5	+0.6	+0.3	112
Claset	1/1000	114.7	14.5	+0.2	-0.7	--
	10/1000	113.9	15.1	-0.5	-0.1	--
	20/1000	114.0	14.5	-0.4	-0.7	--
Coherex	10/1000	115.4	13.4	+0.8	-1.8	--
	143/1000	114.9	14.0	+0.4	-1.2	--
	250/1000	113.6	12.9	-0.8	-2.3	--
FR-20	0.5/1000	114.3	15.0	-0.2	-0.2	102
	1/1000	112.4	14.9	-1.8	-0.3	124
	2/1000	113.8	14.8	-0.6	-0.4	108
Kelpak	1/1000	114.1	14.5	-0.4	-0.7	--
	10/1000	114.6	14.8	+0.1	-0.4	--
	20/1000	114.3	14.0	-0.2	-1.2	--
Paczyme	1/1000	115.0	15.5	+0.4	+0.3	98
	2/1000	114.4	16.2	-0.1	+1.0	105
	4/1000	114.0	14.5	-0.4	-0.7	62
Pen-E-Pac	0.5/1000	115.2	15.0	+0.6	-0.2	115
	1/1000	115.5	15.0	+0.9	-0.2	123
	3/1000	115.7	16.4	+1.0	+1.2	124
Petro-S	100/1000	116.6	13.8	+1.8	-1.4	--
	200/1000	116.7	13.5	+1.9	-1.7	--
	300/1000	117.2	13.7	+2.4	-1.5	--
PVO X-1000	50/1000	115.2	14.4	+0.6	-0.8	--
	100/1000	114.4	15.5	-0.1	+0.3	--
	250/1000	113.0	15.8	-1.3	+0.6	--
PVO X-2100	50/1000	115.1	14.0	+0.5	-1.2	--
	100/1000	112.3	14.0	-1.9	-1.2	--
	250/1000	111.9	14.7	-2.3	-0.5	--
Road Packer	1/1000	114.6	14.9	+0.1	-0.3	--
	5/1000	113.9	14.3	-0.5	-0.9	--
	10/1000	112.8	16.1	-1.5	+0.9	--
SA-1	1/1000	114.5	14.7	0.0	-0.5	--
	10/1000	113.5	15.0	-0.9	-0.2	--
	20/1000	114.0	15.3	-0.4	+0.1	--
SC-518	1/1000	116.1	15.1	+1.4	-0.1	133
	5/1000	117.5	15.4	+2.6	+0.2	112
	10/1000	117.1	15.4	+2.3	+0.2	124
SS-13	1/1000	117.6	15.3	+2.7	+0.1	116
	2/1000	116.0	15.3	+1.3	+0.1	107
	4/1000	115.9	15.5	+1.2	+0.3	110
Terra Krete #1	0.5/1000	114.5	14.9	0.0	-0.3	--
	10/1000	114.3	14.5	-0.2	-0.7	--
	20/1000	115.3	15.0	+0.7	-0.2	--
Terra Krete #2	10/1000	114.3	14.7	-0.2	-0.5	--
	50/1000	114.8	15.3	+0.3	+0.1	--
	100/1000	113.8	15.3	-0.6	+0.1	--
Thinwater	1/12000	115.7	14.6	+1.0	-0.6	--
	1/6000	114.4	14.4	-0.1	-0.8	--
	1/1000	115.0	15.0	+0.4	-0.2	--

Table 10. Moisture-density and spherical bearing value results, Grundite soil.

Chemical Product	Concentration gal./gal. Water	Max. Dry Density, pcf	OMC, %	% Inc. or Dec. in Max. Dry Density	Inc. or Dec. in OMC	Adjusted Average SBV, %
Untreated		105.4	19.5	--	--	100
Clapak	1/1000	103.1	19.0	-2.2	-0.5	82
	10/1000	104.3	18.8	-1.0	-0.7	72
	20/1000	104.4	18.8	-1.0	-0.7	73
Claset	1/1000	105.8	18.2	+0.4	-1.3	97
	10/1000	105.3	19.3	-0.1	-0.2	81
	20/1000	103.3	17.7	-2.0	-1.8	90
Coherex	100/1000	102.7	19.5	-2.6	0.0	106
	143/1000	101.4	19.3	-3.8	-0.2	95
	250/1000	102.8	19.3	-2.5	-0.2	84
FR-20	0.5/1000	105.2	20.0	-0.2	+0.5	81
	1/1000	--	--	--	--	--
	2/1000	102.5	23.0	-2.8	+3.5	85
Kelpak	1/1000	104.0	21.0	-1.3	+1.5	66
	10/1000	105.7	20.6	+0.3	+1.1	87
	20/1000	104.8	19.8	-0.6	+0.3	67
Petro-S	100/1000	104.2	17.1	-1.1	-2.4	--
	200/1000	102.6	20.0	-2.7	+0.5	--
	300/1000	102.6	17.0	-2.7	-2.5	--
PVO X-1000	50/1000	104.4	18.5	-1.0	-1.0	89
	100/1000	103.5	16.8	-1.8	-2.7	81
	250/1000	103.4	18.6	-1.9	-0.9	74
PVO X-2100	50/1000	102.9	17.6	-2.4	-1.9	86
	100/1000	100.3	19.4	-4.8	-0.1	60
	250/1000	102.0	19.5	-3.2	0.0	54
Road Packer	1/1000	103.4	19.2	-1.9	-0.3	--
	5/1000	105.0	18.5	-0.4	-1.0	--
	10/1000	104.7	18.5	-0.6	-1.0	--
SA-1	1/1000	104.1	17.8	-1.2	-1.7	72
	10/1000	105.8	18.1	+0.4	-1.4	87
	20/1000	104.8	17.8	-0.6	-1.7	67
SS-13	1/1000	102.6	19.0	-2.7	-0.5	82
	2/1000	104.6	19.1	-0.8	-0.4	104
	4/1000	104.9	18.8	-0.5	-0.7	92
Terra Krete #1	0.5/1000	104.0	19.7	-1.3	+0.2	68
	10/1000	106.4	19.0	+1.0	-0.5	68
	20/1000	103.8	19.0	-1.5	-0.5	59
Terra Krete #2	10/1000	102.0	20.1	-3.2	+0.6	--
	50/1000	102.0	19.4	-3.2	-0.1	--
	100/1000	103.7	18.6	-1.6	-0.9	--
Thinwater	1/12000	104.8	19.5	-0.6	0.0	--
	1/6000	103.3	18.5	-2.0	-1.0	--
	1/1000	101.8	19.7	-3.4	+0.2	--

Table 11. Moisture-density and spherical bearing value results, <u>Cecil Series</u>.

Chemical Product	Concentration gal./gal. Water	Max. Dry Density, pcf	OMC, %	% Inc. or Dec. in Max. Dry Density	Inc. or Dec. in OMC	Adjusted Average SBV, %
Untreated		97.1	23.0	--	--	100
Clapak	1/1000	100.3	20.8	+3.3	-2.2	93
	10/1000	100.5	21.4	+3.5	-1.6	70
	20/1000	99.8	21.5	+2.8	-1.5	58
Claset	1/1000	96.0	24.5	-1.1	+1.5	122
	10/1000	95.6	24.8	-1.5	+1.8	101
	20/1000	99.7	22.8	+2.7	-0.2	61
Coherex	100/1000	98.0	22.6	+0.9	-0.4	108
	143/1000	97.3	20.0	+0.2	-3.0	117
	250/1000	96.4	21.0	-0.7	-2.0	85
FR-20	0.5/1000	98.4	22.6	+1.3	-0.4	97
	1/1000	98.5	22.7	+1.4	-0.3	101
	2/1000	95.5	23.1	-1.6	+0.1	104
Kelpak	1/1000	100.4	22.1	+3.4	-0.9	111
	10/1000	99.4	23.6	+2.4	+0.6	105
	20/1000	97.8	21.6	+0.7	-1.4	96
Paczyme	1/1000	97.2	23.3	+0.1	+0.3	103
	2/1000	97.3	24.0	+0.2	+1.0	102
	4/1000	97.2	23.3	+0.1	+0.3	--
Pen-E-Pac	0.5/1000	98.1	23.9	+1.0	+0.9	104
	1/1000	99.2	22.8	+2.2	-0.2	99
	3/1000	98.1	22.2	+1.0	-0.8	89
Petro-S	100/1000	100.0	20.9	+3.0	-2.1	74
	200/1000	99.8	21.9	+2.8	-1.1	57
	300/1000	99.6	19.5	+2.6	-3.5	35
PVO X-2100	50/1000	98.9	21.7	+1.9	-1.3	99
	100/1000	98.3	21.9	+1.2	-1.1	100
Road Packer	1/1000	98.0	22.5	+0.9	-0.5	92
	5/1000	97.0	24.0	-0.1	+1.0	97
	10/1000	97.5	23.8	+0.4	+0.8	91
SA-1	1/1000	98.9	23.2	+1.9	+0.2	84
	10/1000	100.1	21.9	+3.1	-1.1	55
	20/1000	99.3	22.5	+2.3	-0.5	51
SC-518	1/1000	99.6	23.0	+2.6	0.0	98
	5/1000	99.1	22.4	+2.1	-0.6	97
	10/1000	101.1	22.6	+4.1	-0.4	85
SS-13	1/1000	97.5	23.5	+0.4	+0.5	118
	2/1000	97.3	23.5	+0.2	+0.5	112
	4/1000	95.5	23.7	-1.6	+0.7	95
Terra Krete #1	1/1000	96.6	24.7	-0.5	+1.7	83
	10/1000	95.4	24.9	-1.8	+1.9	86
	20/1000	97.6	22.7	+0.5	-0.3	95
Terra Krete #2	1/1000	--	--	--	--	--
	10/1000	96.2	23.9	-0.9	+0.9	98
	20/1000	--	--	--	--	--
Thinwater	1/12000	99.1	22.8	+2.1	-0.2	107
	1/6000	97.8	24.2	+0.7	+1.2	110
	1/1000	98.3	23.0	+1.2	0.0	111

Table 12. Moisture-density and spherical bearing value results, Decatur Series.

Chemical Product	Concentration gal./gal. Water	Max. Dry Density, pcf	OMC, %	% Inc. or Dec. in Max. Dry Density	Inc. or Dec. in OMC	Adjusted Average SBV, %
Untreated	1/1000	95.3	24.4	--	--	100
Clapak	1/1000	96.2	22.9	+0.9	-1.5	85
	10/1000	98.3	24.2	+3.1	-0.2	72
	20/1000	99.0	23.2	+3.9	-1.2	52
Claset	1/1000	97.0	22.8	+1.8	-1.6	78
	10/1000	98.4	22.8	+3.3	-1.6	59
	20/1000	99.1	23.7	+4.0	-0.7	62
Coherex	1/1000	96.0	22.9	+0.7	-1.5	62
	143/1000	95.2	23.5	-0.1	-0.9	56
	250/1000	97.4	21.8	+2.2	-2.6	49
FR-20	0.5/1000	97.4	26.3	+2.2	+1.9	91
	1/1000	96.6	24.2	+1.4	-0.2	78
	2/1000	96.6	25.6	+1.4	+1.2	93
Kelpak	1/1000	94.4	26.6	-0.9	+2.2	78
	10/1000	96.1	24.5	+0.8	+0.1	91
	20/1000	96.0	24.0	+0.7	-0.4	86
Paczyme	1/1000	95.2	25.5	-0.1	+1.1	106
	2/1000	93.9	26.5	-1.5	+2.1	89
	4/1000	93.8	26.3	-1.6	+1.9	88
Pen-E-Pac	0.5/1000	98.4	24.2	+3.3	-0.2	75
	1/1000	99.9	24.5	+4.8	+0.1	80
	3/1000	98.4	23.3	+3.3	-1.1	62
Petro-S	100/1000	96.9	24.0	+1.7	-0.4	63
	200/1000	98.0	23.2	+2.8	-1.2	42
	300/1000	100.9	20.5	+5.9	-3.9	30
PVO X-2100	50/1000	95.4	24.6	+0.1	+0.2	86
	100/1000	--	--	--	--	--
	250/1000	--	--	--	--	--
Road Packer	1/1000	97.0	23.9	+1.8	-0.5	80
	5/1000	97.0	25.0	+1.8	+0.6	64
	10/1000	97.0	23.0	+1.8	-1.4	64
SA-1	1/1000	95.6	24.3	+0.3	-0.1	80
	10/1000	99.7	23.1	+4.6	-1.3	72
	20/1000	97.7	22.6	+2.5	-1.8	64
SC-518	1/1000	99.4	24.0	+4.3	-0.4	90
	5/1000	101.0	21.8	+6.0	-2.6	79
	10/1000	99.8	23.3	+4.7	-1.1	83
SS-13	1/1000	97.2	25.4	+2.0	+1.0	88
	2/1000	97.5	25.2	+2.3	+0.8	91
	4/1000	95.9	26.9	+0.6	+2.5	89
Terra Krete #1	1/1000	95.6	24.4	+0.3	0.0	109
	10/1000	95.3	25.6	0.0	+1.2	95
	20/1000	91.5	23.5	-4.0	-0.9	87
Terra Krete #2	10/1000	95.7	24.7	+0.4	+0.3	102
	50/1000	--	--	--	--	--
	100/1000	--	--	--	--	--
Thinwater	1/12000	94.2	25.5	-1.1	+1.1	83
	1/6000	94.2	24.0	-1.1	-0.4	84
	1/1000	97.3	24.3	+2.1	-0.1	96

Table 13. Moisture-density and spherical bearing value results, Dundee Series.

Chemical Product	Concentration gal./gal. Water	Max. Dry Density, pcf	OMC, %	% Inc. or Dec. in Max. Dry Density	Inc. or Dec. in OMC	Adjusted Average SBV, %
Untreated		102.1	19.0	--	--	100
Clapak	1/1000	101.1	19.3	-1.0	+0.3	95
	10/1000	101.4	18.6	-0.7	-0.4	88
	20/1000	100.7	20.2	-1.4	+1.2	80
Claset	1/1000	103.9	17.7	+1.8	-1.3	88
	10/1000	105.2	17.3	+3.0	-1.7	82
	20/1000	103.9	18.0	+1.8	-1.0	72
Coherex	100/1000	102.9	19.0	+0.8	0.0	90
	143/1000	102.3	17.6	+0.2	-1.4	93
	250/1000	102.3	17.2	+0.2	-1.8	98
FR-20	0.5/1000	101.0	19.0	-1.1	0.0	86
	1/1000	--	--	--	--	--
	2/1000	101.2	19.0	-0.9	0.0	94
Kelpak	1/1000	102.8	18.6	+0.7	-0.4	84
	10/1000	102.3	18.7	+0.2	-0.3	103
	20/1000	102.2	20.2	+0.1	+1.2	90
Paczyme	1/1000	103.9	19.0	+1.8	0.0	89
	2/1000	102.2	19.1	+0.1	+0.1	89
	4/1000	101.8	20.0	-0.3	+1.0	90
Pen-E-Pac	0.5/1000	102.3	19.0	+0.2	0.0	90
	1/1000	102.7	18.3	+0.6	-0.7	104
	3/1000	102.7	17.1	+0.6	-1.9	107
Petro-S	100/1000	104.1	16.5	+2.0	-2.5	73
	200/1000	103.1	17.0	+1.0	-2.0	73
	300/1000	104.7	17.3	+2.5	-1.7	69
PVO X-1000	50/1000	102.4	18.2	+0.3	-0.8	96
	100/1000	--	--	--	--	--
	250/1000	--	--	--	--	--
PVO X-2100	50/1000	102.3	19.1	+0.2	+0.1	92
	100/1000	--	--	--	--	--
	250/1000	--	--	--	--	--
Road Packer	1/1000	102.2	18.9	+0.1	-0.1	105
	5/1000	102.6	18.8	+0.5	-0.2	100
	10/1000	102.8	19.1	+0.7	+0.1	100
SA-1	1/1000	103.8	17.5	+1.7	-1.5	114
	10/1000	101.6	19.0	-0.5	0.0	84
	20/1000	101.8	18.2	-0.3	-0.8	104
SC-518	1/1000	103.5	19.6	+1.4	+0.6	99
	5/1000	104.4	18.6	+2.3	-0.4	103
	10/1000	104.8	18.5	+2.6	-0.5	83
SS-13	1/1000	102.3	18.0	+0.2	-1.0	110
	2/1000	102.3	18.7	+0.2	-0.3	118
	4/1000	102.4	17.9	+0.3	-1.1	83
Terra Krete #1	0.5/1000	101.6	20.1	-0.5	+1.1	100
	10/1000	103.2	20.1	+1.1	+1.1	108
	20/1000	102.4	19.0	+0.3	0.0	96

(Continued)

Table 13. Continued.

Chemical Product	Concentration gal./gal. Water	Max. Dry Density, pcf	OMC, %	% Inc. or Dec. in Max. Dry Density	Inc. or Dec. in OMC	Adjusted Average SBV, %
Terra Krete #2	10/1000	101.4	19.0	-0.6	0.0	99
	50/1000	--	--	--	--	--
	100/1000	--	--	--	--	--
Thinwater	1/12000	102.8	18.5	+0.7	-0.5	89
	1/6000	101.7	18.8	-0.4	-0.2	74
	1/1000	102.7	18.6	+0.6	-0.4	106

Table 14. Moisture-density and spherical bearing value results, Loring Series.

Chemical Product	Concentration gal./gal. Water	Max. Dry Density, pcf	OMC, %	% Inc. or Dec. in Max. Dry Density	Inc. or Dec. in OMC	Adjusted Average SBV, %
Untreated		102.3	18.6	--	--	100
Clapak	1/1000	103.6	18.9	+1.3	+0.3	88
	10/1000	104.1	18.5	+1.8	-0.1	77
	20/1000	102.9	19.8	+0.6	+1.2	75
Claset	1/1000	101.2	20.6	-1.1	+2.0	106
	10/1000	99.1	21.3	-3.1	+2.7	90
	20/1000	102.4	18.3	+0.1	-0.3	101
Coherex	100/1000	101.9	18.9	-0.4	+0.3	89
	143/1000	101.5	18.8	-0.8	+0.2	87
	250/1000	102.1	18.4	-0.2	-0.2	74
FR-20	0.5/1000	100.4	20.9	-1.9	+2.3	87
	1/1000	101.8	20.3	-0.5	+1.7	100
	2/1000	101.0	22.6	-1.3	+4.0	95
Kelpak	1/1000	102.5	19.0	+0.2	+0.4	110
	10/1000	102.8	20.9	+0.5	+2.3	101
	20/1000	101.2	19.6	-1.1	+1.0	96
Paczyme	1/1000	102.1	18.1	-0.2	-0.5	100
	2/1000	102.9	19.3	+0.6	+0.7	90
	4/1000	102.3	18.8	0.0	+0.2	99
Pen-E-Pac	0.5/1000	102.6	19.7	+0.3	+1.1	95
	1/1000	102.1	18.9	-0.2	+0.3	91
	3/1000	103.6	18.8	+1.3	+0.2	93
Petro-S	100/1000	104.6	17.6	+2.2	-1.0	64
	200/1000	104.8	17.6	+2.4	-1.0	41
	300/1000	104.7	15.7	+2.3	-2.9	34
PVO X-2100	50/1000	103.3	19.2	+1.0	+0.6	86
	100/1000	102.9	19.0	+0.6	+0.4	78
	250/1000	--	--	--	--	--
Road Packer	1/1000	103.2	20.5	+0.9	+1.9	99
	5/1000	102.7	19.3	+0.4	+0.7	82
	10/1000	102.1	19.5	-0.2	+0.9	86
SA-1	1/1000	102.0	18.7	-0.3	+0.1	90
	10/1000	100.0	19.1	-2.2	+0.5	62
	20/1000	103.7	18.4	+1.4	-0.2	64
SC-518	1/1000	104.4	18.6	+2.1	0.0	106
	5/1000	106.9	18.6	+4.5	0.0	82
	10/1000	105.9	18.0	+3.5	-0.6	87
SS-13	1/1000	103.5	19.0	+1.2	+0.4	97
	2/1000	102.2	18.3	-0.1	-0.3	89
	4/1000	103.5	20.2	+1.2	+1.6	89
Terra Krete #1	0.5/1000	101.3	16.5	-1.0	-2.1	86
	10/1000	100.9	18.8	-1.4	+0.2	95
	20/1000	102.4	18.4	+0.1	-0.2	84
Terra Krete #2	10/1000	101.0	16.9	-1.3	-1.7	92
	50/1000	--	--	--	--	--
	100/1000	--	--	--	--	--
Thinwater	1/12000	101.9	20.3	-0.4	+1.7	--
	1/6000	101.2	20.1	-1.1	+1.5	74
	1/1000	102.2	18.3	-0.1	-0.3	99

Table 15. Moisture-density and spherical bearing value results, Monona Series.

Chemical Product	Concentration gal./gal. Water	Max. Dry Density, pcf	OMC, %	% Inc. or Dec. in Max. Dry Density	Inc. or Dec. in OMC	Adjusted Average SBV, %
Untreated		103.9	18.3	--	--	100
Clapak	1/1000	104.4	18.7	+0.5	+0.4	79
	10/1000	103.6	18.1	-0.3	-0.2	109
	20/1000	104.3	18.4	+0.4	+0.1	103
Claset	1/1000	105.5	17.8	+1.5	-0.5	108
	10/1000	104.2	18.3	+0.3	0.0	91
	20/1000	104.2	17.9	+0.3	-0.4	95
Coherex	100/1000	104.9	18.4	+1.0	+0.1	99
	143/1000	105.8	17.9	+1.8	-0.4	85
	250/1000	105.7	16.4	+1.7	-1.9	48
Kelpak	1/1000	104.7	18.5	+0.8	+0.2	88
	10/1000	104.3	18.5	+0.4	+0.2	104
	20/1000	104.4	18.1	+0.5	-0.2	91
Pen-E-Pac	0.5/1000	105.1	17.1	+1.2	-1.2	95
	1/1000	104.4	18.6	+0.5	+0.3	94
	3/1000	104.1	18.1	+0.2	-0.2	92
Petro-S	100/1000	104.2	15.6	+0.3	-2.7	53
	200/1000	103.9	16.0	0.0	-2.3	90
	300/1000	105.3	15.8	+1.3	-2.5	48
RD-4480	1/1000	103.9	18.3	0.0	0.0	119
	5/1000	103.2	19.5	-0.7	+1.2	113
	10/1000	102.9	18.1	-1.0	-0.2	106
RD-4481	1/1000	105.4	19.0	+1.4	+0.7	101
	5/1000	104.6	19.3	+0.7	+1.0	99
	10/1000	103.1	18.7	-0.8	+0.4	71
RD-4482	1/1000	102.6	19.5	-1.3	+1.2	105
	5/1000	103.1	18.8	-0.8	+0.5	105
	10/1000	102.8	18.9	-1.1	+0.6	103
Road Packer	1/1000	105.7	18.6	+1.7	+0.3	108
	5/1000	105.4	18.5	+1.4	+0.2	85
	10/1000	104.1	18.1	+0.2	-0.2	117
SA-1	1/1000	104.8	17.7	+0.9	-0.6	103
	10/1000	104.8	17.8	+0.9	-0.5	118
	20/1000	105.1	18.4	+1.2	+0.1	116
SC-518	1/1000	104.2	17.9	+0.3	-0.4	112
	5/1000	104.0	18.0	+0.1	-0.3	93
	10/1000	104.8	17.3	+0.8	-1.0	104
SS-13	1/1000	105.0	17.3	+1.1	-1.0	92
	2/1000	105.1	18.2	+1.2	-0.1	91
	4/1000	105.4	18.2	+1.4	-0.1	97
Thinwater	1/12000	105.5	18.0	+1.5	-0.3	113
	1/6000	105.3	18.5	+1.3	+0.2	101
	1/1000	105.3	18.3	+1.3	0.0	110

Table 16. Moisture-density and spherical bearing value results, Shelby Series.

Chemical Product	Concentration gal./gal. Water	Max. Dry Density, pcf	OMC, %	% Inc. or Dec. in Max. Dry Density	Inc. or Dec. in OMC	Adjusted Average SBV, %
Untreated		100.3	20.9	--	--	100
Clapak	1/1000	99.7	21.1	-0.6	+0.2	107
	10/1000	99.4	21.4	-0.9	+0.5	102
	20/1000	98.0	21.2	-2.3	+0.3	98
Claset	1/1000	99.9	20.6	-0.4	-0.3	79
	10/1000	100.1	21.4	-0.2	+0.5	77
	20/1-00	99.1	21.1	-1.2	+0.2	106
Coherex	100/1000	98.3	20.2	-2.0	-0.7	85
	143/1000	98.6	20.6	-1.7	-0.3	76
	200/1000	99.5	19.4	-0.8	-1.5	56
Kelpak	1/1000	98.2	20.7	-2.1	-0.2	75
	10/1000	99.1	20.8	-1.2	-0.1	72
	20/1000	98.5	21.6	-1.8	+0.7	80
Pen-E-Pac	0.5/1000	99.7	21.8	-0.6	+0.9	87
	1/1000	101.4	21.5	+1.1	+0.6	102
	3/1000	99.1	21.4	-1.2	+0.5	109
Petro-S	100/1000	100.0	19.5	-0.3	-1.4	68
	200/1000	99.0	18.7	-1.3	-2.2	62
	300/1000	100.9	18.6	+0.6	-2.3	61
RD-4480	1/1000	100.1	20.8	-0.2	-0.1	79
	5/1000	99.6	20.6	-0.7	-0.3	86
	10/1000	98.6	21.0	-1.7	+0.1	105
RD-4481	1/1000	99.0	20.5	-1.3	-0.4	86
	5/1000	96.4	20.3	-3.9	-0.6	101
	10/1000	94.8	20.4	-5.5	-0.5	89
RD-4482	1/1000	97.5	21.0	-2.8	+0.1	121
	5/1000	98.1	21.3	-2.2	+0.4	102
	10/1000	98.8	20.7	-1.5	-0.2	99
Road Packer	1/1000	98.2	21.5	-2.1	+0.6	83
	5/1000	97.6	21.3	-2.7	+0.4	79
	10/1000	97.9	21.8	-2.4	+0.9	105
SA-1	1/1000	99.6	20.4	-0.7	-0.5	103
	10/1000	99.2	20.7	-1.1	-0.2	73
	20/1000	96.4	21.4	-3.9	+0.5	85
SC-518	1/1000	99.8	21.3	-0.5	+0.4	100
	5/1000	99.1	20.3	-1.2	-0.6	109
	10/1000	99.8	19.6	-0.5	-1.3	80
SS-13	1/1000	99.0	21.2	-1.3	+0.3	98
	2/1000	98.9	21.3	-1.4	+0.4	87
	4/1000	101.0	19.3	+0.7	-1.6	97
Thinwater	1/12000	99.9	21.1	-0.4	+0.2	100
	1/6000	99.2	21.3	-1.1	+0.4	105
	1/1000	99.2	21.0	-1.1	+0.1	99

All comparisons were made relative to test results of the untreated soils. Increase or decrease in density is given as a percentage of maximum dry density of the untreated soil; if the untreated soil had a maximum dry density of 100 pcf while the treated was 102 pcf, the percentage increase would be 2.0%. Increase or decrease in optimum moisture content is given as increase or decrease in actual percent of dry soil weight. Adjusted average SBV is the mathematical average of SBVs produced over a short range of moisture contents (centered on optimum) from a series of compacted specimens treated with the same additive and then adjusted relative to similar SBVs of the untreated soil. This procedure is shown more clearly in the following example, with data from Fig. 6:

Moisture content, %	Untreated SBV, psi	Treated SBV, psi
19	148	142
20	144	138
21	142	132
22	157	71
23	148	37
Mathematical Average:	148 psi	104 psi
Adjusted Average SBV:	148 psi/148 psi × 100% = 100%	104 psi/148 psi × 100% = 70%

Thus, this treated soil averaged about 70% of the SBV of the untreated soil.

In the results, there were specific cases where increases and decreases in density occurred with different concentrations of the same product. These varying effects in density could be caused by treatments, or they could also be attributed to irregularities in testing, i.e., testing procedure, equipment variations, representative soil samples, etc. While moisture-density tests have good repeatability under tightly controlled laboratory conditions, results cannot be expected to be repeated exactly for any given soil or treatment. Standard deviations of OMC and γ_d are often assumed as 1.0% and 2.0 pcf respectively. As will be shown in the Phase II study, average standard deviations of OMC and γ_d for all soils and treatment levels were 0.94% and 1.25 pcf respectively. For this preliminary compaction study, however, it was assumed that effectiveness of an additive must consist for the most part of an increase in density and decrease of OMC.

Summary - Compaction Tests

Table 17 presents a summation of the moisture-density tests of the twenty products, eight soils, and three treatment levels. Shown for each chemical are two effects: 1) a significant increase in maximum dry density, and 2) a significant decrease in optimum

Table 17. Summary of standard moisture-density test results.

Product	Chemical Concentration gals/gals Water	Increase in Standard Dry Density, %		Decrease in OMC, % Dry Soil Weight	
		0.5 to 1.5%	>1.5%	0.5 to 1.5%	>1.5%
Clapak	1/1000	A, Dr, L*, M	C*	Dr*	C*
	10/1000	A	C, Dr, L	G	C
	20/1000	A, L	C, Dr	Dr, G	C
Claset	1/1000	≠	Dr, D, M	A, D, G, M	Dr
	10/1000	--	Dr, D	--	Dr, D
	20/1000	--	C, Dr, D	A, Dr, D, G	--
Coherex	10/1000	A, C, Dr, D, M	--	Dr, S	A
	143/1000	--	M	A, Dr, D, S	C
	250/1000	--	Dr, M	S	A, C, Dr, D, M
Fr-20	0.5 gm/1000 ml	C	Dr	--	--
	1 gm/1000 ml	C, Dr	--	--	--
	2 gm/1000 ml	Dr	--	A	--
Kelpak	1/1000	D, M	C	A, C	--
	10/1000	Dr, L	C	--	--
	20/1000	C, Dr, M	--	A, C	--
Paczyme	1/1000	--	D	L	--
	2/1000	D, L, S	--	--	--
	4/1000	--	--	A	--
Pen-E-Pac	0.5/1000	A, C	Dr	-- M	--
	1/1000	A, D, S	C, Dr	D	--
	3/1000	A, C, D, L	Dr	C, Dr	D
Petro-S	100/1000	M	A, C, Dr, D, L	A, L, S	C, D, G, M
	200/1000	D, M	A, C, Dr, L	C, Dr, L	D, S, M,
	300/1000	S	A, C, Dr, D, L	--	A, C, Dr, D, M, G, L, S
PVO X-1000	50/1000	A	--	A, D, G	--
	100/1000	--	--	--	G
	150/1000	--	--	G	--
PVO X-2100	50/1000	A, L	C	A, C	G
	100/1000	L	C	A, C	--
	250/1000	--	--	A	--
Road Packer	1/1000	C, L	Dr, M	C, Dr	--
	5/1000	D, M	Dr	A, C	--
	10/1000	D	Dr	Dr, G	--
SA-1	1/1000	M	C, D	A, D, S, M	G
	10/1000	M	C, Dr	Dr, G, M	C
	20/1000	L, M	C, Dr	C, D	Dr, G
SC-518	1/1000	A, D	C, Dr, L	--	--
	5/1000	--	A, C, Dr, D, L	C, S	Dr
	10/1000	M	A, C, Dr, D, L	Dr, D, S, M	--
SS-13	1/1000	L, M	A, Dr	D, G, M	--
	2/1000	M	A, Dr	--	--
	4/1000	A, Dr, L, S, M	--	D, G	S
Terra-Krete 1	1/1000	--	--	--	L
	10/1000	D, G	--	A	--
	20/1000	C	--	Dr	--
Terra-Krete 2	1/1000	--	--	A	L
	10/1000	--	--	--	--
	20/1000	--	--	G	--
Thinwater	1/12000	A, D, M	C	A, D	--
	1/6000	C, M	--	A, G	--
	1/1000	C, D, M	Dr	--	--

(Continued)

Table 17. Continued.

Product	Chemical Concentration gals/gals Water	Increase in Standard Dry Density, %		Decrease in OMC, % Dry Soil Weight	
		0.5 to 1.5%	>1.5%	0.5 to 1.5%	>1.5%
RD-4480	1/1000	--	--	--	--
	5/1000	--	--	M	--
	10/1000	--	--	--	--
RD-4481	1/1000	M	--	M	--
	5/1000	M	--	M	--
	10/1000	--	--	--	--
RD-4482	1/1000	--	--	M	--
	5/1000	--	--	M	--
	10/1000	--	--	M	--

*Initials represent the following soils: A = AASHO, C = Cecil, Dr = Decatur, D = Dundee, G = Grundite, L = Loring, S = Shelby, M = Monona

≠Dash indicates no improvement or decrease in standard density, and no improvement or increase in OMC.

moisture content. As previously stated, increase in density is shown as a percentage increase above that of maximum density of the untreated soil, while decrease in optimum moisture content is shown as the decrease in actual percent of dry soil weight. An effective compaction aid is here defined as one that increased maximum dry density, γ_d, and decreased optimum moisture content, OMC, over 0.5%. Thus, Table 17 shows the relative effectiveness of each product with a variety of soils.

The following can be concluded from the compaction results:

1. Clapak appeared effective with the Decatur and Cecil series, primarily kaolinitic clays, producing up to a 3.5% increase in γ_d and 1.5% reduction in OMC. The 1/1000 concentration produced 100% of untreated γ_d of the Cecil series at 4.0% lower moisture content.
2. Claset was most effective in the Decatur series (kaolinitic) with a 4.0% increase in γ_d, but only 0.7% reduction in OMC: 100% of untreated γ_d was achieved at 3.7% lower moisture. Good improvement was also shown for the Dundee series, an acidic montmorillonite clay. Scattered improvements with various concentrations of treatment were also noted with the Monona, a basic montmorillonitic clay series soil.
3. Coherex was somewhat effective with the Decatur, AASHO, and Monona series (primarily kaolinitic, illitic, and basic montmorillonitic clays, respectively). Coherex proved most successful in reduction of OMC, the 250/1000 concentration producing 100% untreated γ_d of the Decatur soil at 4.6% lower moisture content.
4. FR-20 was of little value in any soil. Some slight improvement in γ_d was noted in the Cecil and Decatur series (kaolinitic), but generally, FR-20 had a detrimental effect on compaction of all soils.
5. Kelpak was of little value except in increasing γ_d of the Cecil series (a kaolinitic clay).
6. Paczyme was of little value in any soil except to increase γ_d of the Dundee (acidic montmorillonite).
7. Pen-E-Pac was somewhat effective in the Cecil, Dundee, and Decatur soils (kaolinitic and acidic montmorillonitic clays). Most improvement was noted in Decatur, with 4.8% increase in γ_d, but little change in OMC. The 3/1000 concentration produced 100% untreated γ_d of the Cecil series at 3.5% lower moisture content.
8. Petro-S appeared effective as a compaction aid, increasing γ_d in seven of the eight soils, while lowering OMC for all soils. It was most effective in kaolinitic Decatur with a 5.9% increase in γ_d and 3.5% reduction in OMC; 300/1000 concentration achieved 100% untreated γ_d at 5.6% lower moisture. With the Grundite (highly illitic) clay, Petro-S significantly reduced OMC but contributed no increase in γ_d.

9. PVO X-1000 decreased OMC of the illitic Grundite but with no improvement in densification.
10. PVO X-2100 appeared somewhat more effective than X-1000, showing increased γ_d with the kaolinitic Cecil series and some improvement of OMC of the illitic Grundite.
11. Road Packer was somewhat effective, through improvement of γ_d only, with the kaolinitic Decatur and acidic montmorillonite Monona series (the latter at low concentration only).
12. SA-1 appeared effective in the Cecil, Decatur, and Dundee series,(kaolinitic and acidic montmorillonitic clays). SA-1 generally showed scattered improvement in γ_d and/or OMC, depending on concentration used. The 20/1000 concentration achieved 100% untreated γ_d of Decatur at 3.1% lower moisture content.
13. SC-518 produced good γ_d increases in five of the seven soils tested, but appeared limited in improvement of OMC. Greatest γ_d improvements were in the kaolinitic and acidic montmorillonitic clays. Significant increases in OMC occurred in the illitic AASHO and acidic montmorillonite Loring. SC-518 was most effective with the kaolinitic Decatur series, producing a 6.0% increase in γ_d and 2.2% reduction in OMC; 5/1000 concentration achieved 100% untreated γ_d at 4.7% lower moisture content.
14. SS-13 increased γ_d in the AASHO and Decatur (illitic and kaolinitic clays), while significantly reducing OMC in the Shelby (basic montmorillonite) only.
15. Terra Krete #1 was basically an ineffective treatment in all eight soils.
16. Terra Krete #2 decreased γ_d in all soils and was an ineffective compaction aid.
17. Thinwater showed good improvement, in densification only, with the kaolinitic Cecil and Decatur series.
18. RD-4480 was tested only with the Monona and Shelby series (acidic montmorillonite clays). No improvements were obtained in either γ_d or OMC.
19. RD-4481 was also tested only with the Monona and Shelby series. Other than a slight improvement in γ_d at the lowest concentration in the Monona, RD-4481 was ineffective to deleterious for both soils.
20. RD-4482 was tested only with the Monona and Shelby series and showed no improvement in moisture-density for either.

Only two of the treatments, Petro-S and SC-518, produced reasonably consistent improvement in γ_d and/or OMC for the soils tested. Relative effectiveness of these treatments, however, was dependent on soil type. For example, both products showed greatest effectiveness in the kaolinitic Decatur and provided little improvement in the acidic montmorillonitic Shelby series. For the other soils tested, both treatments produced relatively similar improvement in γ_d and OMC.

It is of interest to note the correlation of effectiveness whitin certain soil types, but the lack of correlation between product effectiveness and predominant clay mineral. For example, AASHO and Grundite are both predominantly illitic soils (Table 7), and yet, Petro-S increased γ_d of the AASHO while reducing γ_d of the Grundite. If the other products are analyzed in a similar manner, similar trends are noted. No products exhibited totally consistent effectiveness with soils of similar clay mineralogy. As a further example, Claset may be effective with the Dundee but not the Loring, and with the Decatur but not the Cecil. Comparison of these clays' mineralogy shows that both Dundee and Loring soils are predominantly montmorillonitic clays with some illite present in the Dundee. However, Claset was not significantly effective in the predominantly illitic soils. Decatur and Cecil series are both predominantly kaolinitic and contain smaller amounts of illite with some vermiculite detectable in the Decatur, and gibbsite in the Cecil. Therefore, although clay mineralogy appears to be important, there is only limited conclusive evidence correlating predominant clay minerals to product effectiveness.

Table 18 shows the number of products, at various treatment levels, which produced good to significant improvement in γ_d and/or OMC for any soil. From this table it can be seen that kaolinitic Decatur and Cecil series had the largest number of increases in density greater than 1.5% while acidic montmorillinitic Shelby and illitic Grundite had the least. The number of similar reductions in OMC did not vary significantly between the different soils.

Table 18. Clay content versus effectiveness of chemical products of each soil series.

Soil	Percent Clay (< 0.005 mm)	Number of Products that Increased γ_d > 1.5%	Number of Products that Decreased OMC > 1.5%
Decatur	58.0	24	6
AASHO	52.5	6	3
Cecil	47.0	18	6
Shelby	40.0	0	3
Grundite	39.0	0	6
Dundee	29.7	9	6
Loring	27.0	7	3
Monona	21.0	3	4

The soils of Table 18 are listed in decreasing order of percentage of 5μ clay-size particles. It is of interest to note the trend between number of increases in density greater than 1.5% and percentage of clay, i.e., the higher the percentage of clay, the greater the number of density improvements. For example, Decatur soil had the highest percentage of clay and also produced the most significant increases in density. If the AASHO, Shelby, and Grundite soils are disregarded, the number of treatment levels increasing density for any given soil will correlate exactly with percentage of clay-size particles. As discussed previously, a correlation between clay content and product effectiveness would be expected since chemical compaction aid effectiveness should maximize with the clay-size particles. An effective compaction aid should alter surface activity to improve compactability, and would be more pronounced on a soil where surface and electrical forces dominate, i.e., a clay soil.

AASHO, Shelby, and Grundite soils did not show the above correlation between clay content and number of increases in density, which may be due to the large clay aggregations initially present in these three soils. It is believed that effectiveness of the chemical compaction aids was hindered by the clay aggregations. Of the three soils, AASHO showed the most improvement in density, which was probably attributable to the high clay content (it is the second highest percentage clay of all soils tested). No increases in density greater than 1.5% were noted in the treated Shelby or Grundite soils.

In summary, product effectiveness seems to be related to a soils percentage clay and mineralogy. Effectiveness, however, does not appear as a direct relationship to a predominant clay mineral, but more possibly, to the "mixed" mineralogy of the individual soil. It is believed that chemical properties of the soils (pH, cation exchange capacity, etc.) play a key role in the M-D effectiveness of products with any given soil. This would indicate that most chemical products are surfactants, or contain surfactants, since such chemicals alter the surface chemistry of most soils, changing the electrostatic forces thereon and reducing surface tension of the pore water.

The preceding discussion, summary, and analysis illustrate effectiveness of the products in increasing density or reducing optimum moisture content of various soils. While this approach provides a generalized type of improvement expected with a particular product, it does not evaluate or rate the product's total M-D effectiveness on all soils. The following is a means of further evaluating the potentials of increased density and decreased optimum moisture content due to the various products.

A quantitative analysis was made by deriving a formula for testing universality of the beneficial effects of the chemicals. It was

felt that a product's performance rating should include:
1) number or percent of soils that benefit from the product,
2) extent of the beneficiation, and 3) the extra cost involved with the treatment. For this purpose, the extent of beneficiation was separated into two categories: Category I, 0.5 to 1.5% increase in γ_d or reduction in OMC, and category II, more than 1.5% increase in γ_d or reduction in OMC. A beneficiation amounting to less than 0.5% was regarded as totally insignificant.

Since only limited cost data were available for the chemicals, it was assumed for purposes of this analysis that the manufacturer's recommendations of treatment levels were within economical bounds. Since changing treatment level would not appreciably change handling or distribution costs, a geometric concentration scale was adopted whereby doubling or halving the amount of chemical was assumed to change the total cost by a factor $\sqrt{2}$. By this relationship then, reducing the amount of chemical by a factor of 10 was assumed to reduce cost by $\sqrt{10} = 3$.

Reduction of optimum moisture content is beneficial in dry climates and detrimental in wet climates; this factor was therefore incorporated as a ± term in the evaluation formula:

$$\text{Relative Effectiveness} = \frac{F_1 + 2F_2}{\sqrt{(C/C_r)}} \pm \frac{F_3 + 2F_4}{\sqrt{(C/C_r)}} \qquad (9)$$

where:

F_1 is the numerical fraction of soils tested showing category I (0.5 to 1.5%) improvement in density.
F_2 is the analogous fraction showing category II (>1 5% improvement in density.
F_3 is the analogous fraction showing category I decrease in OMC.
F_4 is the analogous fraction showing category II decrease in OMC.
C is the concentration used.
C_r is the approximate recommended treatment level.

Table 19 presents preliminary effectiveness ratings obtained using the above equation. The formula evaluation allows the chemicals to be grouped on the basis of their effects on soil compaction and to be arranged in decreasing order of rating within the groups. Averaged ratings were used in each case because in a field situation, considerable latitude may exist in amount of chemical actually introduced. The highest rating possible, using the approximate manufacturer's recommended application rate, was 2.0; higher ratings are possible if a lower application rate was effective. The rating also weighs heavily on effectiveness with a wide variety of soils regardless of their clay mineralogy.

Table 19. Preliminary effectiveness ratings of various chemical compaction aids.

Clapak	2.37		1.19	PVO X-1000*	0.24		0.71
	0.88		0.38		0.00		0.33
	0.53		0.35		0.00		0.14
	1.26	±	0.64		0.08	±	0.39
Claset	1.98		2.37	PVO X-2100*	0.94		0.94
	0.50		0.50		0.50		0.33
	0.53		0.35		0.00		0.11
	1.00	±	1.07		0.48	±	0.46
Coherex	2.36		1.89	Road Packer	1.68		0.56
	0.25		0.63		0.50		0.25
	0.38		1.04		0.27		0.18
	1.00	±	1.19		0.81	±	0.33
FR-20*	0.71		0.00	SA-1	1.98		2.37
	0.33		0.00		0.63		0.63
	0.17		0.17		0.53		0.53
	0.40	±	0.06		1.04	±	1.18
Kelpak	1.58		0.79	SC-518	2.24		0.00
	0.50		0.00		1.25		0.50
	0.27		0.18		0.97		0.35
	0.78	±	0.32		1.49	±	0.28
Paczyme*	0.47		0.24	SS-13	1.06		0.53
	0.33		0.00		0.63		0.00
	0.00		0.12		0.44		0.35
	0.27	±	0.12		0.71	±	0.29
Pen-E-Pac	0.88		0.18	Terra-Krete 1*	0.00		1.05
	1.00		0.13		0.33		0.17
	0.43		0.29		0.12		0.12
	0.77	±	0.20		0.15	±	0.45
Petro-S	1.77		1.94	Terra-Krete 2*	0.00		1.58
	1.13		1.13		0.00		0.00
	1.22		1.63		0.00		0.12
	1.37	±	1.57		0.00	±	0.57
				Thinwater	0.88		0.35
					0.53		0.53
					0.76		0.00
					0.56	±	0.29

---

*Tested with 6 soils only.

Note: Concentrations are given in Table 17. In most cases, the middle concentration was that recommended by the manufacturer.

The ten chemicals thus evaluated to be most effective for allowing increased compacted density, were rated as follows; the dashed line represents an arbitrary cutoff of Phase I products for evaluation in Phase II:

SC-518	1.49
Petro-S	1.37
Clapak	1.26
SA-1	1.04
Claset	1.00
Coherex	1.00
------------------	------
Road Packer	0.81
Kelpak	0.78
Pen-E-Pac	0.77
SS-13	0.71

The ten chemicals most effective at reducing optimum moisture content are shown below; asterisks indicate appearance in this group as well as in the preceding group:

*Petro-S	1.57
*Coherex	1.19
*SA-1	1.18
*Claset	1.07
*Clapak	0.64
Terra-Krete 2	0.57
------------------	------
PVO X-2100	0.46
Terra-Krete 1	0.45
Road Packer	0.33
Kelpak	0.32

While nearly all of the chemicals most effective for increasing density also are effective at reducing optimum moisture content, as predicted from the discussion of mechanisms, the highest rated chemical based on density, SC-518, had little effect on optimum moisture content. It was replaced in the listing by Terra-Krete 2.

It also should be noted that some of the high ratings relate in part to effectiveness of the chemical at treatment levels far less than recommended by the manufacturer. The following are relative density effectiveness ratings for low chemical concentrations; the asterisk indicates appearance in this as well as in the group showing increased compacted density:

*Clapak	2.37
*Coherex	2.36
*SC-518	2.24
*Claset	1.98
*SA-1	1.98
*Petro-S	1.77
------------------	------
Road Packer	1.68
Kelpac	1.58
SS-13	1.06
PVO X-2100	0.94

These are essentially the same chemicals previously noted as most effective, but in somewhat different order.

In a like manner, the following are relative OMC effectiveness ratings for low chemical concentrations:

*Claset	2.37
*SA-1	2.37
*Petro-S	1.94
*Coherex	1.89
Terra-Krete 2	1.58
*Clapak	1.19
------------------	------
Terra-Krete 1	1.05
PVO X-2100	0.94
Kelpak	0.79
PVO X-1000	0.71

The five asterisked chemicals are once again essentially the same as the previously noted most effective in density, but are in different order. In addition, the highest noted chemical based on density, SC-518, had little effect on OMC at low concentrations and was again replaced in the listing by Terra-Krete 2.

The following six chemicals appeared to rate highest by this quantitative procedure:

Category I: Increase density or cause a moderate decrease in optimum moisture content: SC-518, Clapak.

Category II: Increase density and significantly decrease optimum moisture content: Petro-S, SA-1, Claset, Coherex.

Quantitative performance ratings (Table 18) and product effectiveness evaluation (Tables 9 through 17) correlated well. Products that produced consistent increases in density or consistent reductions in OMC rated high with their respective performance ratings. Thus, Petro-S, SC-518, Clapak, Claset, SA-1, and Coherex indicated promise as M-D compaction aids for a variety of fine-grained soils.

Summary - Spherical Bearing Tests

In a 1958 paper on the structure of compacted clay, Lambe[49] postulated that increasing moisture content during compaction tends to increase particle repulsion, thereby permitting more orderly alignment of soil particles, i.e., parallel particle orientation or dispersion. Parallel particle alignment increases during compaction, maximizing on the wet side of optimum moisture. A soil with a high degree of parallel alignment is much weaker than soil in a flocculated state. Thus, soil strength significantly decreases when compacted at higher than optimum moisture content. This trend was found in SBV data in this investigation: the SBV generally decreased with increasing moisture content, dropping off rapidly after OMC due to the more rapid change in soil structure (dispersion) when compacted on the wet side of OMC. Typical SBV data are shown in the example of Fig. 6.

SBVs for effective compaction aids were generally found to be lower than SBVs of the chemical products not effective in improving density. As previously discussed, an effective compaction aid should reduce sliding particle friction through a reduction of normal force, reduce pore fluid surface tension, and/or increase particle repulsions to increase compactability of a soil. Any of these alterations should reduce particle interaction and decrease soil strength. Thus, a chemical that improved compactability of a soil would also be expected to reduce the strength immediately after compaction. This was reflected in lower SBVs with effective compaction aids and decreasing SBVs with increasing concentration of chemical product.

Another factor that may account for lower SBVs with effective compaction aids was the method in which SBVs were averaged. Since SBV drops off rapidly after OMC, adjusted average SBV is dependent on OMC of a given treatment. Thus, when the M-D curve shifted to the left, the adjusted average SBV was reduced. The opposite occurs when the M-D curve shifted to the right. Therefore, an effective compaction aid that shifted the M-D curve to the left also reduced adjusted average SBV. This could be seen with Petro-S, Coherex, and SA-1 treatments; the three products most effective in reducing optimum moisture content were also the products attaining lowest SBV. Petro-S had the lowest SBV of all treatments.

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[49] T. W. Lambe, "The Structure of Compacted Clay." J. ASCE, 84: SM2 (1958), pp. 1-34.

SBV mean and standard deviation for all treated soils are shown in Table 20 for each chemical and concentration. Concepts earlier discussed in this section can be seen in the data. Clapak, Claset, Coherex, Petro-S, and SC-518, all effective compaction aids, had decreased SBVs with increasing concentrations, while RD-4480, FR-20, Pen-E-Pac, Road Packer, and Thinwater, all ineffective compaction aids, had generally increased SBVs with increasing concentrations of product. No correlations were noted with the standard deviations.

Table 20 shows the relative "immediate" strength that could be anticipated from a given product when introduced into, and compacted with, various types of fine-grained soils. It must be remembered that no curing time was permitted with the treatments so the SBV shown is not an indication of potential final strength that might be achieved with a particular product.

Shear Parameters, Shear Strength, Bearing Capacity

The Iowa Bore Hole Shear Test (BHST)[50] was adapted for use with 1/30 cu ft Proctor-size specimens for determination of cohesion (c) and angle of internal friction (ϕ) of six of the soils, untreated and treated, with a number of the chemical compaction aids, at concentration levels indicative of varying M-D benefits. The bulk of the chemicals was evaluated with the Monona and Shelby series since supply of the other six soils was extremely limited following completion of initial M-D and SBV studies. Preparation of chemical concentrations and compaction processing was identical to the methods previously described.

Specimens were molded at less than, equal to, and greater than OMC as based on the previously determined M-D relations, variations on either side of OMC being up to about 3% moisture. After molding, each specimen, still in the mold, was sealed in Saran Wrap and placed in a 75 ^{0}F constant temperature and 100% relative humidity room for a period of about 24 hours. Upon completion of moist curing, each specimen was weighed and prepared for BHST testing by centrally boring a three-inch diameter hole through the specimen while still in the mold.

The Iowa BHST apparatus, Fig. 10, consists of three basic units: a shear head comprising of two opposing expandable corrugated plates, a pulling device to induce shear, and a console supplying constant normal pressure to the shear head. As adapted for this study the test was conducted in the following manner:

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[50] R. L. Handy and N. S. Fox, "A Soil Bore-Hole Direct-Shear Test Device," Highw. Res. News, No. 27 (1967).

Table 20. Mean and standard deviation of adjusted average spherical bearing values for each chemical treatment.

Chemical Product	Concentration, gal./gal. water	Mean, %	Standard Deviation, %
Clapak	1/1000	90.4	8.9
	10/1000	88.9	19.6
	20/1000	81.4	21.4
Claset	1/1000	96.7	16.3
	10/1000	83.0	13.3
	20/1000	83.7	18.7
Coherex	100/1000	91.3	15.6
	143/1000	87.0	18.7
	250/1000	70.6	19.8
FR-20	0.5 g/1000	90.7	7.7
	1 g/1000	100.8	18.8
	2 g/1000	96.6	8.3
Kelpak	1/1000	87.4	17.2
	10/1000	94.7	12.2
	20/1000	86.6	10.3
Paczyme	1/1000	99.2	6.5
	2/1000	95.0	7.8
	4/1000	84.8	15.9
Pen-E-Pac	0.5/1000	94.4	12.7
	1/1000	99.0	13.3
	3/1000	96.6	19.6
Petro-S	100/1000	82.6	14.2
	200/1000	76.5	23.5
	300/1000	71.3	32.7
RD-4480	1/1000	99.0	28.3
	5/1000	99.5	19.1
	10/1000	105.5	0.7
RD-4481	1/1000	93.5	10.6
	5/1000	100.0	1.4
	10/1000	80.0	12.7
RD-4482	1/1000	113.0	11.3
	5/1000	103.5	2.1
	10/1000	101.1	2.8

Table 20. (Continued).

Chemical Product	Concentration, gal./gal. water	Mean, %	Standard Deviation, %
PVO X-1000	50/1000	92.5	5.0
PVO X-2100	50/1000	90.2	5.2
	100/1000	79.3	20.0
Road Packer	1/1000	94.5	11.5
	5/1000	84.5	13.1
	10/1000	93.8	18.2
SA-1	1/1000	92.3	14.9
	10/1000	78.7	20.6
	20/1000	78.7	23.8
SC-518	1/1000	106.7	13.8
	5/1000	96.4	12.8
	10/1000	92.3	16.1
SS-13	1/1000	100.1	13.2
	2/1000	99.9	11.9
	4/1000	93.6	8.6
Terra Krete #1	0.5/1000	89.2	15.9
	10/1000	90.4	14.8
	20/1000	84.2	15.0
Terra Krete #2	10/1000	97.7	5.1
Thinwater	1/12000	98.4	12.4
	1/6000	91.3	16.0
	1/1000	103.5	6.4

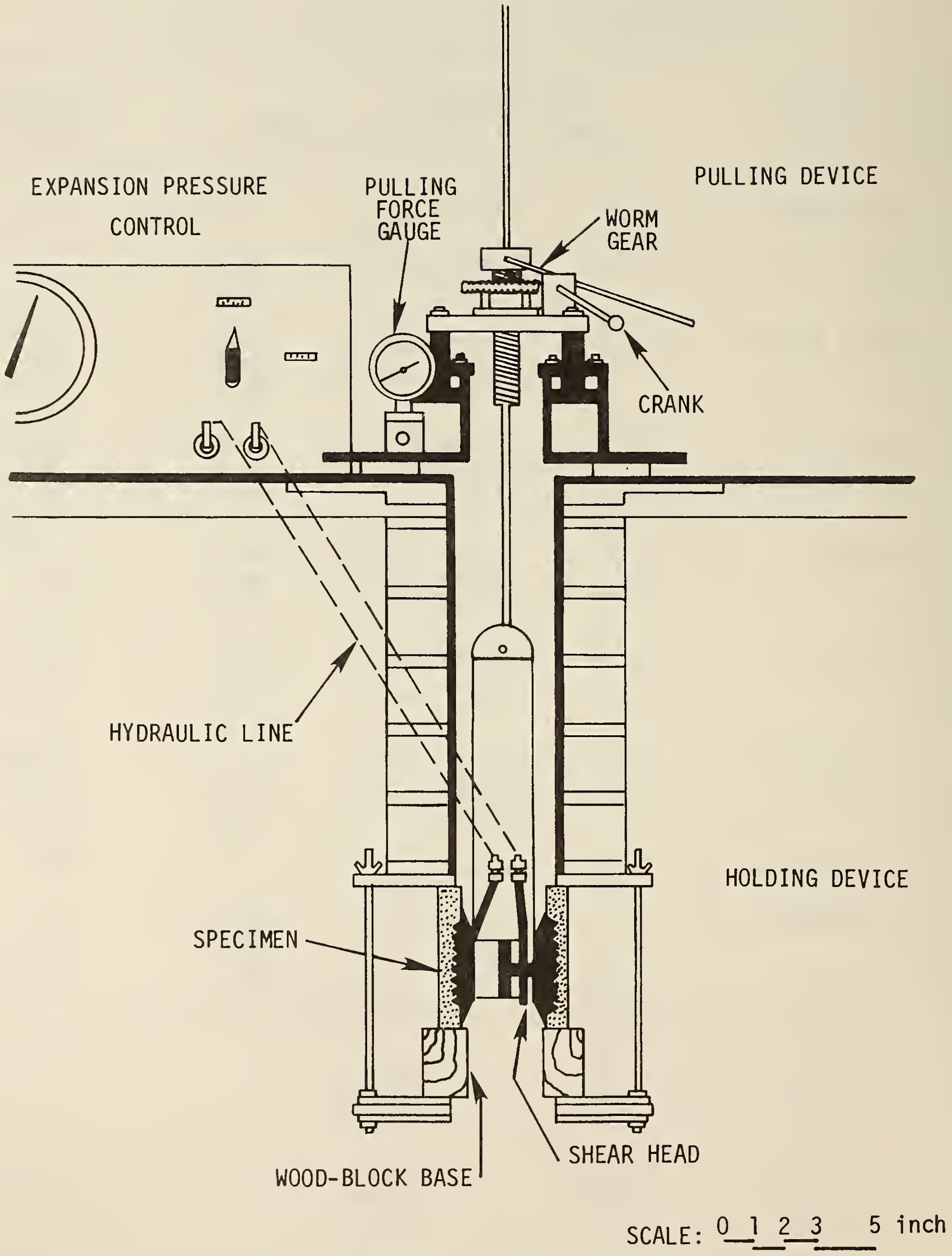

Fig. 10. Schematic of Iowa Bore-Hole Shear Test (BHST) device as adapted for laboratory use with 1/30 cu. ft. specimens.

1. The mold containing the bored specimen was clamped into a holding device which resisted all soil, mold, or other apparatus movements other than that created by the shear head within the soil.
2. The shear head was inserted into the bored hole of the soil specimen, and the shear head plates were forced outward against the circumference of the hole thereby exerting a controlled contact or normal (σ) pressure against the soil. To allow for consolidation, σ was maintained for a period of five minutes prior to shearing.
3. The shear head was axially pulled up the hole, causing shear of the soil in contact with the shear plates. Pulling rate was controlled by a crank, worm gear, and clamping arrangement, and shear deformation rate was measured by counting the number of turns of the crank per unit of time since one turn equaled 0.001 in. displacement. Pulling force was measured by means of a gauge on the hydraulic pulling system, and shear strength (τ) was determined as the maximum pulling force divided by contact area of the shear plates.
4. After a maximum pulling force was attained, it was backed off, the normal pressure was increased, and the process repeated several times, producing a Mohr-Coulomb failure envelope for determination of c and ϕ.
5. The diametrically opposed shear head plates were then retracted and cleaned, and the specimen was turned 90° for duplication of the test process and results (steps 1 through 4).

Readings of expanding and pulling forces were expressed in terms of shear stress (τ) psi, and normal stress (σ) psi. These values were then plotted to produce a Mohr-Coulomb failure envelope. A "best fit" line was drawn for each data set and subsequently the angle of internal friction (ϕ) and cohesion (c) were obtained.

Characteristics of the BHST test results are best described by illustrating a typical test. Figure 11 shows a BHST data sheet and Mohr-Coulomb failure envelope for a compacted specimen of AASHO soil treated with Petro-S at a chemical concentration of 100/1000. A line best fitting the points produced $c = 4.3$ psi and $\phi = 41.5^{\circ}$. As shown in Fig. 11, the failure envelope plots nearly a straight line. The first outlying point is suspect for incomplete seating of shear plates. With higher normal stresses, the failure envelope is slightly curved, caused by partially or imperfectly drained pore pressure. In this example, the last point lies above the solid straight line. When this last point is extended through the origin, the dashed line crosses the visually-fitted failure envelope. The normal stress at which the lines cross each other probably indicates a preconsolidation load.

PROJECT: CHEMICAL COMPACTION AIDS
CIVIL ENGINEERING DEPARTMENT SITE: AASHO HOLE N/A
IOWA STATE UNIVERSITY SAMPLE 3 DEPTH N/A
SOIL ENGINEERING LOCATION: TREATED w/PETRO-S 100/1000
HANDY HOLE-PULLER TECHNICIAN YANG DATE 8/30/74
MOISTURE CONTENT: 13.9% DRY UNIT WEIGHT 115.6 lb/cu.ft.

TRIAL		1	2	3	4	5	6	7	8	RESULTS
γ_1	GAUGE	47	78	93	110	127	175			RUN #1
	psi	13.1	21.6	25.6	30	34.9	48.0			r: 0.9994
σ_1	GAUGE	57	75	92	113	135	184			c: 4.23 psi
	psi	15.1	20	24.1	29.6	35.0	47.9			ϕ: 41.21 deg
γ_2	GAUGE									RUN #2
	psi									r:
σ_2	GAUGE									c: psi
	psi									ϕ: deg

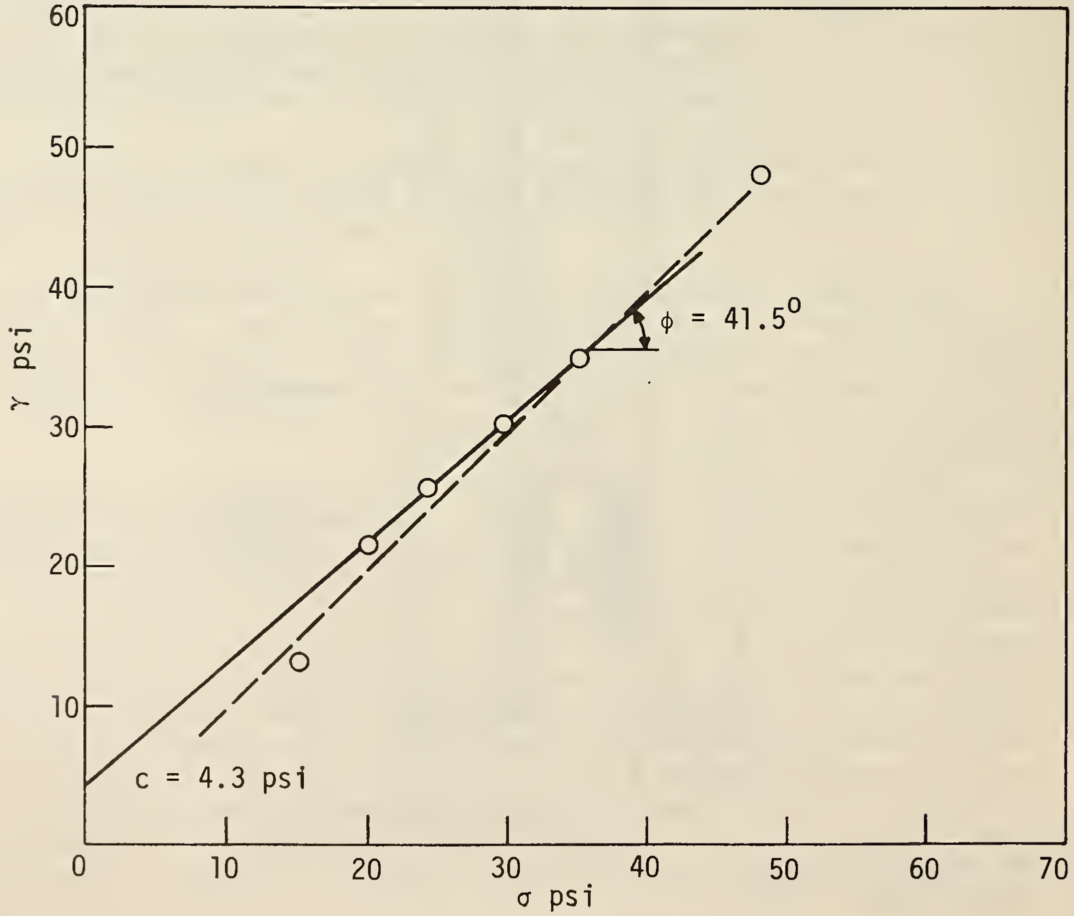

Fig. 11. A typical set of BHST data.

shear.[51] This relationship is

$$q_d = 1.3cN_c + 0.6\ rN_\gamma + \gamma D_f N_q \qquad (11)$$

where

N_c, N_γ, and N_q are dimensionless factors dependent on ϕ,
γ is soil unit weight
r is radius of a circular foundation
D_f is the surcharge or depth of foundation below the soil surface.

In local shear, Terzaghi modified Eq. (11) to include:

$$c' = 2/3\ c, \text{ and } \tan\phi' = 2/3 \tan\phi$$

With the type of testing conducted in this study, plus the assumption that the circular footing may represent a near direct soil contact with a tire, the second and third terms of Eq. (11) were negligible. Thus, the equation could be rewritten as

$$q_d = 1.3\ (2/3c)\ (N'_c) \qquad (12)$$

where N'_c is the reduced dimensionless bearing capacity factor dependent on the reduced angle of internal friction. Results of bearing capacity calculations from Eq. (12) were used for relative comparisons of effect of chemical treatment on the six soils.

Figures 12 and 13 graphically illustrate results of this shear parameter, shear strength, and bearing capacity study. A major portion of the analysis was conducted from similar graphs produced from the data for all untreated and treated soils used.

Table 21 presents actual values of cohesion (c), angle of internal friction (ϕ), bearing capacity (q_d), and shear strength (τ) of the untreated soil following 24-hour moist curing. The treated soils are presented as a percentage of the untreated soil under identical curing conditions. The data in Table 21 are averages of values determined at and above OMC, since $c - \phi$ values determined below OMC were exceedingly erratic, oftentimes due to hairline cracking of the specimens under the varying $\sigma - \tau$ stresses. In addition, it was assumed that more critical stability conditions of subgrade soils exist on the wet side of optimum. Average SBV values of the specimens are also presented in Table 21 but represent no curing (i.e. were determined immediately following compaction). All values of τ represent an average of those values determined at the normal stresses of 12 and 15 psi since (as may be seen from Fig. 13) variation of τ between these assumed σ's was quite small. The data thus reflect shearing strengths which might be anticipated with reasonable confining

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[51] K. Terzaghi and R. B. Peck, <u>Soil Mechanics in Engineering Practice</u> (New York: John Wiley and Sons, Inc., 1949), pp. 167-75.

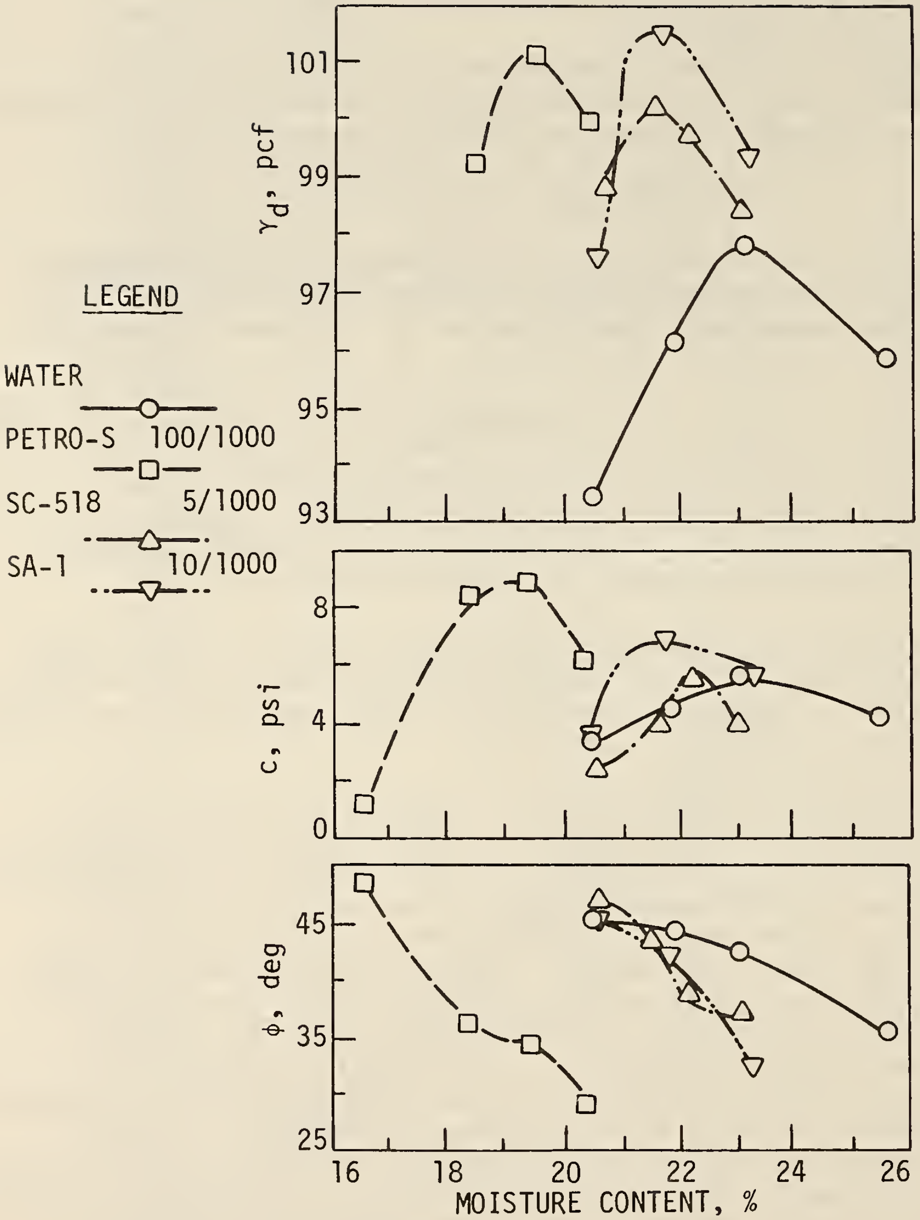

Fig. 12. Dry density, cohesion and angle of internal friction versus moisture content, untreated and treated Decatur series.

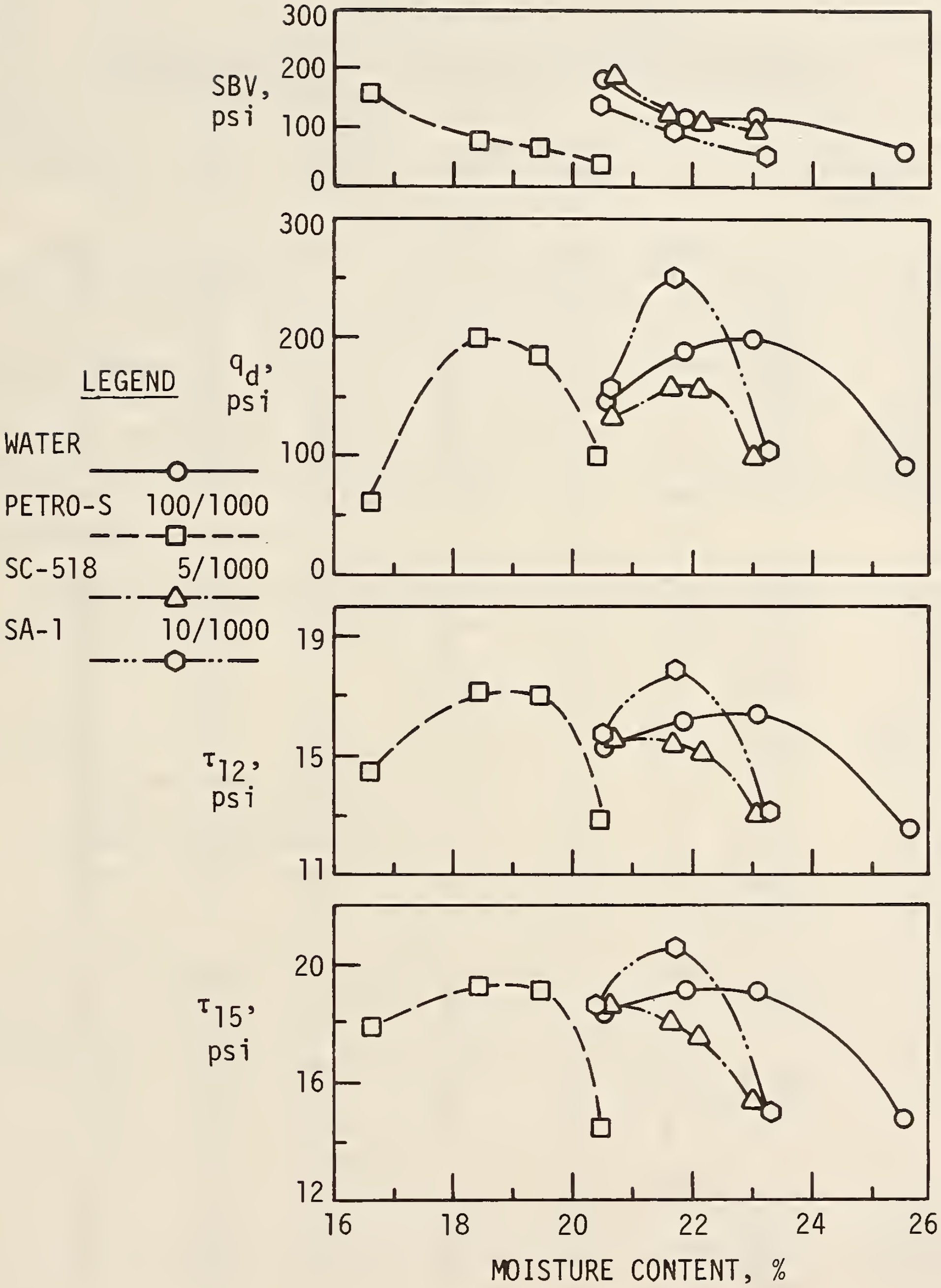

Fig. 13. Spherical Bearing Value, ultimate bearing capacity and shear strength versus moisture content, untreated and treated Decatur series.

Table 21. Cohesion, angle of internal friction, bearing capacity, shear strength, and spherical bearing value of treated soils as a percentage of untreated.*

Soil	Additive and Water Concentration, gals/gals		OMC	Dry Density, γ_d	Cohesion, c	Angle of Internal Friction, ϕ	Bearing, Capacity, q_d	Shear Strength, τ	Spherical Bearing Value, SBV
Monona	Water	--	(18.5)	(103.8)	(1.8)	(39.8)	(53)	(12.9)	(86)
	Petro-S	100/1000	84	100	226	96	208	114	105
	SC-518	5/1000	97	100	150	92	120	96	94
	SA-1	10/1000	95	100	129	102	140	110	145
	Thinwater	1/1000	99	101	164	96	160	104	100
	Claset	10/1000	97	100	208	94	177	109	99
	SS-13	2/1000	98	101	204	97	189	112	93
	Clapak	10/1000	98	100	155	92	133	101	117
	Coherex	100/1000	99	101	150	96	150	105	108
	Pen-E-Pac	3/1000	98	100	133	96	126	103	78
	Road Packer	1/1000	101	102	78	103	88	102	99
	PVO-X-2100	50/1000	97	100	102	102	114	103	101
	Kelpak	1/1000	100	101	143	101	151	107	93
Shelby	Water	--	(20.9)	(100.0)	(5.5)	(43.2)	(191.0)	(17.4)	(116)
	Petro-S	100/1000	93	100	122	100	125	107	78
	SC-518	5/1000	97	99	114	101	133	111	106
	SA-1	10/1000	100	99	94	97	99	99	97
	Thinwater	1/1000	100	100	173	96	164	121	116
	Claset	10/1000	102	100	97	98	88	98	73
	SS-13	2/1000	102	99	123	98	134	110	106
	Clapak	10/1000	102	99	109	94	102	101	78
	Coherex	100/1000	97	98	142	97	138	109	80
	Pen-E-Pak	3/1000	102	99	100	100	100	100	65
	Road Packer	1/1000	103	98	177	89	140	116	68
	PVO-X-2100	50/1000	102	99	72	99	78	95	103
	Kelpak	1/1000	99	98	155	94	154	115	83
	FR-20	5/1000	108	96	90	102	108	103	62
	RD-4480	1/1000	100	100	127	96	119	108	97
	RD-4481	1/1000	98	99	125	98	132	110	88
	RD-4482	5/1000	102	98	89	92	75	92	91
	RD-4480	1/1000	99	100	161	94	147	103	131
	RD-4481	1/1000	103	102	117	94	102	97	84
	RD 4482	5/1000	102	99	67	95	58	92	101
Grundite	Water	--	(21.2)	(101.0)	(6.0)	(29.0)	(92.5)	(13.4)	(105)
	Petro-S	100/1000	90	101	102	109	110	105	109
	SA-1	10/1000	99	100	112	99	103	104	104
AASHO	Water	--	(15.7)	(114.3)	(5.9)	(34.3)	(153.0)	(16.0)	(55)
	Petro-S	100/1000	89	101	107	109	107	104	145
	SC-518	5/1000	94	101	90	113	102	100	138
	SA-1	10/1000	96	101	136	99	113	107	104
	FR-20	5/1000	97	98	180	96	128	119	133
Dundee	Water		(19.1)	(102.1)	(4.8)	(37.8)	(111.5)	(14.7)	(98)
	Petro-S	100/1000	98	99	155	92	117	106	100
	SC-518	5/1000	97	99	128	108	166	118	112
	SA-1	1/1000	97	99	104	105	121	107	97
	Thinwater	1/1000	91	99	108	112	164	117	105
	Claset	10/1000	94	100	106	103	114	105	98
	SS-13	2/1000	96	102	78	109	101	101	105
Decatur	Water	--	(23.1)	(97.9)	(5.1)	(40.0)	(164.5)	(16.3)	(94)
	Petro-S	300/1000	83	103	144	79	82	96	73
	SC-518	5/1000	95	104	89	96	72	92	99
	SA-1	10/1000	93	102	125	98	117	105	82
	Thinwater	1/1000	92	102	77	111	106	103	112
	Claset	10/1000	93	102	147	90	107	105	82
	SS-13	2/1000	98	102	79	109	97	102	70

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*Note. Values in parentheses are actual values of OMC (% dry soil weight), γ_d (pcf), c (psi), ϕ (degrees), q_d (psi), τ (psi), and SBV (psi) of the untreated soils.

A second method for determining c and ϕ involved fittinging values of σ and τ into a Mohr-Coulomb failure envelope as a linear model, using a linear regression program adapted to a Hewlett-Packard model 9100B calculator. By obtaining a linear regression, the correlation coefficient, r, of the linear relationship between the variables of normal and shear stresses (Fig. 11) was determined as 0.9994, and c and ϕ were calculated as 4.2 psi and 41.2°, respectively. In all data sets, correlation coefficients were greater than 0.9.

Shear Test Results. The BHST is essentially analogous to a consolidated drained shear test, depending on consolidation time and rate of shearing. In this study, 5 min and 0.120 in./min were utilized for consolidation time and shearing rate, respectively. Conditions of partially drained and/or undrained shear may occur, depending on whether induced pore pressure can dissipate. Pore pressure measurement seemed inappropriate herein, considering the high clay-content, fine-grained soils that were used. Thus, shear strength is on a total stress basis, and refers to a peak shearing resistance.

Shear strength of the treated and untreated soils at a particular normal stress was determined from the Coulomb equation,

$$\tau = c + \sigma \tan \phi \qquad (10)$$

in which

τ denotes shear strength, psi
c denotes cohesion, psi
σ denotes normal stress, psi
ϕ denotes the angle of internal friction, degrees.

In order to evaluate shear strength of untreated and treated soils, it was necessary to calculate a value of normal stress potentially acting at a significant point within a subgrade soil mass. For highways, the legal single axle load in most states ranges between 18,000 to 20,000 lb, implying that a load on one set of dual tires will be in the vicinity of 9,000 lb. For conventional truck tires, contact pressures were assumed in the range of 60 to 90 psi. Thus, pressures normally transmitted to the top of a subgrade at an assumed 15 in. depth below the surface are reduced to a range of about 12 to 15 psi as based on Boussinesq analysis. Shear strengths were therefore determined for the assumed normal stresses of 12 and 15 psi and were calculated on the basis of the shear parameters determined by BHST.

Ultimate bearing capacity (q_d) may be defined as the maximum load per unit area which a soil can support without rupture. In order to compare effects of the chemical aids on bearing capacity, q_d was determined by Terzaghi's equation for circular footings under local stresses and within reasonable construction limits of moisture content, particularly where chemical concentrations are added on the job site and where moisture contents have a habit of running above OMC.

Also to be noted from Table 21, c values vary from 67 to 226% of the untreated soils. Friction angles of the chemically treated soils ranged from a low of 79% to a high of 113% of the untreated ϕ angles. Bearing capacity, q_d, of the treated soils ranged from about 58% to over 200% of the untreated soil bearing capacities. Shearing strengths varied from 92% to 121% of the untreated τ's. Spherical bearing values varied from 62% to 145% of the untreated SBV's. Performance of each treated soil, relative to the untreated soil, could thus be evaluated in the categories of increase in τ and q_d, as well as the comparative relationship of $\tau - q_d$, after 24 hours moist curing versus SBV immediately following compaction.

Summary. Previous studies by Olson and Daniel[52] and by Diamond et al.[53] have illustrated that variations of moisture content during compaction of fine-grained soils cause significant changes in soil shear parameters and strength. In general, as moisture content increases, cohesion increases, reaching a peak at or near optimum moisture content, then decreasing with additional moisture. The same changes in moisture content gradually decrease the angle of internal friction. However, the highest density does not necessarily yield the highest strength, which suggests that strength of a compacted soil is not solely related to either density or tightness of the mineral skeleton.

The above characteristics have been confirmed in this study and were illustrated for untreated and chemically-treated Decatur series soil (Fig. 12 and 13). However, due to the combined effects of mineralogy and chemicals, variations of the preceding characteristics were noted with (1) each soil and its respective treatments, or (2) with each chemical when applied in the six soils. For example, Figs. 12 and 13 illustrate that maximum q_d and τ occurred at about OMC of the untreated and 10/1000 SA-1 treated Decatur, and at less than OMC with the 100/1000 Petro-S treatment. Maximum q_d of the 5/1000 SC-518 treatment developed at about OMC of the mix, yet maximum τ was observed at less than OMC.

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[52] R. E. Olson and D. E. Daniel, "Stress-Strain Properties of Compacted Clays." J. Geotech. Eng. Div. ASCE, No. GT10 (Oct. 1974).

[53] S. Diamond, C. W. Lowell, Jr., and S. Ahmed, "Pore Sizes and Strength of a Compacted Clay" Technical Paper, School of Civil Engineering, Purdue University (West Lafayette, Indiana: Feb. 19, 1974).

Portions of the preceding characteristics and variations noted in Items 1 and 2 of the preceding paragraph may be attributable to variations of angle of internal friction and cohesion within the vicinity of OMC (Fig. 12). The untreated and SA-1 treated Decatur series showed gently descending ϕ angle curves with increasing moisture content, while Petro-S and SC-518 produced definite leveling breaks in the ϕ versus moisture content curves, that of the Petro-S being in the vicinity of OMC and that of the SC-518 occurring at greater than OMC. Cohesion of the untreated and of the Petro-S and SA-1 treated soils increased to a maximum near their respective OMCs, while c did not peak with the SC-518 treatment until on the wet side of optimum moisture. These c-ϕ combinations thus produced the aforementioned variations of q_d and τ, and appear attributable to the chemicals used with the Decatur series soil. Similar c-ϕ combinations, producing similar q_d - τ variations, were found within each soil-chemical series of shear tests and bearing strength analyses.

Table 22 summarizes Table 21 in a slightly different fashion in that C, ϕ, q_d, and τ for each soil are grouped for each product, and the variation of each physical property is noted as greater than (+), equal to (0), or less than (-) the untreated soil. Above the dashed line are noted the six chemical products concluded as having the greatest effectiveness of M-D relations from the preceding section of the Phase I study.

The products showing an increase in both bearing capacity and shear strength also showed increases in c, ϕ, or combinations of both parameters. If one parameter was less than that of the untreated, yet q_d and τ were both greater than the untreated, this simply indicated that the one parameter was large enough to offset reduction in the other.

It must be assumed that even though a chemical may improve M-D relations of a fine-grained soil, if it decreases overall bearing capacity and shear strength of that soil, it is undesirable and should not be utilized. It must also be emphasized that products may reduce M-D relations but will still significantly improve shear strength and bearing capacity; such has been noted for portland cement and lime for many years and is shown in the literature review. With the study emphasized herein, an arbitrary cutoff of the number of chemical products had to be ascertained due to time and dollar limitations of the total study. The major purpose of the study was relative to compaction and attainment of increases in density and ease of compactability of fine-grained soils. However, increasing density is principally for the purpose of increasing resistance to such properties as resistance to deformation, bearing capacity, improvement of shear strength, etc.

From Tables 21 and 22, it thus appears that the six products showing the greatest improvement in M-D basically showed fair to good improvement in shear parameters, bearing capacity, and shear strength with the largest variety of clay mineralogies.

Table 22. Summation of variation of c, ϕ, q_d, and τ from untreated soil.

Additive	Monona				Shelby				Grundite				AASHO				Dundee				Decatur			
	c	ϕ	q_d	τ	c	ϕ	q_d	τ	c	ϕ	q_d	τ	c	ϕ	q_d	τ	c	ϕ	q_d	τ	c	ϕ	q_d	τ
Coherex	+	-	+	+	+	-	+	+																
Petro-S	+	-	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	-	+	+	+	-	-	-
Clapak	+	-	+	+	+	-	+	+																
Claset	+	-	+	+	-	-	-	-									+	+	+	+	+	-	+	+
SA-1	+	+	+	+	-	-	-	-	+	-	+	+	+	-	+	+	+	+	+	+	+	-	+	+
SC-518	+	-	+	-	+	+	+	+					-	+	+	0	+	+	+	+	-	-	-	-
Thinwater	+	-	+	+	+	-	+	+									+	+	+	+	-	+	+	+
SS-13	+	-	+	+	+	-	+	+									-	+	+	+	-	+	-	+
Pen-E-Pak	+	-	+	+	0	0	0	0																
Road Packer	-	+	-	+	+	-	+	+																
X-2100	+	+	+	+	-	-	-	-																
Kelpak	+	+	+	+	+	-	+	+																
FR-20					-	+	+	+					+	-	+	+								
RD -4480	+	-	+	+	+	-	+	+																
RD-4481	+	-	+	-	+	-	+	+																
RD-4482	-	-	-	-	-	-	-	-																

As indicated in the Literature Review, a number of chemical compaction aids presently on the market appear to contain unknown surfactants. Three known surfactants were therefore tested with the Monona and Shelby soils in an effort to determine their effects on the M-D and bearing characteristics. Rd-4480 is weakly cationic, RD-4481 anionic, and RD-4482 non-ionic. Tap-water dilutions of these products were made at concentrations of 1, 5, and 10 parts per 1000 parts water. M-D, c, ϕ, q_d, SBV, and τ results with the RD surfactants have been presented in Tables 15, 16, 17, 20, and 21. In general, RD-4480 cationic decreased OMC of the Monona by 1% while contributing nothing to the M-D relations of the plastic Shelby soil. The anionic RD-4481 increased both density and OMC in the silty Monona while decreasing both in the Shelby. RD-4482 produced similar results in both soils by decreasing density and increasing OMC relative to the untreated.

Of these three surfactants, only the anionic chemical RD-4481 made a beneficial contribution to the M-D relations of the two soils, increasing density of the Monona and decreasing OMC of the Shelby. Neither contribution was of any significance and was offset by somewhat negative effects in the OMC of the Monona and a slight reduction in density of the Shelby.

If added in sufficient quantities, cationic (positively charged) chemicals attracted to negatively charged clay surfaces create a flocculated structure which in turn reduces density and usually increases OMC. Such compounds, through the cation exchange process, may also release other ions already present on the clay particle surface. An anionic (negatively charged) product may have some difficulty in finding a positively charged surface but may also create limited dispersive characteristics of the aggregations already present, thus potentially increasing M-D effectiveness. Non-ionic compounds would not be expected to produce exchange reactions but might reduce surface tension characteristics.

Through the introduction of the surfactants, it will be noted in Table 21 that ϕ was reduced by a fairly constant percentage as compared to that of the untreated. However, cohesion was definitely higher in both soils with the cationic RD-4480, less high with the anionic RD-4481 (though still somewhat improved over the untreated), and significantly less with the non-ionic RD-4482. The net effect of these changes of c and ϕ was a general lowering of bearing capacity (q_d) and shearing strength (τ) from cationic to anionic to non-ionic with the latter surfactant causing a significant lowering of both q_d and τ from those of the untreated.

No definitive conclusion could be reached as to what type surfactant may be a part of the six compaction aid products evaluated as most effective, but the M-D data obtained with the RD chemicals indicate the anionic variety. It may at least be concluded that the non-ionic surfactant is of no value in improving either M-D relations, shear strength, or bearing capacity of the montmorillonitic Monona and Shelby soils. In addition, the anionic RD-4481 surfactant provides no improvement in either q_d or τ of the silty Monona soil.

Of the sixteen compaction aids evaluated using the Iowa Bore Hole Shear Test, essentially ten increased cohesion in the tested soils, two decreased cohesion, and four left it unchanged. All six chemicals selected for further testing increased soil cohesion. Essentially none of the sixteen compaction aids improved the angle of internal friction (ϕ); six decreased ϕ, while ten provided relatively little change in ϕ. Of the six chemicals selected for further study, Petro-S, SC-518, and SA-1 essentially caused little change in ϕ of the tested soils, while Claset, Clapak, and Coherex decreased ϕ.

Atterberg Limits

Portions of the literature review indicated that a number of the chemical products have no reported effects on Atterberg Limits of soils. It was felt that if the chemical products contained surfactants and/or wetting agents creating dispersed or flocculated soil structures, these products would certainly cause Atterberg limit changes.

Three soils were selected: AASHO, Shelby, and Decatur, respectively representing illitic, montmorillonitic, and kaolinitic mineralogies. The middle chemical concentrations from the M-D studies were used for each product.

Only one change was made from the standard AASHTO Specification T-89 for LL, PL, and PI determinations.[47] To the air-dried minus No. 40 sieve fraction of each soil, the exact amount of liquid chemical concentration was added to produce the same moisture content as the plastic limit of the untreated soil. After thorough mixing of the concentration, water was then incrementally added to obtain the liquid limit, and then water was again added if necessary or the soil-chemical combination was dried out to obtain the plastic limit. Thus, the amount of chemical product contained in each soil sample was at least similar to that contained in the M-D, c, ϕ, q_d, SBV, and τ studies.

Table 23 presents the results of the Atterberg limits study. It should be noted that the chemically-produced variations in LL, PL, and PI are small for the illitic AASHO soil. From Table 7, it may be seen that the cation exchange capacity of this soil is low, 11.3 m.e./100 g. The montmorillonitic Shelby had a CEC of 29.6 m.e./100 g and, as noted in Table 23, many of the products produced significant changes in all three Atterberg values for this soil.

With the kaolinitic Decatur soil, changes in the values of LL, PL, and PI were somewhat more pronounced than with the AASHO but were much

Table 23. Atterburg limit changes of chemically treated selected soils.[*]

Chemical Product	Concentration, gal./gal. Water	AASHO			Shelby			Decatur		
		Liquid Limit, %	Plastic Limit, %	Plasticity Index, %	Liquid Limit, %	Plastic Limit, %	Plasticity Index, %	Liquid Limit, %	Plastic Limit, %	Plasticity Index, %
None-Water	-	33.5	19.4	14.1	53.6	31.7	21.9	55.0	29.0	26.0
Clapak[†]	10/1000	0	+	--	-	-4	+++	-5	-5	0
Claset[†]	10/1000	0	+	-	-	--	0	--	--	0
Coherex[†]	143/1000	--	0	--	+++	---	+7	-4	+++	-8
FR-20	1/1000	+	++	-	+	0	+	--	+7	-9
Kelpak	10/1000	-	-	0	+8	+21	-13	---	-5	+
Paczyme	2/1000	++	0	+	+	+5	---	+4	++	+
Pen-E-Pac	1/1000	0	0	0	0	-4	+5	n.d.	-6	n.d.
Petro-S[†]	200/1000	-4	--	-	---	---	0	-7	-2	-4
PVO X-2100	100/1000	+	0	0	-18	-4	-13	--	-5	++
Road Packer	5/1000	0	0	0	++	-13	+16	0	+	-
SA-1[†]	10/1000	-	0	-	0	-5	+5	-4	0	-4
SC-518[†]	5/1000	0	0	0	0	++	---	0	+++	---
SS-13	5/1000	-	0	0	--	-14	+12	++	0	++
Terra-Krete 1	10/1000	0	+	-	-	-16	+14	-	-5	+++
Thinwater	1/6000	0	0	0	-	--	0	+4	0	+4

[†] Signifies those products selected for Phase II studies based on M-D effectiveness.

[*] Changes are designated by whole number. Thus a 3.9 increase in P.I. would be designated +++.

less dramatic than with the Shelby. The Decatur had a CEC of 13.4 m.e./ 100 g, slightly greater than AASHO but considerably less than Shelby.

Perhaps most significant is that the products selected as most effective on the basis of M-D relationships are not those eliciting the greatest changes in Atterberg Limits. Thus, changes in Atterberg Limits are not a good predictor of effectiveness of a chemical compaction aid. For example, the chemicals which produced the greatest changes in P.I. of the Shelby soil are Kelpak (-13), PVO X-2100 (-13), Road Packer (+16), SS-13 (+12), and Terra-Krete 1 (+14), none of which were selected. The average change in Shelby soil P.I. caused by the six selected chemicals was 3.0, with most of the chemicals increasing the P.I. or leaving it unchanged and one (SC-518) decreasing the P.I. In the case of the other two soils, all of the selected chemicals decreased the P.I. or left it essentially unchanged. Thus, the selected chemicals, with the exception of SC-518, appear to have a dispersing effect on the montmorillonitic soil and a mild flocculating effect on the illitic and kaolinitic soils.

A linear regression of density effectiveness ratings (Table 19, first terms only) against average change in P.I. (regardless of sign from Table 23) gave a negative slope and r = -0.38. Application of the t-test indicated a probability of only 18%, or less than one-in-five that this could be due to chance. Thus, there does appear to be a negative correlation between change in P.I. and effectiveness as a compaction aid.

In Table 17, it can be seen that only a few of the chemicals were effective for increasing density of the Shelby soil: Pen-E-Pac, Petro-S, and SS-13. In Table 23, all of these reduced the plastic limit. On the other hand when we consider all of the chemicals, eleven reduced the P.L. of the Shelby, three increased it, and one left it essentially unchanged. Thus, the random selection of three could easily give three which reduce the P.L. and therefore, no conclusion could be drawn.

Similarly, from Table 17, the following chemicals in the amounts used in Atterberg limits tests gave greater than 1.5% increase in density of the Decatur soil: Clapak, Claset, Pen-E-Pac, Petro-S, Road Packer, SA-1, SC-518, SS-13; four decreased P.L., two increased it, and two exerted no change. Of all chemicals tested, seven decreased P.L., five increased it, and three exerted no change. Thus, about half of all chemicals decreased the P.L. and, because about half of those which were effective decreased the P.L., no relation could be defined. A similar situation existed for the illitic AASHO soil.

It may be concluded that Atterberg limits tests are inconclusive with regard to defining the role of chemical aids to soil compaction except that chemicals which cause a large change in Atterberg limits of a particular soil probably will not significantly aid compaction of that soil. The latter was pertinent to selection of known chemicals as trial compaction aids for Phase II of the study.

Supplemental Tests

As a possible means of categorizing the various chemical compaction aid products and/or developing a further understanding of their potential mechanistic influences of fine-grained soils, a series of supplemental tests were conducted. These included dielectric dispersion measurements, surface tension of the chemical concentrations and leachates through various soils, pH of the diluted chemicals, flocculation-dispersion characteristics through settling times and sediment volumes, and scanning electron microscopy evaluation.

Dielectric Dispersion Measurements. Radio-frequency electrical response characteristics of clay-water-electrolyte systems have been studied by Arulanandan, Mitchell, and Fernando et al,[54-58] who suggest that such techniques are indicative of a soil being in a dispersed or flocculated state.

When an alternating electric field is applied to a clay-water system, a response is produced which is measureable in terms of resistance R and capacitance C. The capacitance can be converted to a quantity termed the dielectric constant, ε, defined as C/C_o in which C_o is the capacitance measured with a vacuum between the electrodes. Thus, ε is a measure of the tendency of soil to store potential energy under the influence of an electrical field. If a specific size sample is used, the following relationships have been developed to calculate the dielectric constant ε and conductivity

$$\varepsilon = \frac{Cd}{A\varepsilon_o} \quad \text{and} \quad \sigma = \frac{d}{RA} \tag{13}$$

where:

d = specimen length
A = cross-sectional area
ε_o = dielectric constant of a vacuum (8.85×10^{-14} farads/cm)
R = resistance

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[54] K. Arulanandan, S. S. Smith, T. A. Linkhart, and K. S. Spiegler, "Characterization of Clays by Electrical Methods," presented to the Sixth Annual Meeting of Clay and Clay Minerals Society (1969).

[55] K. Arulanandan et al., "Significance of the Magnitude of Dielectric Dispersion in Soil Technology," HRB Record, No. 426 (1973).

[56] J. K. Mitchell and K. Arulanandan, "Electrical Dispersion in Relation to Soil Structure," J. Soil Mech. and Found. Div., ASCE, Proc. Paper 5853, 58:SM2 (March 1968), pp. 447-671.

[57] M. J. Fernando, R. E. Smith, and K. Arulanandan, "A New Approach to Determination of Expansion Index" (to be published).

[58] M. J. Fernando, R. G. Burau, and K. Arulanandan, "A New Approach to Determination of Cation Exchange Capacity" (to be published).

The dielectric constant of a wet clay depends on many variables: type and amount of clay, water content, temperature, type and amount of exchangeable ions in the system, soil structure, etc. In the present study, these variables were held nearly constant except insofar as they were influenced by the presence of a chemical compaction aid in order to reflect the net effect of the chemical additive.

It also has been shown[54-56] that the dielectric constant is a function of the radio frequency, and the difference in the constant measured at two given frequencies is defined as the dielectric dispersion, E. Magnitude of dielectric dispersion has been found to be highest for montmorillonite clays and lowest for kaolinite clays. Arulanandan et al.[55] report that E is reduced by flocculation and suggest that the reason may be a reduced ability for particle orientation during passage of the electrical current.

Fine-grained soil passing a No. 40 U.S. Standard sieve was mixed with chemical solution to about the soil liquid limit in order to obtain a partial slurry. Chemical concentrations used were those generally showing greatest M-D effectiveness. The soil-chemical mixture was packed into a cell consisting of a simple cylindrical plexiglass tube containing two platinum-coated electrodes at the ends. Resistance and capacitance of the mix were then measured with an RX Meter (Type 250, Boonton Radio Corp., Division of Hewlett-Packard, Rockaway, N.J.) at various frequencies ranging from 3 to 70 MHz. The RX Meter is essentially a Schering Bridge with oscillator, amplifier-detector, and null indicator designed to measure equivalent parallel conductance in the range 0.0 to 0.067 mhos, at frequencies of 0.5 to 250 MHz.

Results are presented in Table 24 for five soils and nine chemicals. The dielectric property shown is the dielectric dispersion, E, obtained as the difference of dielectric constant measured at 5 and at 70 MHz. The conductivity, σ, is that measured at 5 MHz. Also noted is the moisture content of the sample.

A chemical additive dispersion index (DI) may be defined as

$$DI = \frac{E_c - E_w}{E_w} \times 100 \qquad (14)$$

where E_c was the dielectric dispersion of the soil with the chemical additive and E_w was the dielectric dispersion of the soil containing a like amount of water only. If the DI is positive, the effect of the chemical may be dispersive even though the system may still be flocculated. If the DI is negative, the effect may be towards flocculation. Thus, sign and magnitude of the DI may suggest effectiveness of the chemical agent as a dispersant or flocculant.

SA-1 and SC-518 may be termed dispersants with five of the six soils used as indicated by positive DI as seen in Table 25. As indicated

Table 24. Results of dielectric dispersion measurements.

Chemical		AASHO	Loring	Decatur	Shelby	Monona
	E	12.0	22.7	23.1	24.6	28
Water	w/c	36.7	41.1	49.5	51.5	35.1
	σ	0.0015	0.00019	0.00031	0.00077	0.00059
	E	13.3	35.2	24.2	31.0	14.0
SA-1	w/c	38.4	41.1	47.2	51.9	33.6
(1/1000)	σ	0.0014	0.00060	0.00055	0.00120	0.00150
	E	23.7	42.7	22.4	48.3	43.5
SC-518	w/c	33.4	57.5	46.1	51.4	35.7
(5/1000)	σ	0.0011	0.00020	0.00025	0.00051	0.00045
	E	17.7	19.6	36.9	33.4	21.9
Thinwater	w/c	35.9	44.2	45.5	51.6	34.4
(1/1000)	σ	0.0016	0.00023	0.00029	0.00051	0.00059
	E	21.5	18.6	11.2	?	31.7
Claset	w/c	36.1	40.3	49.2	49.4	33.9
(10/1000)	σ	0.0033	0.0027	0.0033	0.0043	0.0037
	E	10.5	25.5	39.0	39.9	26.8
SS-13	w/c	32.8	40.7	53.6	52.1	36.2
(2/1000)	σ	0.0012	0.00020	0.00057	0.00088	0.00055
Road	E	9.6	23.1	19.7	22.3	18.5
Packer	w/c	35.2	42.2	48.1	54.9	35.3
(5/1000)	σ	0.0014	0.00032	0.00039	0.0012	0.0010
	E	9.3	19.5	19.8	40.1	27.0
Paczyme	w/c	37.4	43.2	49.9	52.6	35.1
(2/1000)	σ	0.0013	0.00018	0.00028	0.00082	0.00066
	E	?	19.3	20.9	38.4	24.3
Pen-E-Pac	w/c	36.1	44.3	53.8	54.8	35.8
(1/1000)	σ	?	0.00019	0.00028	0.0011	0.00058
	E	?	?	?	?	?
Petro-S	w/c	34.2	39.6	43.7	51.4	33.4
(100/1000)	σ	0.0032	0.0035	0.0039	0.0038	0.0032

Table 25. Dispersion indexes.*

Chemical	AASHO	Loring	Decatur	Shelby	Monona
SA-1	10.8	55.1	$\underline{\underline{5.2}}$	26.0	$\underline{-14.3}$
SC-518	$\underline{\underline{97.5}}$	$\underline{\underline{88.1}}$	$\underline{\underline{-3.0}}$	96.3	55.4
Thinwater	47.5	-13.7	59.7	35.8	$\underline{-21.8}$
Claset	79.2	-18.1	$\underline{\underline{-51.5}}$	?	13.2
SS-13	$\underline{\underline{-12.5}}$	12.3	$\underline{\underline{68.8}}$	62.2	$\underline{-4.3}$
Road Packer	-20.0	1.8	$\underline{\underline{-14.7}}$	-9.3	$\underline{-33.9}$
Paczyme	-22.5	$\underline{-15.4}$	$\underline{-14.3}$	$\underline{63.0}$	-3.6
Pen-E-Pac	$\underline{?}$	-15.0	$\underline{\underline{-9.5}}$	$\underline{56.1}$	-13.2
Petro-S	$\underline{\underline{?}}$	$\underline{\underline{?}}$	$\underline{\underline{?}}$	?	$\underline{?}$

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*Double underline: Increased density >1.5% in M-D tests.
Single underline: Increased density 0.5 - 1.5% in some M-D tests.

by the underlined portions in Table 25, (from M-D tests, Table 17) SA-1 was considered an effective compaction aid only with the Decatur soil and slightly effective with the Monona, whereas the dielectric data indicate it acts as a flocculent. The correlation is somewhat better with SC-518, but, as can be seen by comparing underlined DI values in Table 25 with those which are not underlined, the relation is inconsistent. This may be due in part to the much higher moisture content used in the dielectric studies.

With Petro-S it was impossible to balance the bridge at the higher frequencies. Regardless of soil type, conductance was nearly constant and appreciably higher than with water or any of the other chemicals. It is thought that the concentration of 100/1000 Petro-S may have been too great for this type of measurement due to the similarities of conductance of the Petro-S treated soils and that the chemical may have been flooding the clay-water-electrolyte system.

Linear regressions of dispersion index (Table 25) versus OMC, γ_d, SBV, q_d and τ (from Table 21) are presented in Table 26. Dispersion index as a function of change in OMC gave a correlation coefficient of only 0.007 with slope of 0.092. Application of the t-test indicated a probability of 51.2% that the regression relation was not due to chance, i.e., there was a 48.8% probability that these two parameters were unrelated. Fitting only the data showing strong dielectric characteristics gave a negative regression coefficient of -0.074 with a 58.6% probability of a true correlation. Both indicate no relation.

Comparison of DI with maximum density indicated that five of the twelve assumed dispersants increased γ_d, while five decreased it and two left it the same. Of the eight flocculants, four produced the same density, while the others increased γ_d. A linear regression, having a negative correlation coefficient of -0.363 and a slope of -10.123, was found between DI and γ_d. Application of the t-test indicated a probability of 94.3% that a negative correlation existed. Fitting the eleven strongest DIs with maximum density, a better correlation coefficient was obtained with $r = -0.548$ and $m = -21.464$. However, application of the t-test indicated essentially the same probability, 93.4%.

Comparison of DI with shear strength indicated that two of the twelve dispersants decreased τ while nine increased it and one left it the same. Seven of the assumed flocculants increased τ while only one decreased it. The linear regression for this relationship was $r = -0.080$ and $m = -0.493$, with a 63.2% probability of a true correlation.

The highest correlation coefficient was obtained between DI and SBV (0.408) with a probability of 96.3% that the positive relationship was not due to chance. This correlation at least partially corroborates the dispersion-soil structure-SBV observations presented within the preceding SBV summary section of this report.

Table 26. Summation of linear regression and analyses of dispersion index (DI), optimum moisture content (OMC), dry unit weight (γ_d), Spherical Bearing Value (SBV), bearing capacity (q_d), and shear strength (τ).

		OMC	γ_d	SBV	q_d	τ
DI (20)[a]	r[b]	0.007	-0.363	0.408	-0.038	-0.080
	m[c]	0.092	-10.123	0.734	-0.013	-0.493
	t[d]	0.030	-1.653	1.896	-0.161	-0.341
	p[e]	51.2	94.3	96.3	56.3	63.2
OMC (49)	r		-0.519	-0.272	-0.133	-0.083
	m		-1.438	-0.066	-0.019	-0.056
	t		-4.163	-1.938	-0.920	-0.571
	p		100.0	97.1	81.9	71.5
γ_d (49)	r			0.108	-0.192	-0.135
	m			0.008	-0.010	-0.014
	t			0.745	-1.341	-0.934
	p			77.0	90.7	82.3
SBV (49)	r				0.262	0.151
	m				0.065	0.425
	t				1.861	1.047
	p				96.6	85.0
q_d (49)	r					0.672
	m					2.964
	t					6.221
	p					100.0

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[a] Number of paired data entries, a.

[b] r = linear regression correlation coefficient.

[c] m = slope of the best fit line.

[d] $t = \dfrac{r\sqrt{a - 2}}{\sqrt{1 - r^2}}$

[e] p = probability of the t-test in percent.

Comparison of DI and q_d produced a low correlation and probability indicating that such predictability is poor at best. Comparison of probabilities of relationships between the other variables of Table 26, excluding DI, indicate good relationship only between OMC - γ_d and q_d - τ.

Thus, within the limits investigated, dielectric characteristics were neither a simple nor conclusive measure of effectiveness of a compaction aid.

Role of Surface Tension. It was anticipated that chemical compaction aids for the most part would be surfactants which tend to concentrate in air-water interfaces and, by interrupting dipolar attractions in the water surfaces, decrease their surface tension. The result would be a decrease in the pressure differential between atmospheric and pore water pressure, the latter being reduced because of outward pull of meniscii on annular rings of water at soil grain contacts. The negative pore water pressure ordinarily present in partly saturated soils pulls soil grains together, increasing their friction and hence their resistance to shear and compaction.

In order to test this hypothesis, surface tension tests were performed on the various chemical admixtures diluted in water, Table 27 and Fig. 14. As a control, surface tension tests were performed on tap water with no additives and gave a quite reasonable average value of 73.0 dynes/cm.

A Cenco-DuNouy tensiometer was used to determine the surface tension of the various additives. This instrument uses a fine torsion wire for applying the force required to withdraw a platinum-iridium ring from the surface of a liquid. The instrument was calibrated before each testing session so that each division on the graduated dial corresponded to a force of one dyne; appropriate corrections were made, and surface tension values were determined in dynes per centimeter.

Products were diluted with tap water to the same concentrations used in the compaction study. To measure surface tension, the diluted chemical was placed in a glass container and mounted on the platform directly beneath the platinum-iridium ring. The ring was immersed approximately 5 mm into the liquid, and the platform was lowered until the ring was at the surface of the liquid. Then slowly, the platform was continuously lowered until the film between ring and liquid was broken. The force required to break the liquid film in dynes per cm was recorded. Testing procedure was in accordance with recommendations of the instrument manufacturer. Three tests were repeated for each product concentration, and the results were averaged.

Surface tension values ranged from 29.3 for SC-518 to 74.3 dynes/cm for Claset, with most products having a surface tension lower than tap water. In most cases, surface tension decreased with increasing con-

Table 27. Average pH and surface tension values for various water concentrations of chemical products.

Chemical Product	Concentration, gal./gal. water	pH	Surface Tension dynes/cm
No treatment (tap water)	--	6.95	73.0
Clapak*	1/1000	2.24	66.0
	10/1000	1.92	48.9
	20/1000	1.74	47.8
Claset*	1/1000	4.28	74.3
	10/1000	3.20	73.5
	20/1000	2.65	73.4
Coherex*	100/1000	7.18	37.3
	143/1000	7.07	37.2
	250/1000	6.71	36.2
FR-20	0.5 g/1000 ml	7.22	63.5
	1 g/1000 ml	6.98	57.2
	2 g/1000 ml	6.15	53.5
Kelpak	1/1000	6.88	71.8
	10/1000	6.86	63.7
	20/1000	6.63	47.9
Paczyme	1/1000	7.20	45.7
	2/1000	7.18	39.8
	4/1000	6.73	36.8
Pen-E-Pac	0.5/1000	7.15	32.7
	1/1000	7.06	32.2
	3/1000	6.95	32.3
Petro-S*	100/1000	8.34	34.5
	200/1000	8.79	36.3
	300/1000	9.02	36.9
PVO X-1000	50/1000	7.51	41.5
	100/1000	7.47	40.4
	250/1000	6.97	39.5
PVO X-2100	50/1000	6.43	36.9
	100/1000	6.27	37.0
	250/1000	6.15	37.0

(Continued)

Table 27 (Continued).

Chemical Product	Concentration, gal./gal. water	pH	Surface Tension dynes/cm
Road Packer	1/1000	6.43	70.0
	5/1000	2.45	65.2
	10/1000	2.20	60.7
RD-4480	1/1000	9.57	50.6
	5/1000	9.84	61.2
	10/1000	10.15	63.3
RD-4481	1/1000	7.12	42.3
	5/1000	7.15	43.5
	10/1000	7.15	44.6
RD-4482	1/1000	8.05	41.7
	5/1000	8.94	41.5
	10/1000	9.37	41.3
SA-1*	1/1000	1.95	56.8
	10/1000	1.66	40.6
	20/1000	1.63	38.1
SC-518*	1/1000	7.05	32.4
	5/1000	7.16	29.3
	10/1000	6.77	29.8
SS-13	1/1000	7.27	46.9
	2/1000	7.34	44.2
	4/1000	7.47	42.8
Terra Krete #1	1/1000	6.73	43.1
	10/1000	5.79	35.3
	20/1000	4.32	34.3
Terra Krete #2	10/1000	4.60	41.1
	50/1000	3.35	35.3
	100/1000	2.87	35.3
Thinwater	1/12000	7.26	34.6
	1/6000	7.13	34.6
	1/1000	7.07	34.5

*Denotes chemicals rating highest in the M-D studies.

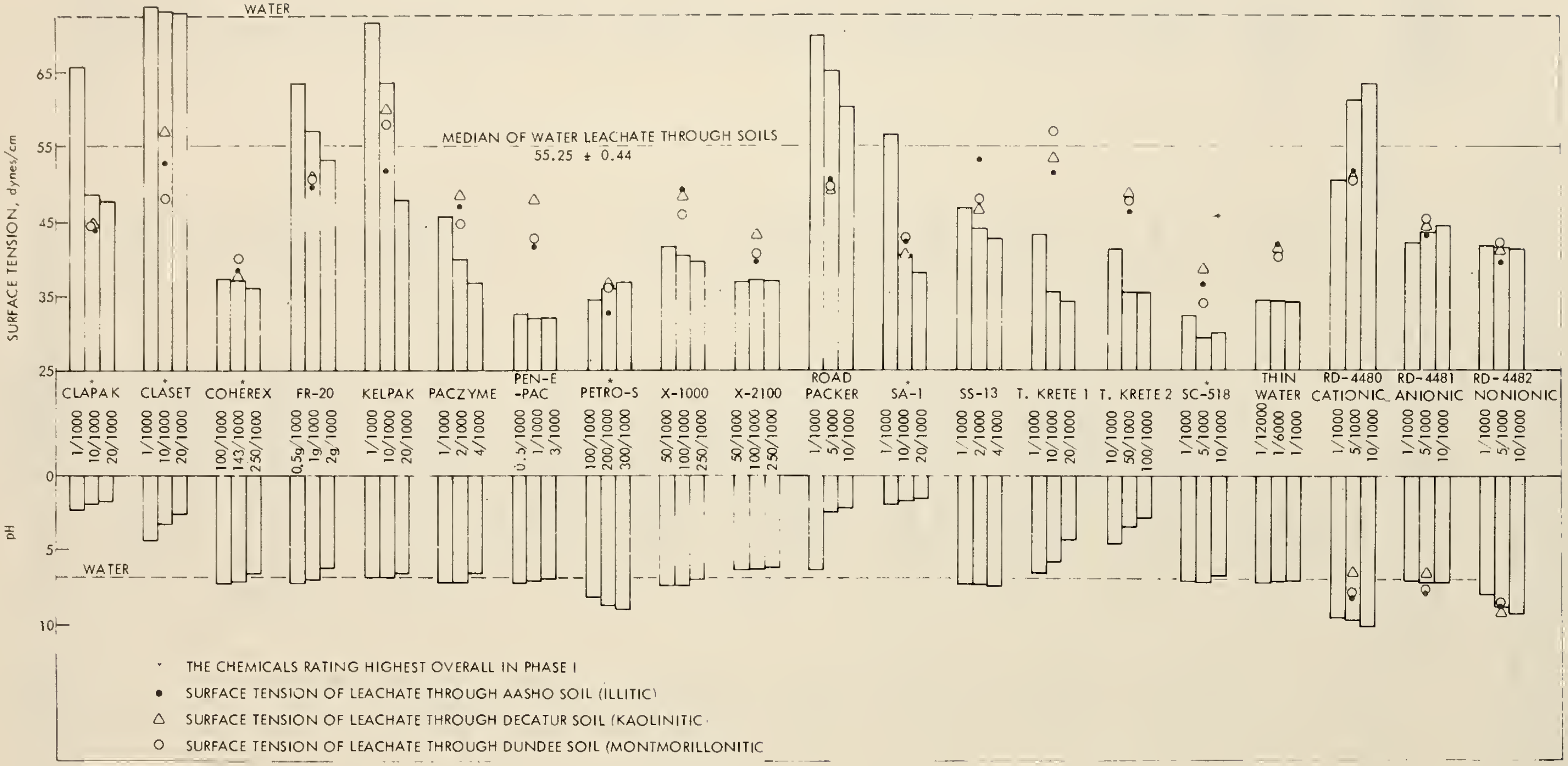

Fig. 14. Surface tension and pH of chemical concentrates and leachates.

centration, the magnitude of reduction varying with each product. It may be noted, however, that products of lowest surface tension had similar values for all concentrations. All but one of the chemicals reduced surface tension, six reducing it by a factor of 2. However, only two of these six were effective enough as compaction aids to be considered for further tests. It was concluded that surface tension reduction of a chemical-water concentration alone is not a good criterion for selection of a compaction aid. Nevertheless, the aid evaluated as most effective in M-D preliminary tests, SC-518, gave the greatest reduction in surface tension of the twenty chemicals tested: 60%.

The preceding observations do not support the hypothesized concepts presented above. The following possibilities may be considered: 1) Products could undergo a chemical change, such as cation exchange, when in contact with the soil such that surface tension of the original chemical additive is not the same as surface tension of the pore fluid; and/or 2) Surface tension does not play a key role in compactability of fine-grained soils, while electrical attractions and repulsions between clay particles dominate compaction characteristics of clayey soils.

It is believed that both of the preceding concepts are partially true, and both are pertinent to the study of chemical compaction aids. However, both are interrelated and therefore, it is difficult to distinguish between the two individual effects. Since cation exchange between chemical and soil will cause an alteration in clay particle attraction and repulsion as well as alter surface tension properties of the pore fluid, exact chemical make-up of the products must be known before definitive evaluations can be made.

In addition, a major difference between surface tension as measured in the DuNouy platinum ring test apparatus and as it exists at the water/air interface in compacting soil is the amount of surface area involved. This factor was indirectly evaluated from surface tension measurements on different concentrations of the individual chemicals--a lower concentration corresponding to a larger surface area as it may exist in the soil. This suggests that a change in surface tension as a function of concentration might be a negative indicator of effectiveness of a compaction aid. The chemicals found least susceptible to the changing concentrations were Claset, which did not reduce surface tension, and Coherex, Pen-E-Pac, the two PVO-X products, Thinwater, and RD 4482. Several products showed a reverse tendency, i.e., increasing concentrations causing a slight increase in surface tension: Petro-S, RD 4480, and RD 4481. Of these ten products, three were considered for further M-D and other tests, indicating that surface tension of lower concentrations of the chemicals is also not a good criterion.

Therefore, experiments were performed whereby the diluted chemicals were actually leached through selected soils and surface tension of the leachate measured. As control, the same soils were leached with tap water and the leach-through water's surface tension was measured. One surprising result was that the tap water, after being leached through the soil, showed considerably lower surface tension regardless of type of soil; the surface tension after leaching ranged from 54.8 to 55.8 dynes/cm. The soils used in this experiment were the AASHO illitic, Decatur kaolinitic, and Dundee montmorillonitic. Results are presented in Fig. 14.

With some of the chemicals, the greatest reduction in surface tension occurred after leaching through the soil, indicating an additive effect of the chemical with that of the surface tension-reducing chemicals, (most likely organic compounds) already in the soil. These chemicals include Clapak, Claset, FR-20, Road Packer, SA-1, and RD-4480. Three of these six were selected for further tests. A few chemicals gave higher surface tensions after leaching through soil than before leaching. These were Coherex, Paczyme, Pen-E-Pac, PVO-X products, SS-13, the Terra Krete products, SC-518, and Thinwater. Only three of these ten were selected for further tests, so no conclusion could be reached.

Since there were no consistent relationships, the various possible correlations were investigated by a consideration of regression statistics. A linear regression of average compactability rating, Table 19, as a function of the reduction in surface tension of tap water gave a correlation coefficient of only 0.12. Application of the t-test indicated a probability of only 34% that the regression relationship was not due to chance--that is, on the basis of the data obtained, there was a two-thirds probability that these two parameters were unrelated. In contrast to this, the correlation coefficient between compactability rating and reduction in surface tension of the soil leachate was 0.52, and application of the t-test indicated a 97% probability that this relation was <u>not</u> due to chance. Thus, there appeared to be a definite correlation between effectiveness of the chemical compaction aids and their ability to reduce surface tension of the soil leachate. However, the relationship was not perfect, and this test alone did not delineate effective compaction aids; <u>the regression only pointed out the trend</u>.

Other regressions of effectiveness rating indicated an 81% probability (P) of a negative correlation with the average change in plasticity index, regardless of sign; this possibility was pointed out in the Atterberg limit study. There also existed a positive correlation to dielectric dispersion, P = 87%, and to dielectric conductivity, P = 76%. A somewhat better correlation, P = 91%, was obtained with the dielectric dispersion index or with the change in dielectric constant with changing radio frequency of the current used in the measurement.

A second part of the empirical compactability rating was related to reduction in optimum moisture content. As in the case of the compactability rating, the OMC rating was unrelated to effectiveness of the chemicals in reducing surface tension of water, P = 18%, but showed a strong positive correlation with ~~effectiveness of the~~ chemicals in reducing surface tension of soil leachate, P = 90%. The OMC rating also correlated with compactability rating, r = 0.5, with the probability of 96% that this relationship was not due to chance. This was as anticipated in the Theory of Compaction where it was suggested, on the basis of hypothesized compaction mechanisms, that an effective compaction aid would probably reduce surface tension of the soil water and thus reduce optimum moisture content.

Role of pH. pH tests were performed on the diluted chemicals in order to ascertain their acidity. The average of three pH values was obtained for each product concentration using a Corning, Model 12, pH Meter. Products were diluted with tap water to the same concentrations used in the compaction study. The pH meter was calibrated with appropriate buffer solutions before each testing session, the instrument being capable of making all necessary temperature corrections. Testing was done in accordance with recommendations of the instrument manufacturer. Shown in Table 27 and Fig. 14 are the average pH results for each product and chemical concentration as well as average values obtained for the tap water.

The measured pH's ranged from highly acidic, as low as 1.6, to alkaline, as high as 10.2. As would be expected, pH values decreased or increased, respectively, with increasing chemical concentration. Highly acidic products included Clapak and SA-1. Somewhat less acidic, but still highly acidic, were Claset, Road Packer, and Terra Krete #2. In all of the other products, pH ranged around 6 or 7 except for Petro-S and the RD products, which were mildly alkaline to alkaline respectively.

An acidic nature of compaction aids was generally anticipated since hydrogen ions tend to disperse clay. On the other hand, a high concentration of hydrogen ions may react with the soil to release divalent and trivalent ions such as calcium and aluminum which tend to flocculate a soil. A mildly acidic condition may be preferable because of the pH-dependency of the clay-cation exchange capacity; an excess of hydrogen ions decreases the negative charge on the clay and hence reduces exchange capacity and strength of a flocculation. This also rules against the use of a highly alkaline additive, such as lime, which increases exchange capacity, creates stronger flocs, and probably promotes greater absorption of chemicals from the system thereby reducing their effectiveness as surfactants.

The pH tests tend to bear this out: two of the six chemicals selected for further tests were highly acidic, and one was somewhat less acidic. However, two were near neutral and one was slightly alkaline.

A linear regression of compactability effectiveness (Table 19) versus pH gave a very low correlation coefficient, r = 0.10, with only a 30% probability of a true correlation. Thus, within the limits investigated (pH 1.6 to 10.2), pH does not appear related to M-D effectiveness of a chemical compaction aid.

Flocculation-Dispersion Study. No reported investigations give any direct indication of whether products disperse soils (increase particle repulsions) or flocculate soils (reduce particle repulsions) to improve compactability. A study was therefore undertaken to examine flocculation-dispersion characteristics of individual chemical products on three selected soils representing varying clay mineralogy: AASHO soil (predominantly illitic), Loring series (predominantly montmorillonitic), and Decatur series (predominantly kaolinitic).

Flocculation-dispersion characteristics were evaluated by studying settling times and sediment volumes of treated and untreated soils in test tubes containing a distilled water medium. Soils were mechanically dispersed and then allowed to settle. Observations were made and photographs were taken at appropriate time intervals. Comparisons were made relative to "no treatment" (distilled water), a known "dispersing agent" (sodium hexametaphosphate), and a known "flocculating agent" (aluminum chloride).

The following sample preparation procedure was used in this study:

1. Four grams of minus No. 200 sieve material were placed in each 75 ml test tube. A maximum of ten products was evaluated in any one testing session.
2. Products were diluted to the mid-concentration used in the M-D study and added to each test tube, the amount added being determined by the amount of chemical present in a treated soil when compacted at maximum dry density. That is:

$$C_T = (C_M) \frac{(S_T)}{(S_M)} \qquad (15)$$

where:

C_T = amount of chemical in each test tube.
C_M = amount of chemical in each compacted specimen at maximum dry density.
S_T = dry soil weight in each test tube, 4 g.
S_M = approximate dry soil weight in each mold at maximum dry density.

3. Test tubes were filled with distilled water, stoppered, and simultaneously hand shaken for a period of 2 min.
4. Test tubes were placed in a rack and soil was allowed to settle.
5. Observations were made over a 3-hour period and photographs were taken at 2, 5, 8, 15, 30, 60, and 120 min.

The "no treatment," "flocculating agent," and "dispersing agent" test tubes were prepared in a similar manner with relatively large amounts of aluminum chloride and sodium hexametaphosphate added. Shown in Table 28 are the exact amounts of chemicals added to each test tube.

Photographs of the flocculation-dispersion tests are shown in Fig. 15-17 and illustrate the characteristics of each soil-chemical product at one time interval: Decatur and Loring series after a settling time of 2 min., and AASHO after 5 min.

If it is assumed that no treatment is "neutral" and neither flocculates nor disperses a soil, then a product causing a slower settling time than distilled water could be categorized as a soil dispersant, while a product causing a faster settling time could be categorized as a soil flocculant. The following flocculation-dispersion characteristics were concluded from the settling time and volume of each chemical treatment:

1. AASHO soil showed some variation in settling times with the different chemical products. FR-20, Kelpak, PVO X-1000, PVO X-2100, SS-13, and Terra Krete #2 showed definite flocculation characteristics while Road Packer, SC-518, and Thinwater showed some slight dispersion characteristics. The AASHO soil had the slowest settling times of the three soils tested.
2. Decatur soil indicated little variation in settling times with varying treatments. No products significantly dispersed the soil, and, in most cases, the products had flocculation-dispersion characteristics similar to distilled water. It will be noted that there was little difference in settling time between distilled water and the flocculating solution (aluminum chloride). FR-20 and Kelpak were the only products producing definite flocculation characteristics in the Decatur series soil.
3. Loring, like AASHO, had some variation in settling times with various treatments, though none of the products could be classified as dispersants. Products producing flocculation were FR-20, Kelpak, Claset, Petro-S, PVO X-1000, PVO X-2100, SA-1, Terra Krete #1, and Terra Krete #2. Remaining products produced effects similar to the "no treatment."

Thus, flocculation-dispersion characteristics of the chemical products varied with the soils tested. This was expected since once again it illustrated the interdependence of clay mineralogy and effectiveness of chemical additives. Although little could be correlated between flocculation-dispersion and the ability of a product to improve compactability of a soil, certain tendencies were noted. Products that rapidly flocculated the soils were not effective compaction aids.

Table 28. Amount of chemical product added to each test tube in flocculation-dispersion study.

Chemical Treatment	Chemical Concentration ml/ml of water	Quantity of Chemicals in each test tube, ml
Clapak	10/1000	0.0059
Claset	10/1000	0.0059
Coherex	143/1000	0.0855
FR-20	1 g/1000 ml	0.0006
Kelpak	10/1000	0.0059
Paczyme	2/1000	0.0012
Pen-E-Pac	1/1000	0.0006
Petro-S	200/1000	0.1195
PVO X-1000	100/1000	0.0598
PVO X-2100	100/1000	0.0598
Road Packer	5/1000	0.0029
SA-1	10/1000	0.0059
SC-518	5/1000	0.0029
SS-13	2/1000	0.0012
Terra Krete #1	10/1000	0.0059
Terra Krete #2	50/1000	0.0299
Thinwater	1/6000	0.0006
Aluminum Chloride	10 g/1000 ml	0.5
Sodium hexametaphosphate	45.7 g/1000 ml	0.5

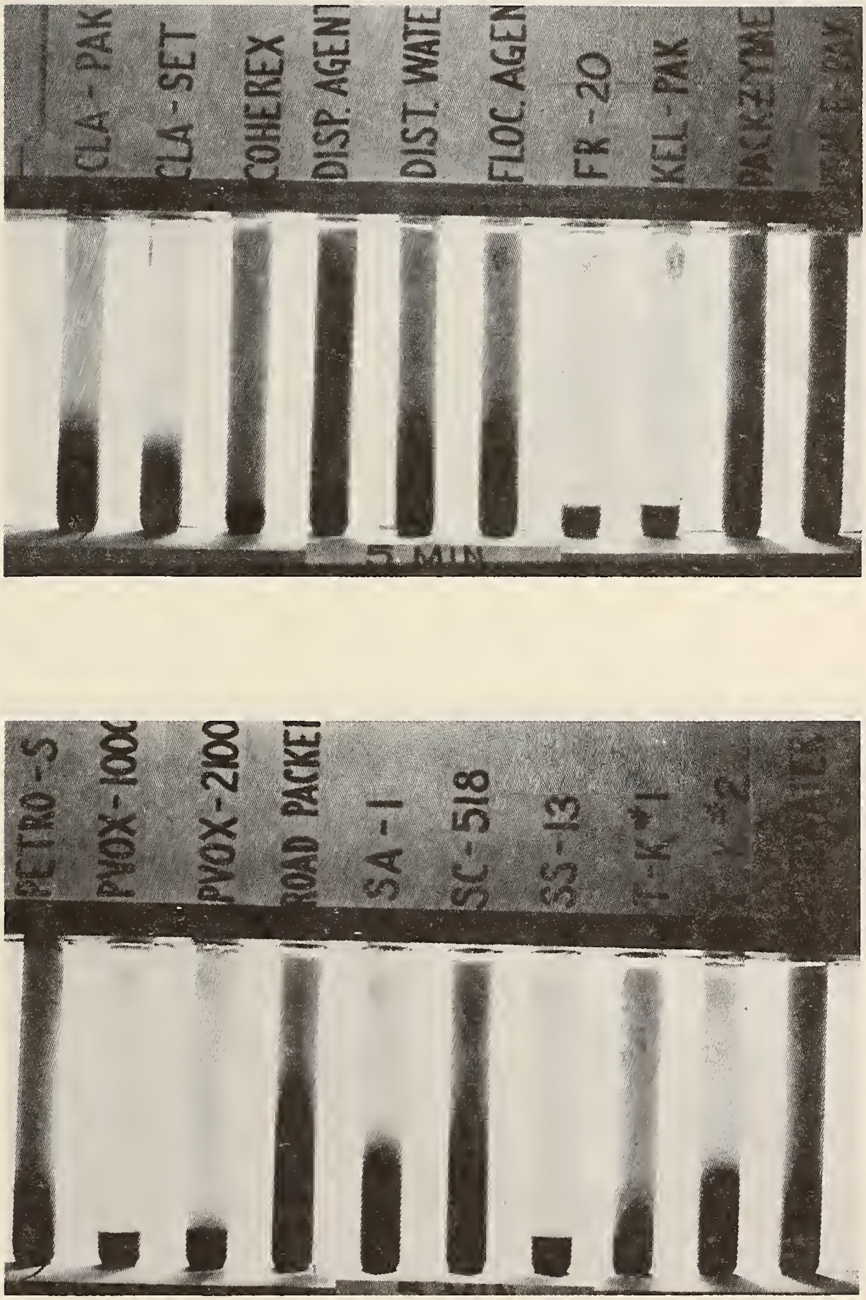

Fig. 15. Settling time for chemically treated AASHO soil, 5 minutes.

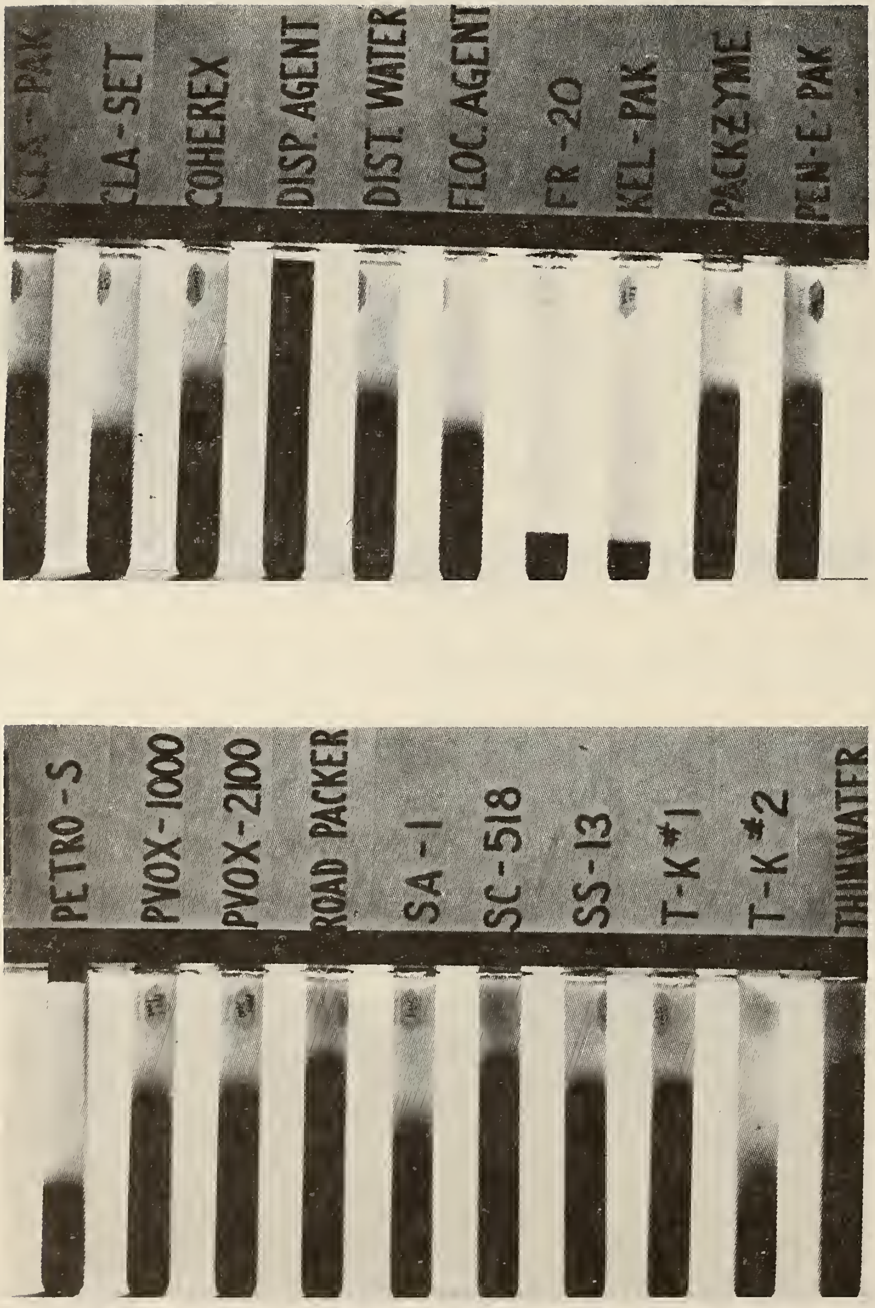

Fig. 16. Settling time for chemically treated Decatur soil, 2 minutes.

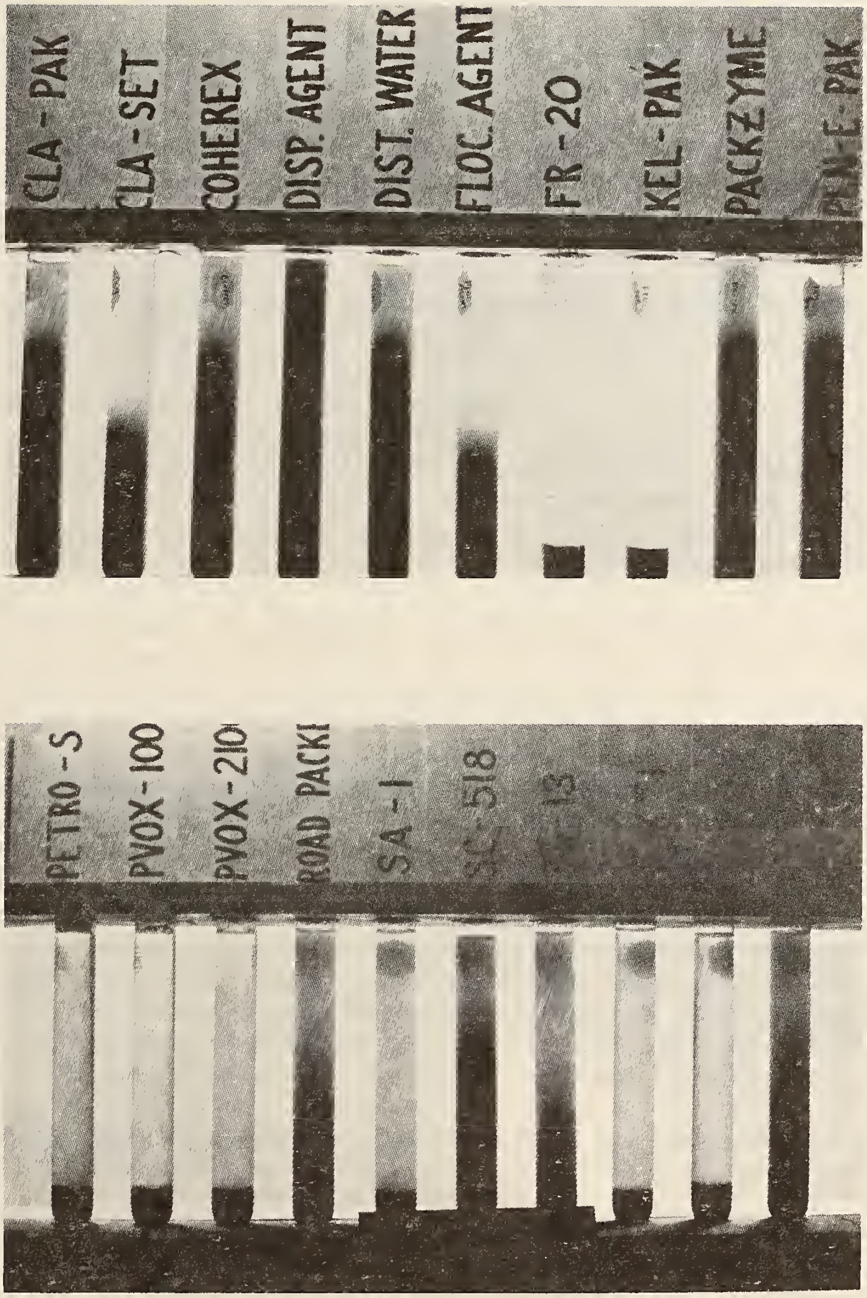

Fig. 17. Settling time for chemically treated Loring soil, 2 minutes.

For example, FR-20, Kelpak, PVO X-1000, and Terra Krete #2 definitely flocculated the tested soils, and all are considered ineffective compaction aids. This would seem reasonable since extreme flocculants reduce clay particle repulsions, create more particle interaction, and thus hinder compaction.

Products considered most effective in increasing density and/or reducing optimum moisture content had flocculation-dispersion characteristics similar to the "no treatment" distilled water, a significant observation since it was generally assumed that an effective compaction aid must disperse a soil by reducing particle interactions in order to increase its compactability.

The following conclusions were drawn from observations in this series of tests:

1. Soil-chemical interactive effects of a product are dependent on clay mineralogy and surfactant characteristics.
2. Products that are strong flocculating agents are probably not good compaction aids.
3. Products may not have to disperse a soil to improve its compactability.

Evaluation by Scanning Electron Microscopy. Treated and untreated soils were observed through scanning electron microscopy in an effort to visually examine structural changes occurring within a soil when treated with various chemical products. As used in this study, "structure" refers to the orientation, fabric, and closeness of contact of the clay particles and/or clay aggregations of a particular soil. Comparisons of chemically-treated soil structure were made relative to "no treatment" with distilled water, soil treatment with the "flocculating agent" aluminum chloride, and soil treatment with "dispersing agent" sodium hexametaphosphate. Samples were prepared, observed at various magnifications, and photomicrographed for further study. Though only the AASHO soil was studied with the scanning electron microscope, it is believed that most, if not all, of the concepts presented in this section are relevant to the other chemically-treated fine-grained soils within the total investigation.

The following sample preparation procedure was used throughout this investigation:

1. One gram of minus No. 200 sieve soil was placed in a 10 ml test tube, one test tube for each chemical product studied.
2. Products were diluted with distilled water to the mid-concentration used in the M-D study, and 8 ml of the solution were added to each test tube.
3. Test tubes were hand-shaken for a period of 2 min, then placed in a test tube rack for 2 min prior to withdrawing a sample.

4. The tip of a 1.0 ml pipette was immersed to a depth of 1 in. in the test tube and 0.2 ml of soil-chemical solution was withdrawn. The solution was placed on a brass stub sample holder and allowed to air-dry for 24 hours.
5. Since soil samples become electrically charged due to bombardment of electrons in the scanning electron microscope, a conductive coating of gold and carbon was placed on each sample.
6. Samples were observed in a type JSM-U3 scanning electron microscope (SEM) and photomicrographs were taken at 200, 600, 1000, and 2000 magnification.

The "no treatment," "flocculating agent," and "dispersing agent" samples were prepared and observed in a manner similar to that above except that 0.002 g aluminum chloride and 0.001 g sodium hexametaphosphate were added to the flocculating and dispersing agent test tubes, respectively.

As indicated above, test tubes of soil-chemical solution were placed in a rack for 2 min prior to pipette sampling. This allowed the larger silt-size particles to settle out, resulting in a greater percentage of clay-size particles in the SEM sample. With a higher percentage of clay present, it was felt that chemical effects would be more evident, and any changes occurring in soil structure could be more readily observed.

By slowly evaporating the solution through air-drying for 24 hours prior to observation, clay particles could move into closer contact, orienting themselves as dictated by the interparticle forces. Thus, clay particles could freely move into any type of preferred particle orientation.

The structure of clay can be ideally described as being either flocculated or dispersed. If attractive forces are greater than repulsive forces, soil particles are presumed flocculated; and if repulsive forces are greater, the soil is presumed dispersed. Flocculation is a state in which there is close aggregation of the particles with little orientation or alignment. Dispersion is the state in which clay particles tend to move away from each other, but there is some particle orientation or alignment. Yong and Warkentin[59] discuss and describe various types of idealized clay structure models. These models are shown in Fig. 18 and illustrate four types of clay structure: fully-oriented, partially oriented, cluster units in random orientation, and packet clusters.

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[59] R. N. Yong and B. P. Warkentin, Soil Properties and Behavior (New York: Elsevier Scientific Publishing Co., 1975).

Fully-oriented clay structure would be a completely dispersed soil with face-to-face particle orientation. The clay particles would not be in clusters but in a more continuous, uniform structure described as a "large fabric unit."

Partially-oriented clay structure is similar to a fully-oriented structure, but the clay particles are in a more random orientation. This is characteristic of a naturally flocculated soil that has been dispersed with a dispersing agent.

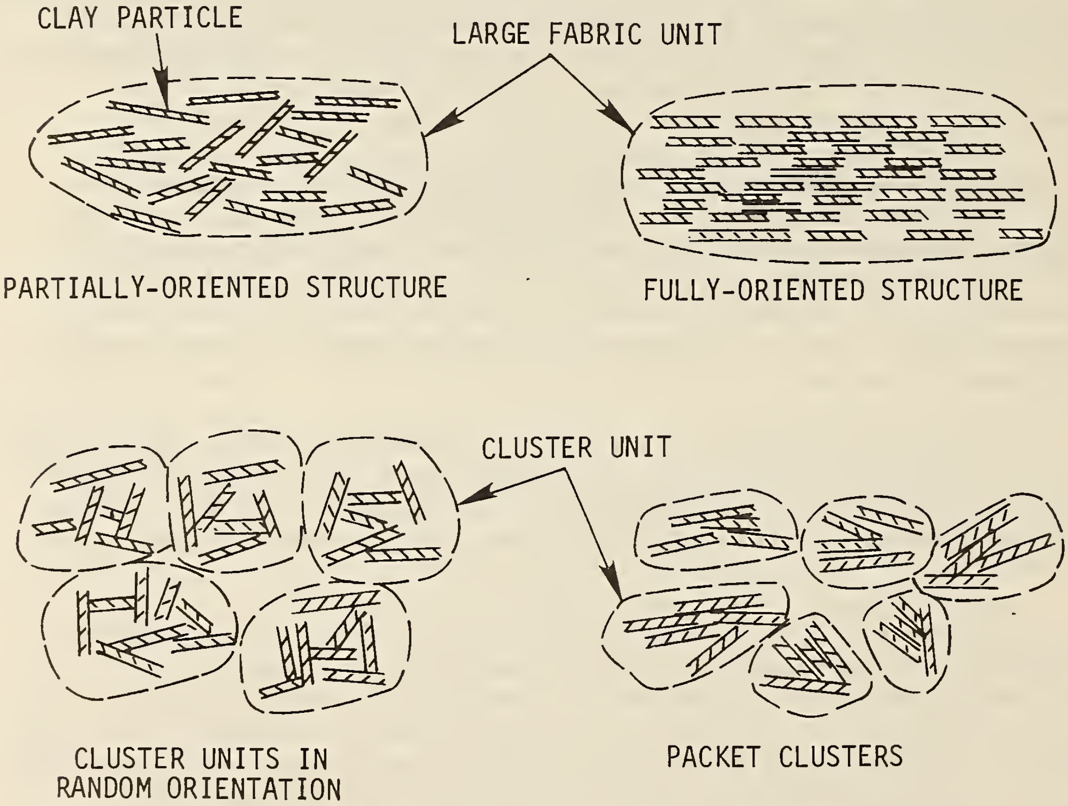

Fig. 18. Idealized clay structure models (Yong and Warkentin, 1975).

Cluster units in random orientation would be a flocculated structure with edge-to-face particle orientation. This type of structure is characteristic of flocculation in a soil where salt is not present.

Packet clusters would be a flocculated structure with face-to-face particle orientation. This type of structure would be characteristic of flocculation in the presence of salt, where salt reduces the repulsive forces through a depression of the diffuse double layer.

Figures 19 through 24 are six micrographs of the treated and untreated AASHO soil at 2000× magnification. Illustrated are the types of structural changes occurring with various chemical additives, and how effective and ineffective compaction aids may alter soil structure. A micrograph of the "no treatment" soil is shown in Fig. 19. Structure of the untreated AASHO soil appears to be partially flocculated with small irregularly-sized cluster units present. The clay particles appear to be in close contact with a somewhat platey appearance. This structure is best described by the idealized model of the cluster units in random orientation, Fig. 18. However, the AASHO cluster units do not appear to be very particulate, indicating the structure is slightly more dispersed than that displayed by the model. The degree of clustering can be better appreciated by comparison with the next figure.

Figure 20 presents a micrograph of the AASHO soil treated with sodium hexametaphosphate (Calgon*), and illustrating a dispersed or oriented clay structure. Dispersed clay particles are very small in comparison to the size of the cluster units shown with the "no treatment." This type of structure is best described by the idealized model of fully-oriented clay structure, Fig. 18.

In Fig. 21, the micrograph of the aluminum salt-flocculated AASHO soil is shown. This structure is more flocculated than the untreated AASHO, and cluster units seem to be more uniform in size with a more particulate, platey structure. This type of structure is best described by the packet clusters shown in Fig. 18.

Presented in Figs. 22 and 23 are micrographs of Petro-S and SC-518 treatments, respectively, the two most effective compaction aids with this soil. Both show a flocculated-type structure, but cluster units appear to be more particulate, more varied in size, and much larger than the untreated soil.

A micrograph of the FR-20 treated AASHO soil is shown in Fig. 24. This structure appears to be strongly flocculated, and giant cluster

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*Commercial product name.

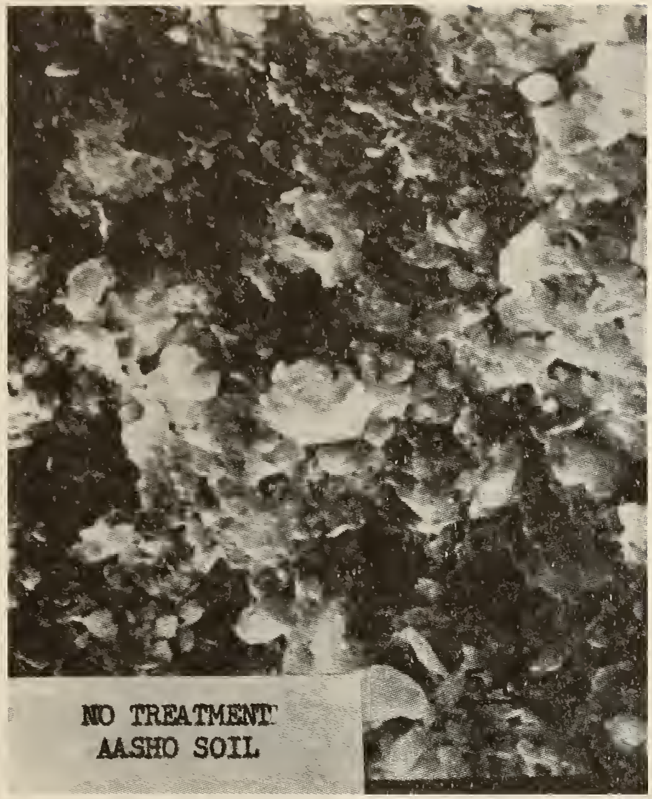

Fig. 19. Micrograph of untreated AASHO soil

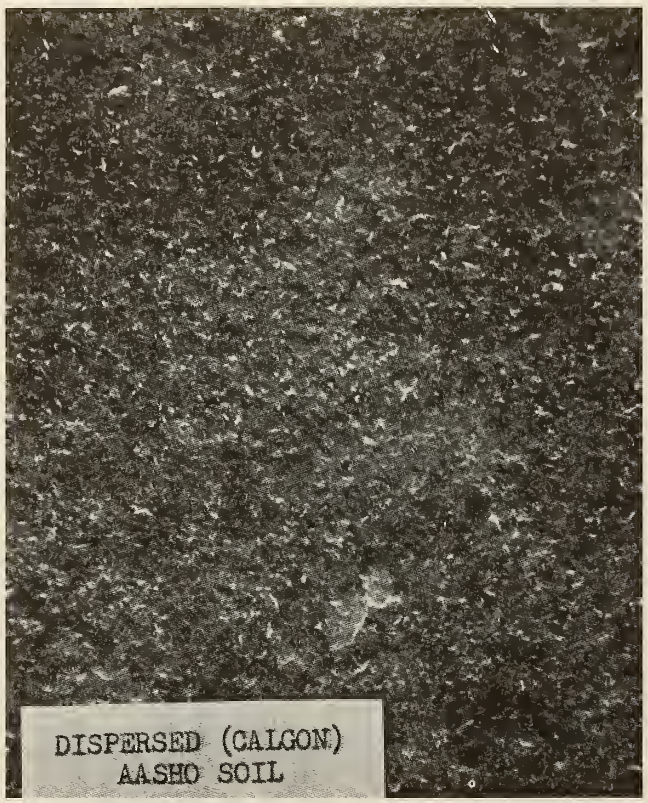

Fig. 20. Micrograph of AASHO soil treated with sodium hexametaphosphate.

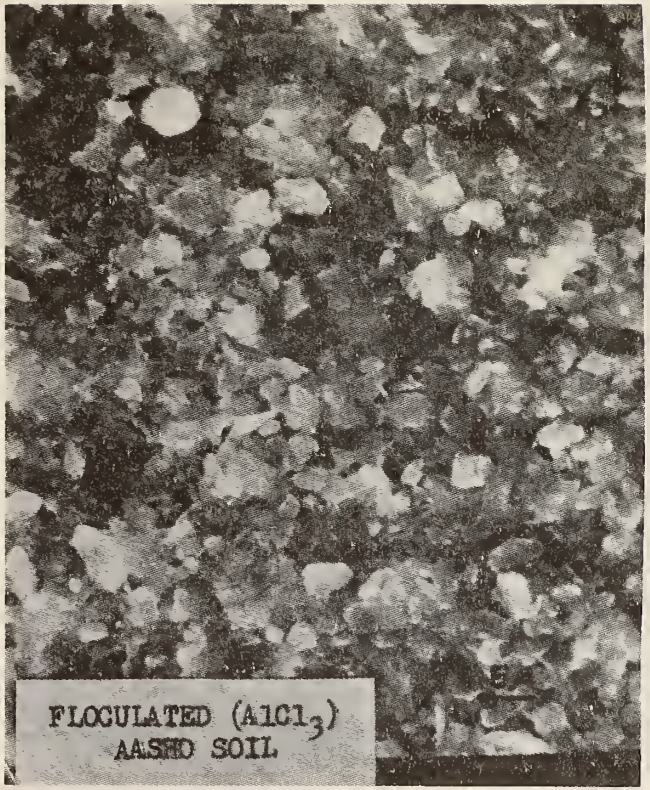

Fig. 21. Micrograph of AASHO soil treated with aluminum chloride.

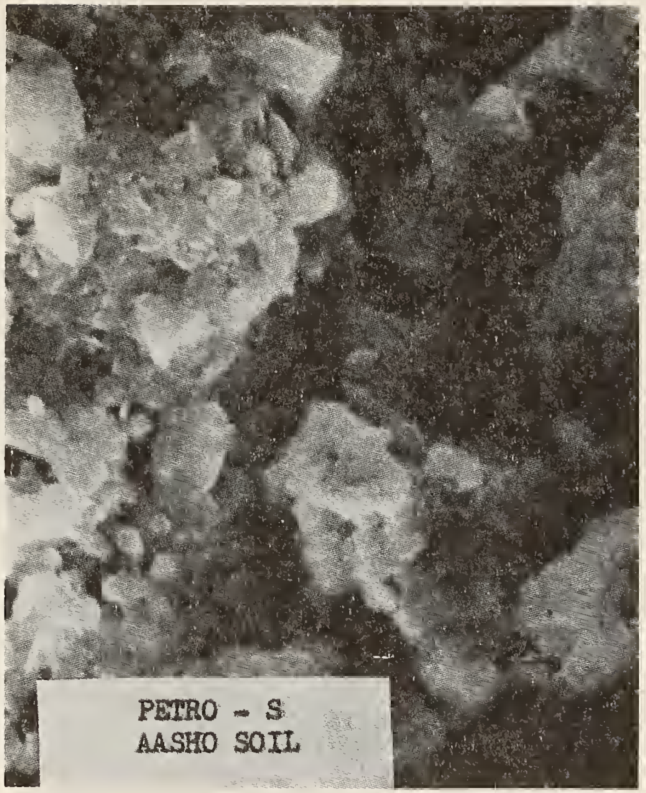

Fig. 22. Micrograph of AASHO soil treated with Petro-S.

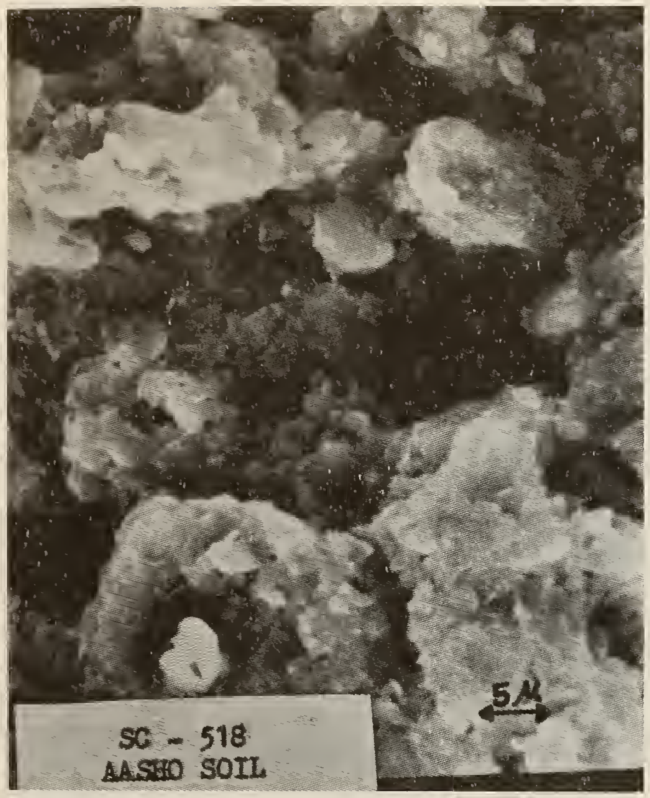

Fig. 23. Micrograph of AASHO soil treated with SC-518.

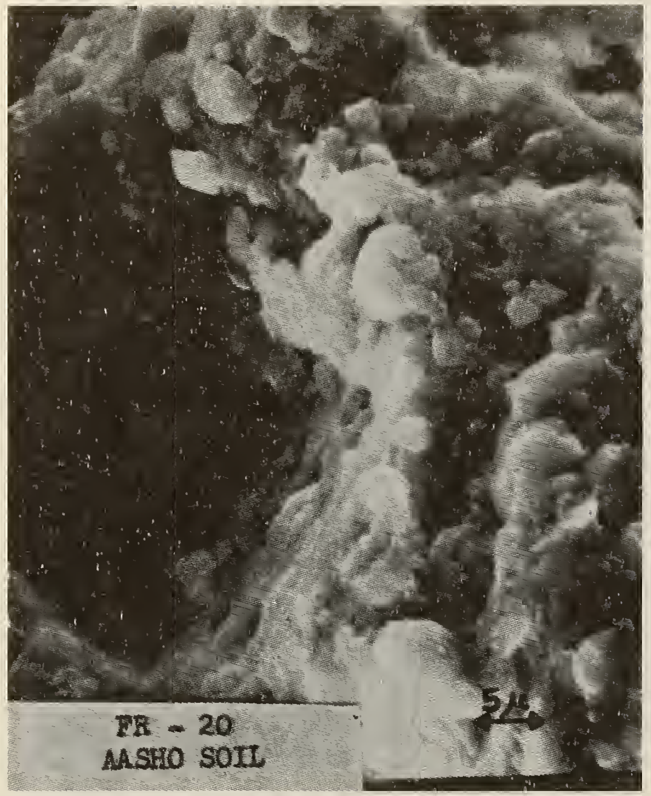

Fig. 24. Micrograph of AASHO soil treated with FR-20.

units are present. A large void is shown (dark area) on the left side of the micrograph, indicating that cluster units are very large since only a portion of one cluster unit could be shown on a single micrograph. This structure is best described by the ideal model of the cluster units in random orientation, Fig. 18. However, the FR-20/AASHO cluster units are much larger than those displayed in the model.

Study of clay structure with scanning electron microscopy correlated well with observations from the flocculation-dispersion study and M-D tests. FR-20 was shown to be an extreme flocculant with the flocculation-dispersion tests, as visually verfied in Fig. 24. SC-518 and Petro-S both had flocculation-dispersion characteristics similar to the untreated AASHO soil, and both showed the same structure appearance in the micrographs. The major difference between Petro-S and SC-518 treated soil structure and the untreated AASHO structure was in size of the cluster units. Petro-S and SC-518 treated soils had cluster units that varied in size, each unit having a more particulate appearance. Maximum size of the cluster units was also somewhat larger with Petro-S and SC-518 treatments when compared to the untreated soil.

Flocculation-dispersion characteristics and soil structure should be related to compactability of fine-grained soils. Products that strongly flocculate a soil should not be good compaction aids since they would hinder compaction by increasing particle interaction. A good compaction aid should reduce particle interaction, thereby permitting easier relative movement between particles. These concepts are substantiated from micrographs and the moisture-density tests. For example, FR-20 was a very strong flocculant that produced large cluster units. The strong attractions between clay particles in the cluster units would resist compaction, and, as it can also be postulated, more void space would be present in the soil due to card-house type flocculated structure of the clay particles. Though FR-20 was not a good compaction aid, it may still be a good soil stabilizer, increasing aggregated particle interaction and thus increasing strength. This is confirmed with its application in the AASHO soil, Table 21. This would be an important concept if one was looking for a good soil stabilizer for such uses as chemical soil stabilization of roadways, land slides, foundations, etc.

Petro-S and SC-518, both considered effective compaction aids, flocculated the soil, significantly varied the size of the individual cluster units, but produced only slight increases in bearing capacity, predominantly through increase of the angle of internal friction of the AASHO soil (Table 21). Also, their clay cluster units are more particulate and distinct appearing, and it is believed that the clusters act very much like a single unit when compacted. It is also believed that such cluster units move more easily relative to each other, and this, in turn, improves compactability of the soil. It can be speculated that varied sizes of cluster units would produce a more well-graded size distribution in a soil, reducing void space and increasing density in much the same manner as a dense-graded asphalt mix.

Effective compaction aids thus appear to "texturize" soil for better compactability. Texturize, in this case, refers to an alteration in size of cluster units to a well-graded size distribution. It can be concluded that effective compaction aids are good soil texturizers, while ineffective compaction aids are poor soil texturizers. In the case of FR-20, a strong flocculant, the soil was obviously poorly texturized since the clay particles were flocculated to such large, uniformly-sized cluster units, that this, along with increased particle interaction, reduced compactability of the soil.

Summary and Conclusions

The physical data presented within this Pilot Laboratory Study, represents laboratory testing involving nearly 4000 standard M-D specimens plus many hundreds of supplemental tests. The specific purpose of this study was to select a few chemicals for continued and more detailed evaluation with a broader range of fine-grained soils of more variable mineralogy to be studied within Phase II.

Increased density is only an indirect but readily measureable goal of treatment, a more general objective being improvement of physical and engineering properties of compacted soil materials. Clapak, Claset, Coherex, Petro-S, SA-1, and SC-518 were rated highest in M-D effectiveness (Table 19) and, as noted in Tables 21 and 22, these same products showed good improvement in shear parameters, bearing capacity, and shear strength with the largest variety of clay mineralogies. However, Petro-S showed a reduction of bearing capacity (q_d) and shear strength (τ) in the predominantly kaolinitic Decatur, whereas Claset and SA-1 decreased q_d and τ in the montmorillonitic Shelby. SC-518 decreased τ in the montmorillonitic Monona and lowered both q_d and τ in the kaolinitic Decatur.

Though making a poorer showing in M-D effectiveness when compared to the six products above, Thinwater and SS-13 improved q_d and τ in four of the six soils (the basic and acidic montmorillonitic plus kaolinitic soils, Tables 21 and 22), and Roadpacker and Kelpak improved the q_d -τ properties of both acidic and basic montmorillonitic soils.

On the basis of the above illustrations, it may be hypothesized, if not concluded, that total M-D, c, ϕ, q_d, and τ effectiveness is highly dependent on clay mineralogy. With this in mind, the following conclusions are presented:

1. Petro-S and SC-518 showed the most potential as compaction aids. Petro-S produced significant improvements in both density and optimum moisture content, while SC-518 produced significant increases in density with modest reductions in optimum moisture content. Both products showed some improvements on almost all soils tested in this investigation, regardless of mineralogy.

2. Clapak, Claset, SA-1, and Coherex indicated good potential as compaction aids on several of the fine-grained soils, particularly the kaolinitic clays. All showed improvement by both increasing density and reducing optimum moisture content.

3. Road Packer, Kelpak, Pen-E-Pac, PVO X-2100, SS-13, and Thinwater showed slight potential as compaction aids with fine-grained soils.

4. FR-20, Paczyme, PVO X-1000, Terra Krete #1, and Terra Krete #2 showed little or no potential as compaction aids with fine-grained soils.

5. Compaction aids tend to decrease internal friction or leave it unchanged, but, in the ordinary range of normal stresses, the lowering of frictional strength is generally more than offset by increased cohesion.

6. Product effectiveness is dependent on clay mineralogy and other soil properties. This dependency leads to a suspicion that most products contain surfactants and/or wetting agents, and, thus, their effectiveness is related to cation exchange capacity and clay mineralogy of a soil. Without knowing more of the chemical composition of the products and their chemical interaction with soil, complete understanding of the chemical-compaction mechanism is impossible.

7. M-D tests with known anionic, cationic, and non-ionic surfactants indicated only the anionic as potentially beneficial to density. However, the benefits were quite small compared to the commercial products mentioned in conclusions 1 and 2 above.

8. pH values of the chemical products are inconclusive in defining the role of a chemical aid to compaction. Effective compaction aids tend to be neutral to highly acidic, but the relationship is not consistent and there appeared to be no correlation between product effectiveness and pH of additive concentration.

9. Surface tension values varied significantly with the different chemical products and there was no direct correlation between

the ability of a product to improve compaction and the surface tension of the additive solution. It should be noted, however, the product most effective in increasing density, SC-518, had the lowest surface tension of all products tested.

Surface tensions of additive solutions, including water, changed upon contact with the soils, and, thus, surface tension of the original chemical additive is not the same as that ultimately in the pore fluid. Hence, effective commercial chemical compaction aids were found generally to reduce surface tension of the soil water, as evidenced by a tendency to reduce surface tension of leachate. Probability of a relation is 97%.

10. Flocculation-dispersion characteristics are somewhat inconclusive in defining the role of chemical aids in compaction, but the relationships are at least helpful for predicting which chemicals will be effective compaction aids. For example, chemical products that appear to be strong soil flocculants are not good compaction aids. Thus, some of the products that are poor compaction aids may be effective soil stabilizers.

    Chemical products do not have to disperse a soil to increase its compactability. Products that have flocculation-dispersion characteristics similar to distilled water (no treatment) show the most promise as effective compaction aids.

11. Chemical products that improve density and optimum moisture content appear to texturize the soil for better compactability. Texturized soils have "cluster units" that are varied in size with an apparent well-graded size distribution. This helps increase density, reducing void space much in the same manner as a dense-graded asphalt mixture. Clay cluster units are more particulate and distinct appearing, and it is believed compactability of a soil is also improved through reduction of particle interactions. This is somewhat displayed with the Atterberg limit tests on the selected soils. Chemical products that improved density generally caused some lowering of the liquid limit value, indicating a reduction in particle interaction.

12. Dielectric measurements indicate that effective compaction aids may have a dispersing tendency, but the data are very inconsistent, perhaps because of the need for dilution of the soil to perform these measurements.

13. Atterberg limits tests are inconclusive in regard to directly defining the role of a chemical aid to compaction, except that chemicals which cause a large change in Atterberg limits

of a particular soil will not significantly aid compaction. Magnitude of change in Atterberg limits appears dependent on cation exchange capacity of the individual soil: the higher the cation exchange capacity, the more dramatic the change. However, chemicals which cause either a significant increase or decrease in the plasticity index of a soil probably will not be effective compaction aids; probability of a relation is 81%.

14. A number of approaches were used in an effort to delineate effective chemical compaction aids for fine-grained soils. In a number of instances, the various parameters indicated relatively high probabilities that relationships were not just due to chance. Unfortunately, the relations were not considered adequately reliable for use as predictions, i.e., there appeared to be enough inevitable exceptions to these trends that moisture-density tests should not be supplanted with other criteria for use in Phase II.

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