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HEMICAL COMPACTION AIDS
OR FINE-GRAINED SOILS

Vol. II
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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

NOTICE

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16. Abstract: Volume I of this report included an extensive review of appropriate subject literature and the Phase I pilot laboratory moisture-density-strength study of 20 chemicals with 8 soils of varying origin and mineralogy. Also included was a theoretical discussion of possible mechanisms of chemical compaction aids, properties of the 26 soils used in the laboratory investigations of Phases I and II, and data from supplemental tests designed to improve understanding of the influences of chemicals on fine-grained soils. Six chemicals were selected for the more extensive laboratory evaluations with the 18 soils of Phase II.

Volume II, contained herein, includes moisture-density-strength screening tests performed on several additional chemicals and an evaluation of the standard AASHTO T-99 moisture-density test results performed on soil specimens prepared under varying conditions of drying, pulverization, and re-use. Theory and applicability of project use of the Iowa K-Test for determination of cohesion, angle of internal friction, lateral stress ratio, and other soil parameters obtained from 1/30 cu ft specimens are described. Also presented are the Phase II laboratory moisture-density strength study of chemicals selected primarily from Phase I as evaluated through both qualitative and statistically related procedures, laboratory compaction growth, and 7-day moist cure results, and a discussion of the mechanisms of chemical compaction aids as evaluated through the assistance of infrared spectrography, vapor pressure osmometer, and zeta potential tests. Based on the total study, an "ideal" compaction aid is described. Phase III presents results of field trials conducted on a roadway embankment near Knoxville, Marion County, Iowa, and a soil-aggregate base near Villanueva, New Mexico. Though detailed conclusions are presented in the respective sections of Volumes I and II, the major findings achieved in relationship to total project of objectives are presented herein.

17. Key Words Moisture Density Relations,
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PREFACE

Volume I of this report presented the prime feasibility analyses of chemical products used as aids for compaction of fine-grained soils and included the principal objectives of Phase I of the total project (i.e., the review of appropriate subject literature and the pilot laboratory study). Also included in Volume I were (1) a model compaction theory of potential mechanisms of chemical compaction aids, (2) a description of the properties of the twenty-six soils utilized in the total study, and (3) analyses of a series of supplemental tests for development of further understanding of potential mechanistic influences of the chemicals on fine-grained soils.

This portion (Volume II) of the report primarily addresses the objectives of Phases II and III of the study. Phase II, Laboratory Study, determines the effects of the more promising Phase I chemical compaction aids on a broader range of fine-grained soils, and Phase III, Field Evaluation, studies several chemicals prior to, during, and following their incorporation into the harsher, less environmentally controlled atmosphere of constructed field test sections. In addition, (1) a testing process is described which was utilized throughout the remainder of the study, (2) changes brought about in moisture-density parameters through slight variations of the T-99 test procedure are analyzed, and (3) analyses of an additional series of supplemental tests used to fingerprint and/or to further the developmental understanding of chemical mechanisms in fine-grained soils.

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*

---

* 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 chemicals in additive
D	diameter of sphere (inches)
D_f	surcharge or depth of foundation below soil surface
d	specimen length
E	dielectric dispersion; vertical deformation modulus
H	initial or air-dry hygroscopic moisture content (percent)
h	penetration of sphere into compacted soil (inches)
K	ratio of soil horizontal to vertical stress
K_i	coefficient of lateral earth pressure
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
S_L	shrinkage limit
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

IOWA K-TEST

A test was desired to evaluate strength of the 1/30 cu ft T-99 compacted soil specimens. Unconfined compression tests were ruled out since the best highway soils are generally granular with low unconfined strengths, whereas clayey soils may have high unconfined strength. Triaxial testing and/or a continued adaptation of the bore hole shear test were considered too time-consuming. In addition, triaxial tests induce too much end restraint from specimens of less than 2.0 height/diameter ratios.

In a prior development with support from the Iowa State University Engineering Research Institute and the Iowa State University Research Foundation, Inc., the Iowa K-Test was adopted and utilized in the remainder of this project,[75,76,77] since the test gives discrete evaluations of c, ϕ, and other strength parameters from single, 1/30 cu ft compacted soil specimens. The specimens are subjected to vertical compression while confined in a split steel mold which acts as a spring, such that spreading of the mold provides a measure of lateral stress. Thus K, or the ratio of soil horizontal to vertical stress, may be continuously monitored and used to obtain strength parameters and moduli as the test progresses. The K-Test simulates an undrained, rapid field loading situation and, therefore, appeared particularly applicable to a fine-grained soil highway embankment.

It is the purpose of this section to only illustrate the principles on which the K-Test is based and its applicability to the study of chemical compaction aids for fine-grained soils.

Preliminary K-Test

In its initial stages, the K-Test device consisted of measuring the circumferential expansion of a 4-in. diameter Proctor density

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[75] U.S. Patent No. 4,047,425. "Testing Device for Measuring Lateral Pressure Induced on a Material by a Vertical Applied Pressure." Inventors: R. L. Handy and J. M. Hoover 1975.

[76] A. J. Lutenegger, "The Iowa Continuous K-Test; A Laboratory Test for Measuring Lateral Stresses in Soils Induced by Vertical Applied Loads." Unpublished Master of Science Thesis, Iowa State University (1977). Copyright 1977, Iowa State University Research Foundation.

[77] R. L. Handy, A. J. Lutenegger, and J. M. Hoover, "The Iowa K-Test." Prepared for presentation at Annual Meeting, Transportation Research Board, Washington D.C., January 1978.

split mold when a compacted soil cylinder was confined in the mold and subjected to vertical stress. The mold was calibrated using a tangential force and later using air pressure in a rubber membrane. Preliminary tests were performed on compacted soils ranging from A-1-a crushed stone to A-7-6 clay with no chemical additives. Figure 25 shows the results from testing three different soils with this primitive apparatus. The higher the lateral stress ratio, K, the lower the stability. The data of Fig. 25 shows that K was not constant but varied as a function of σ_1, the normal or vertical stress.

Soil placed under load at first behaves pseudo-elastically, with strain proportional to stress--a property utilized in pavement design and designated by a modulus of subgrade reaction, k.

Under increasing load, soil grains become increasingly dislocated with respect to one another, and the soil enters a plastic or failed state. For a ϕ-soil (Fig. 26a), the ratio between horizontal and vertical principal stresses becomes constant and is described by

$$\frac{\sigma_3}{\sigma_1} = K = \frac{1 - \sin \phi}{1 + \sin \phi} \qquad (16)$$

and

$$\phi = 90 - 2 \text{ arc } \tan \sqrt{K} \qquad (16a)$$

where σ_1 and σ_3 are the major principal stresses, and ϕ is the angle of internal friction.

Most soils have both internal friction (ϕ) and cohesion (c), or shearing strength under zero-applied normal stress. Extrapolation of the linear failure envelope to the tension side (Fig. 26b) gives a zero-shearing stress intercept sometimes referred to as the intrinsic pressure, σ_i. The lateral stress ratio, then, is not constant but decreases with increasing applied stress. This is because the slopes of tangents from the origin to the Mohr failure circles, OA and OB, are not constant as in Fig. 26a, but decrease as in Fig. 26b. Thus, a decreasing value of determined K is indicative of cohesion, and a constant K means that cohesion is zero.

The two types of behavior of K are shown by data in Fig. 25. A constant K is shown by the curve for the graded crushed stone almost from the beginning of the test; the mean value from 46 data points is $K = 0.1183 \pm 0.009$, the ± entry signifying 95% confidence limits on the mean. Substituting this value in Eq. (16) and solving for ϕ gives $\phi = 52.05^\circ \pm 0.13^\circ$, a reasonable value for compacted, graded crushed stone with a good service record. Triaxial tests on this stone gave $\phi' = 44.5^\circ$ and $c' = 20.0$ psi on an effective stress basis (Wassenaar et al., 1967). The difference may be attributed to negative pore pressure due to dilatancy and to an unreasonably high triaxial test value for cohesion.

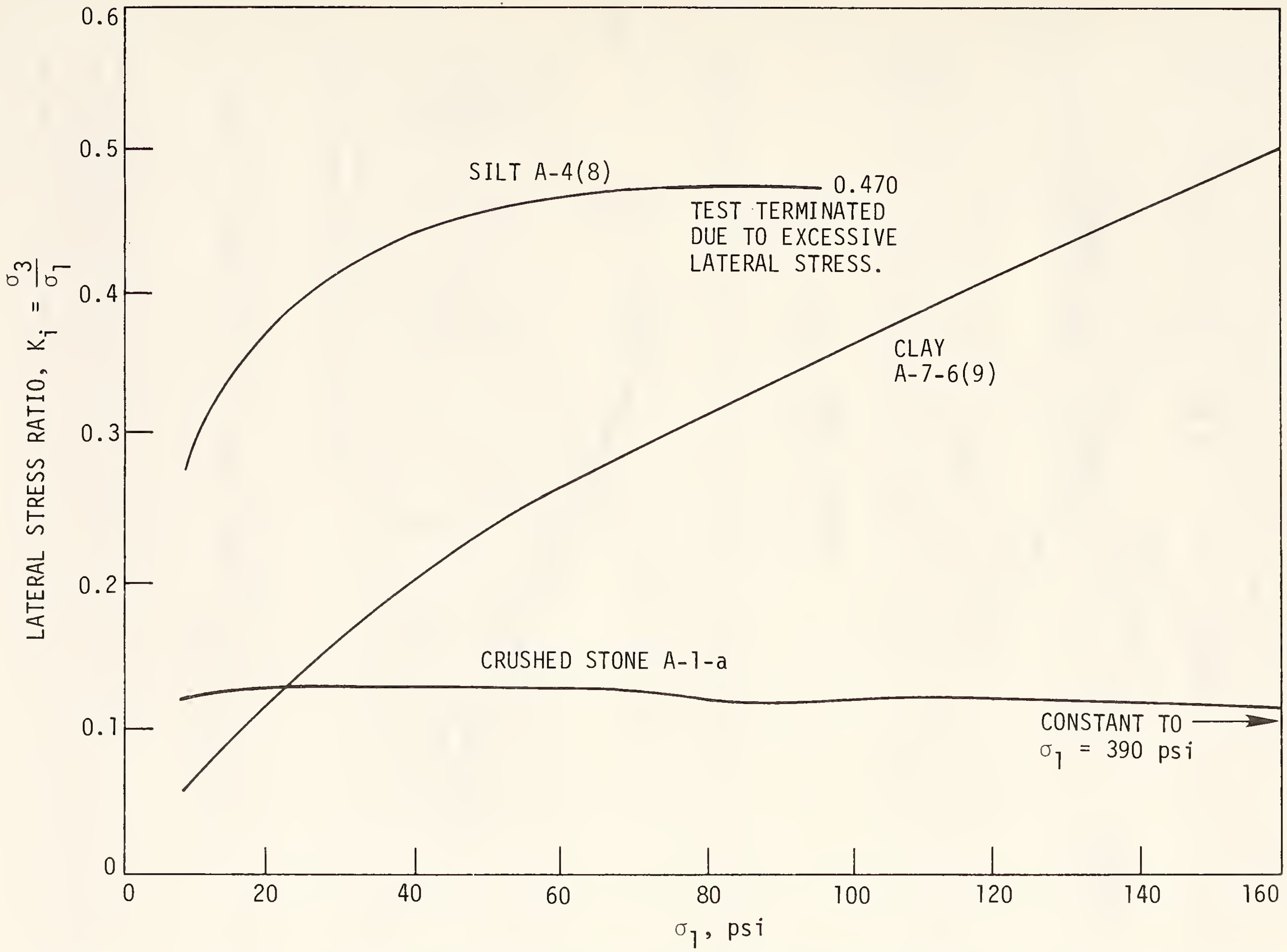


Fig. 25. Lateral stress ratios from several soils compacted with standard effort and optimum moisture content. A lower K_i means a better stability.

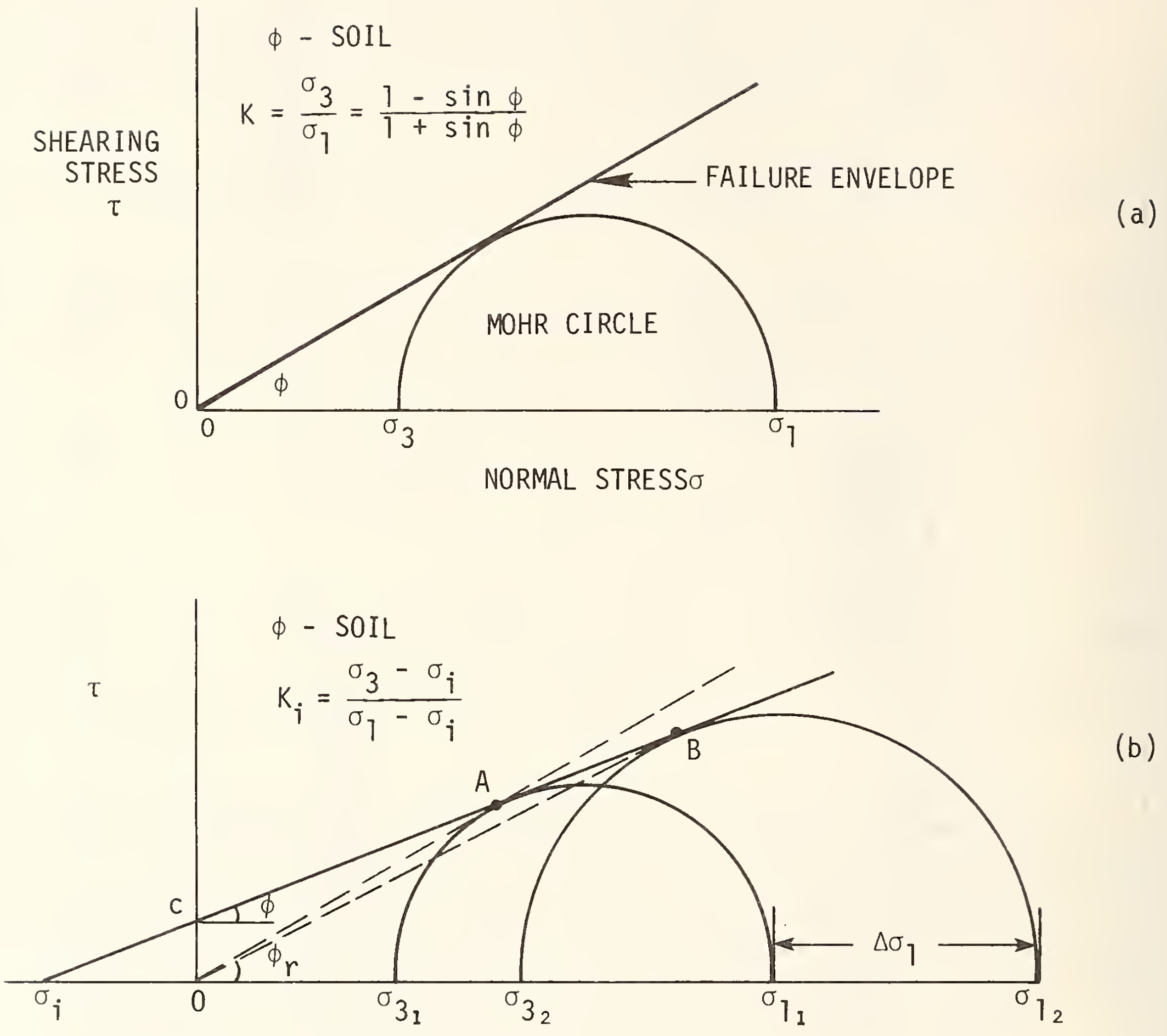


Fig. 26. Lateral stress coefficient, K_i, for (a) frictional soil and (b) cohesive soil.

The curve in Fig. 25 for a loessial silt compacted under standard conditions at near-optimum moisture content indicates a gradual reduction in K as cohesion was lost, until a constant value of 0.470 was reached. Substitution of this value in Eq. (16) gives $\phi = 21.1^{o}$, a reasonable value for loess if there is some positive pore water pressure. The latter is probable because of near-saturation on molding and consolidation during the test. Pore pressures were not monitored during these preliminary trials.

The clay curve in Fig. 25 shows the behavior for clay, with K increasing continuously throughout the test, indicative of a retained cohesion. In this case, c and ϕ cannot be directly ascertained from σ_3/σ_1 values.

For design purposes, it is not necessary to solve for c and ϕ, although a method to do this will be shown later. For example, from the curves in Fig. 25a, a 100 psi applied vertical load (as by a truck tire) will induce the following lateral pressures in soil underneath the load.

Silt: 0.470 × 100 = 47 psi
Clay: 0.360 × 100 = 36 psi
Stone: 0.120 × 100 = 12 psi

These lateral pressures may be entered on the σ_1 scale to give vertical uplift pressures developed in soil adjacent to the loaded area:

Silt: 0.440 × 47 = 20.7 psi
Clay: 0.164 × 36 = 5.9 psi
Stone: 0.12 × 12 = 1.5 psi

These pressures must be constrained by the pavement structure through pressure brought to bear as a result of pavement weight and flexural strength. These indicated pressures will depend in part on the lateral restraint of the system; the lateral restraint offered by the test cell was rather low in this regard so as to encourage plastic failure.

This exercise is not intended to imply a reliability for design, but it does show how the test evaluates a soil on the basis of behavior under realistic stress conditions.

K_i, c, and ϕ

Since this test involves continuous monitoring of σ_3 and σ_1, it is a relatively simple matter to evaluate c and ϕ for any soil from the shifting Mohr circle. For example, in Fig. 26b, a tangent drawn to the two Mohr circles will give a measure of c, ϕ, and the intrinsic pressure σ_i. The larger the base, $\Delta\sigma_1$, over which the differentiation is made, the less random error exists in the results, but also the lower the sensitivity to changes occurring in the soil. A ratio, K_i, may be defined, analogous to K, for cohesionless soils.

From Fig. 26b and the two Mohr circles,

$$K_i = \frac{\sigma_{3_1} - \sigma_i}{\sigma_{1_1} - \sigma_i} = \frac{\sigma_{3_2} - \sigma_i}{\sigma_{1_2} - \sigma_i} \tag{17}$$

Solving for σ_i,

$$\sigma_i = \frac{\sigma_{1_2}\sigma_{3_1} - \sigma_{1_1}\sigma_{3_2}}{\sigma_{1_2} - \sigma_{1_1} - \sigma_{3_2} + \sigma_{3_1}} \tag{18}$$

Once σ_i is evaluated from any two data sets, K_i may be obtained from Eq. (17). K_i then is substituted into Eq. (16) to obtain ϕ, and from Fig. 26b,

$$c = - \sigma_i \tan \phi \tag{19}$$

Example: Two adjacent points for the clay were

	1	2
σ_1	55.720	63.680
σ_3	13.859	17.743

From Eq. (18), $\sigma_i = -26.030$ psi.

From Eq. (17) and the first point, $K_i = 0.4879$

From Eq. (16), $\phi = 20.13°$

From Eq. (19), $c = 9.54$ psi.

The above manipulations were programmed to provide running K_i, c, ϕ values from consecutive data sets. Representative plots are shown in Figs. 27 and 28 for stone and clay, respectively. Developed cohesion averaged zero for stone and increased throughout the test for clay, indicative of consolidation. The friction angle and K_i for the stone were essentially constant, whereas K_i went up and ϕ went down for the clay, indicative of pore pressure and loss of strength upon remolding.

In Fig. 29 can be seen the effect of a shorter $\Delta\sigma_1$ base for calculation of developed c and ϕ for the clay; the scatter for c increased with increased stress due to the longer "lever" exerted

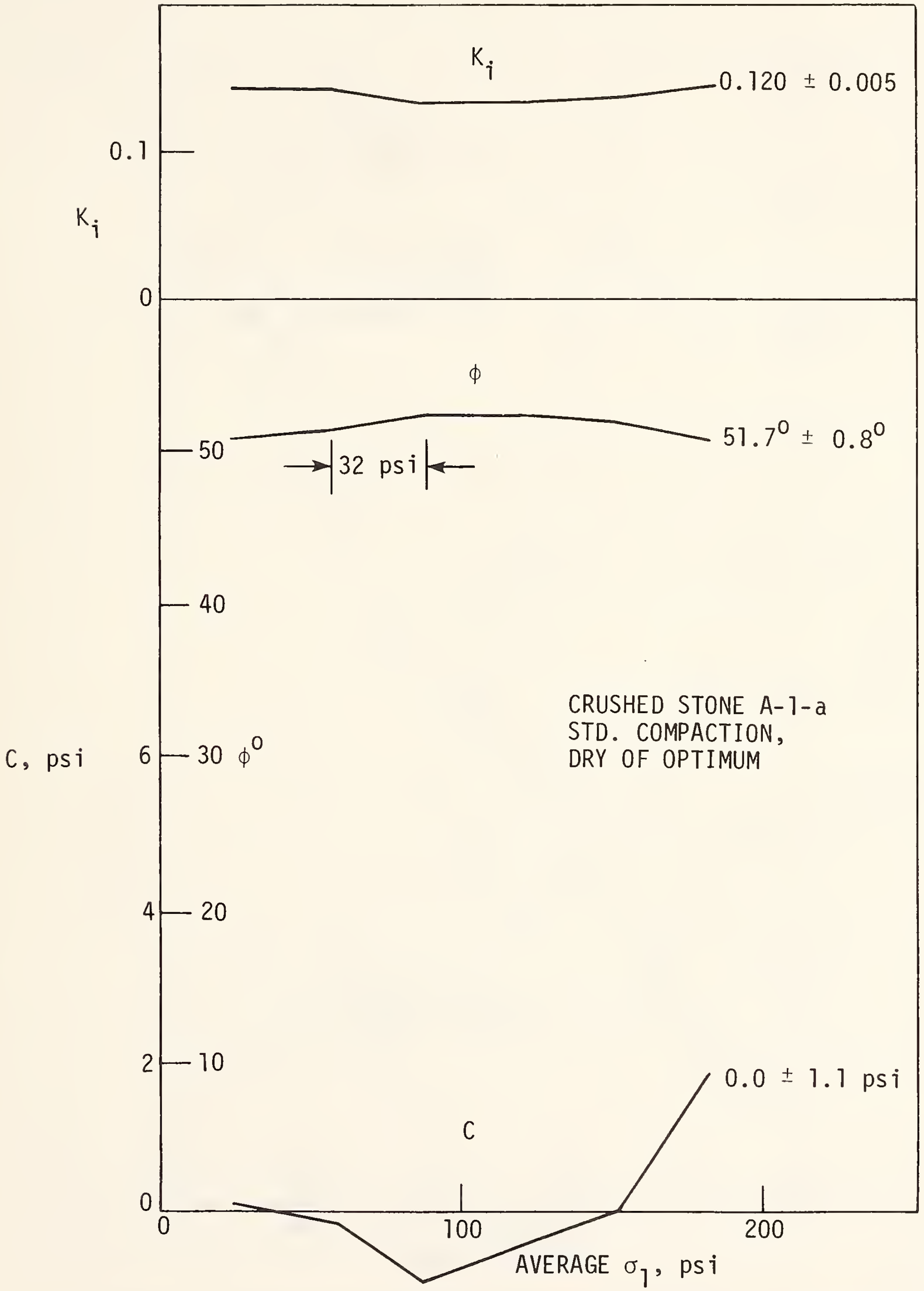


Fig. 27. K-Test diagram for a compacted, graded limestone.

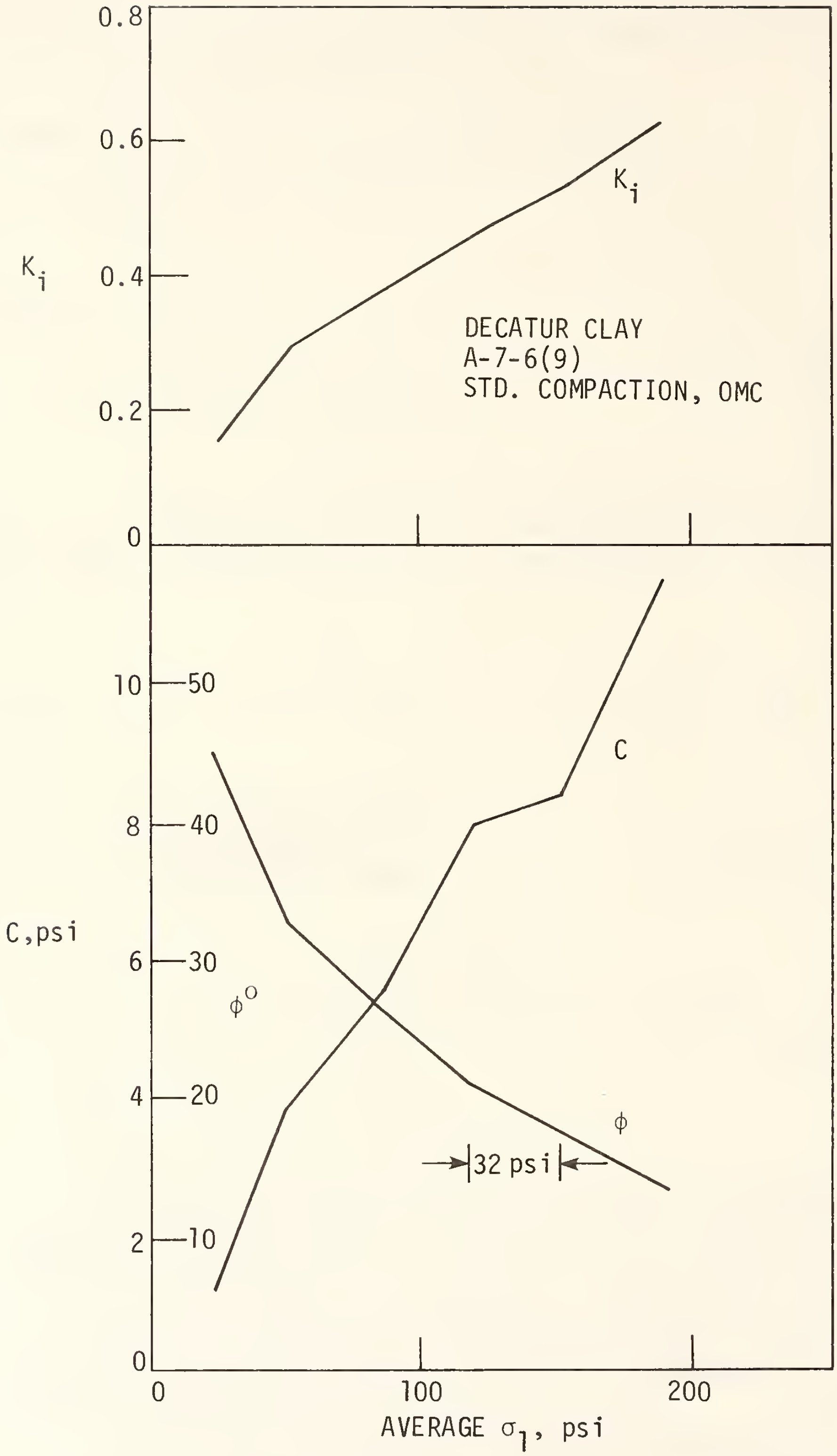


Fig. 28. K-Test diagram for Decatur clay compacted at optimum moisture content.

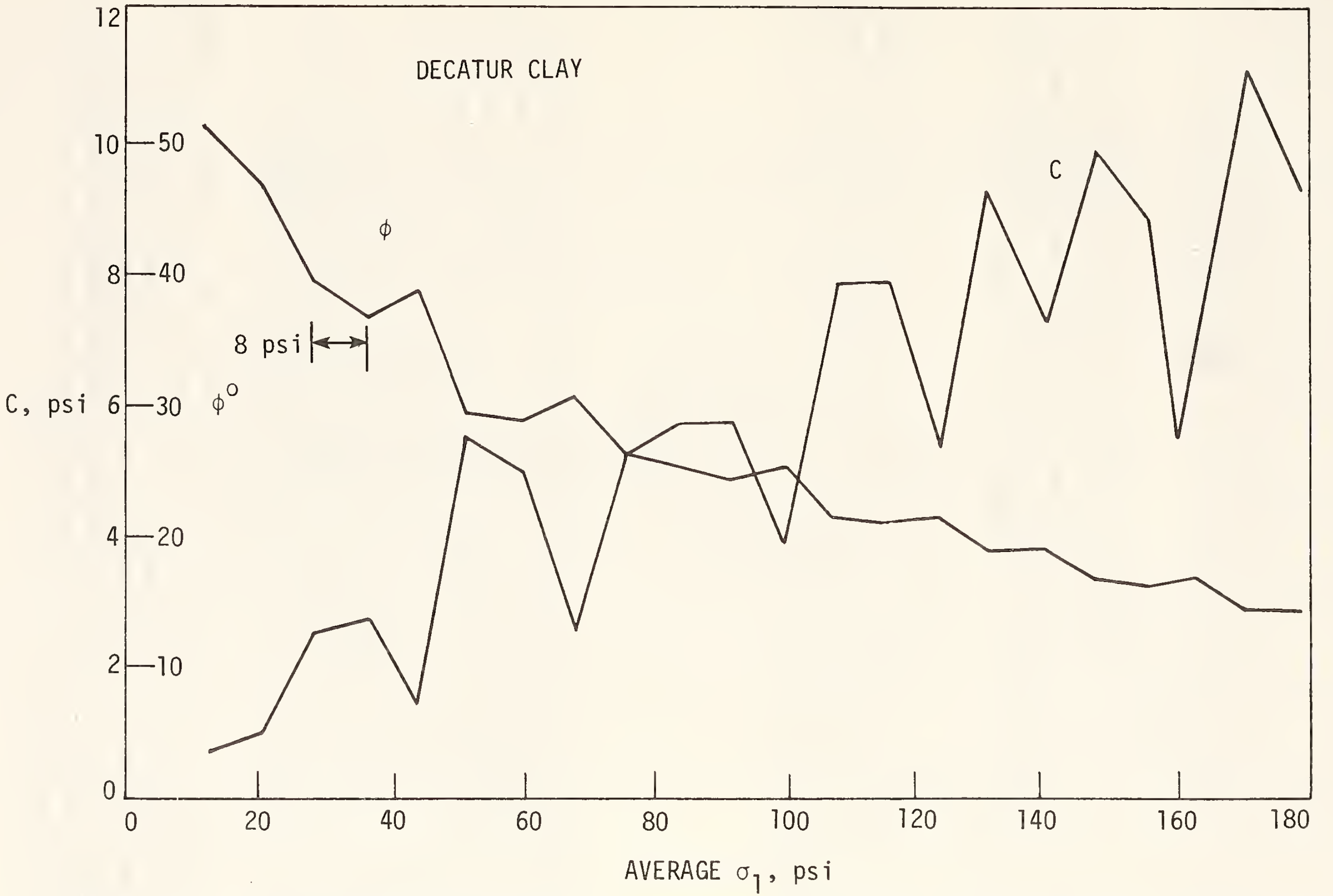


Fig. 29. K-Test diagram for Decatur clay, showing increased resolution and scatter as a result of a shortened $\Delta\sigma_1$ base. The same raw data were used as for Fig. 28.

by the tangent to the Mohr circles (near A and B in Fig. 26b) as the circles translocate to the right. The scatter on ϕ decreases as the tangent curve becomes flatter, the coefficient of variation remaining about the same. Some of the scatter in Fig. 29 is real, the specimen alternately shearing and redeveloping cohesive strength; on the other hand, smoothed curves are preferred for interpretation, and negative cohesion values in Fig. 27 either were impossible or signified positive pore pressures.

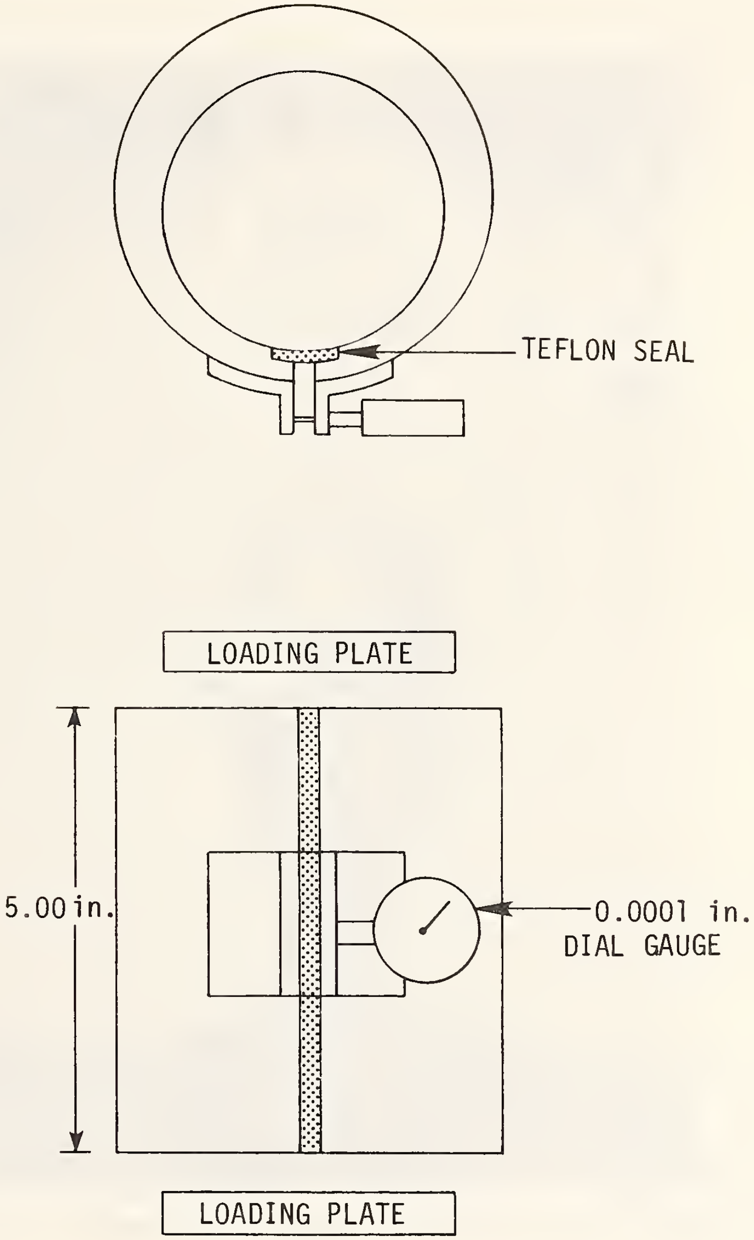
Plots for the crushed stone and silt, similar to those of Fig. 29, were also produced. The crushed stone showed a consistently high ϕ around 51°, with c hovering around zero. The loess first behaved as a weak granular material, with ϕ about 20° and c around 2 psi, then showed effects from pore pressure, ϕ dropping and c increasing with increasing σ_1.

In summary, the trends of c and ϕ shown in Figs. 27, 28, and 29 are as might be expected, although actual indicated values may have been somewhat incorrect. Though subsequent methods of data correction have been suggested,[77] comparative tests indicate that even uncorrected $c - \phi$ parameters are not so seriously in error that they would not be covered by normal design safety factors.

Mold Redesign

The K-Test mold used in subsequent tests, Fig. 30 (a and b), was designed with a thickened wall at the back, which is the zone of maximum bending moment. The opposite side was slotted and had an internal Teflon strip that acted as a seal. The mold was made from cold-rolled steel, the interior being polished and chromium-plated to resist abrasion. A 0.0001 in. dial gage was mounted externally to monitor expansion. It was important that the mold be equal to or slightly oversized compared to the specimen diameter, in order to avoid an initial passive condition if the soil was forced into the mold; that is, the horizontal confining stress initially must not exceed the vertical stress since an initial passive stress state must be overcome before active state K data can be obtained.

Several procedures involving the use of air pressure were used to calibrate the K-Test mold. More successful, however, has been the continued use of a soft plastic 1/30 cu ft molded specimen with K nominally equal to 1.0. In this way, the horizontal stress was assumed to equal the applied vertical stress, and a horizontal stress vs. mold opening calibration was prepared; calibrations were linear, enabling data reduction by linear methods.



(a)

Fig. 30. Constant elasticity model Iowa K-Test mold for Proctor or equivalent sized specimens.

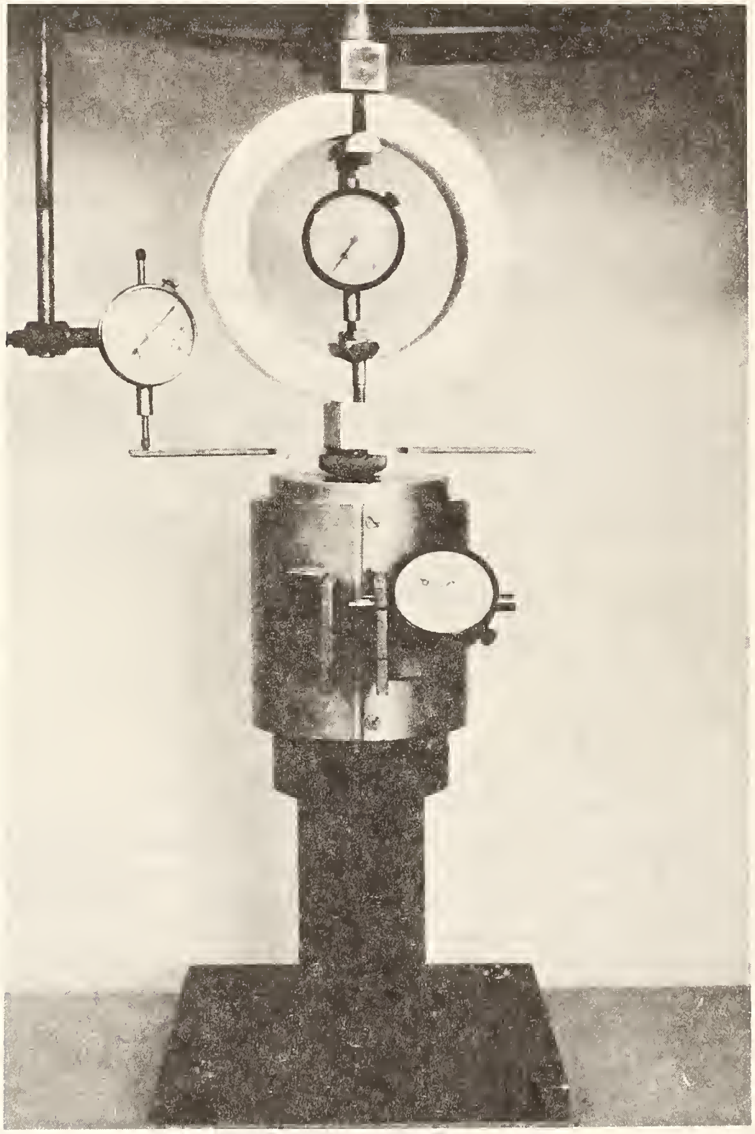


Fig. 30. Continued. (b) Actual model.

Stress Path Interpretation of K-Test Data

Graphs such as Figs. 27, 28, and 29, while of interest for showing how strength may develop in a soil under increasing load, are of little, direct use where mean values of c and ϕ are needed. For this usage, it is more convenient to plot a p-q diagram as in Fig. 31, fit a line by least squares regression, and convert the slope and intercept to ϕ and c.[9] This also had the advantage of allowing several tests to be plotted on a single graph.

E from the K-Test

An estimate of vertical deformation modulus, E, useful in pavement design and required for finite element modeling, may be directly obtained from K-Test stress-strain plots. This E is not a true elastic modulus since the soil is in failure. It may be a fairly accurate index of what happens in the field where horizontal restraint increases with vertical stress, particularly in comparison with the triaxial test where lateral stress is constant.

Other Parameters from the K-Test

Thought not specifically utilized in this project, other parameters may be obtained from K-Tests.[76,77] Poisson's ratio is often required for characterization of stress under load and is the ratio of lateral to vertical deformation. A plot of these deformations may be a direct output from the K-Test, most conveniently made by means of a programmable calculator and plotter.

A major criticism of the K-Test is the undeniable existence and influence of friction between the soil and its confining steel mold and end platens. Platen friction is also a problem in the triaxial test where its effects as a variable are minimized by adapting a standard height-to-diameter ratio, normally 2.0. In the K-Test, this ratio is closer to 1.1 and is coupled with the soil-steel influence from the mold.

In order to ascertain side friction influences, a scheme for measuring these was developed; simply, the K-Test mold was placed on a pressure cell such that the mold was rigidly supported while the soil specimen moved downward, activating the base cell piston. In this way, all side friction was mobilized upward and thereby equaled the difference between top and bottom loads on the specimen. This procedure was found to offer some unique advantages in that:

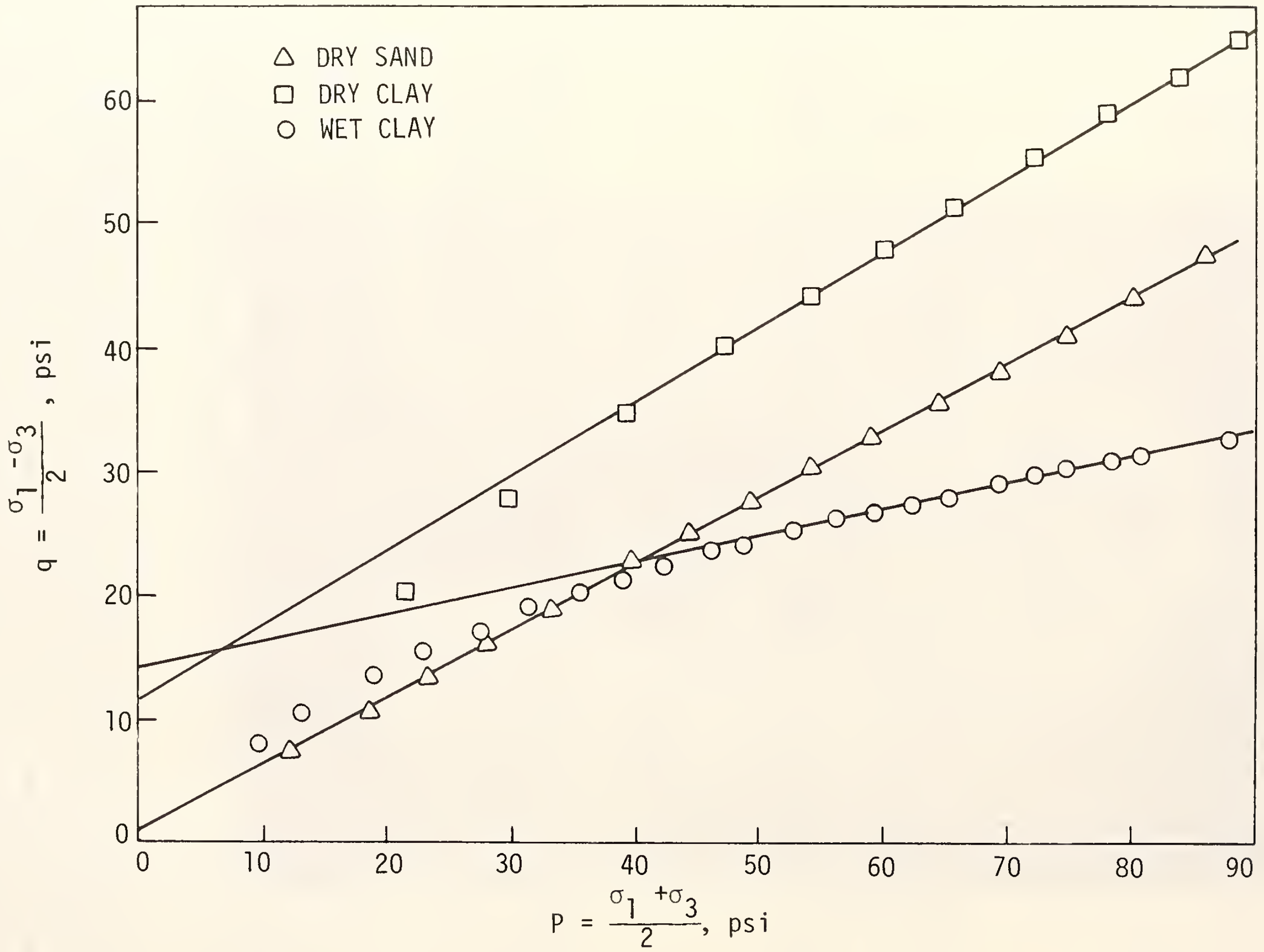


Fig. 31. Stress paths from typical K-Tests.

1. Soil-to-steel friction is directly obtained as a function of normal stress, giving soil-to-steel sliding friction parameters, c_s and ϕ_s, that are potentially useful in design of pile, earth movers, etc.

2. If the measured soil-to-steel side friction parameters are assumed to apply to end platens of similar material and finish, average boundary stresses will be known, and so there exists a potential for a complete solution for stresses within the specimen. This would appear to offer a substantial advance from present triaxial testing.

3. Pore pressure effects may be evaluated directly from the influence on side friction rather than through pressure transducers.

Applicability to Project

A simple and rapid laboratory test was essential for various strength comparisons of the myriad of chemical compaction aid - soil combinations within Phase II. The K-Test allowed such comparisons through analysis of four primary parameters: cohesion (c), angle of internal friction (ϕ), lateral stress ratio (K_i), and vertical deformation modulus (E). Each of these parameters was easily and quickly obtainable through use of 1/30 cu ft T-99 compacted specimens. For comparative purposes only, and due to time limitations, no attempt was made to correct these parameters either for side and end friction effects or for pore water pressures. However, analytical comparisons of changes of each of the observed parameters due to introduction of chemical could be quickly ascertained for each specimen within a moisture-density plot, as is illustrated in Fig. 32 for untreated and SC-518 treated Marias soil series.

As previously indicated, if a chemical is moisture and density effective, it is incorrect to evaluate it only in such terms since high density is but an intermediary to the true objective of a more stable fine-grained soil. For example, improved c, ϕ, and/or E values would indicate improved shearing resistance and vertical stress-strain characteristics. In addition, c and ϕ may be used to predict the maximum load per unit of area which a soil can support without rupture (i.e., its bearing capacity), as well as assist in defining possible flocculation vs. dispersion effects from addition of a chemical to a soil.

In evaluating field applications of any product(s) during Phase III, moisture-density relationships could be easily obtained through conventional in-place M-D techniques. However, stability evaluations would have to heavily rely on empirical tests such as in-place CBR,

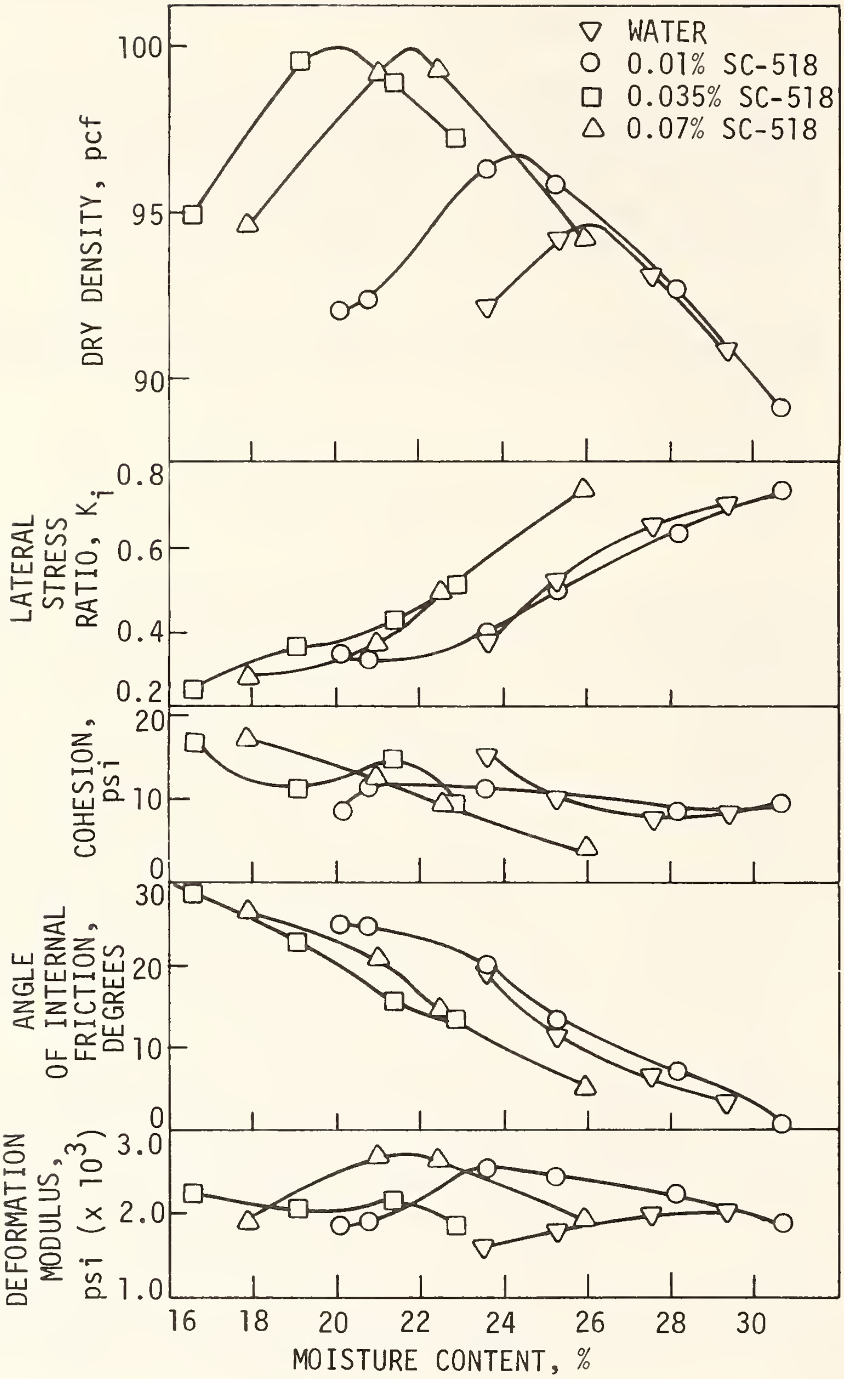


Fig. 32. Relationship of dry density, lateral stress ratio, cohesion, angle of internal friction, and vertical deformation modulus vs. moisture content for untreated and SC-518 treated Marias soil series.

Benkelman Beam, etc. Consequently, a portable K-Test unit, Figs. 33 and 34, was adopted and ultimately used for on-site determination of c, ϕ, and K_i values for 4-in. diameter Shelby tube specimens obtained from the test sections.

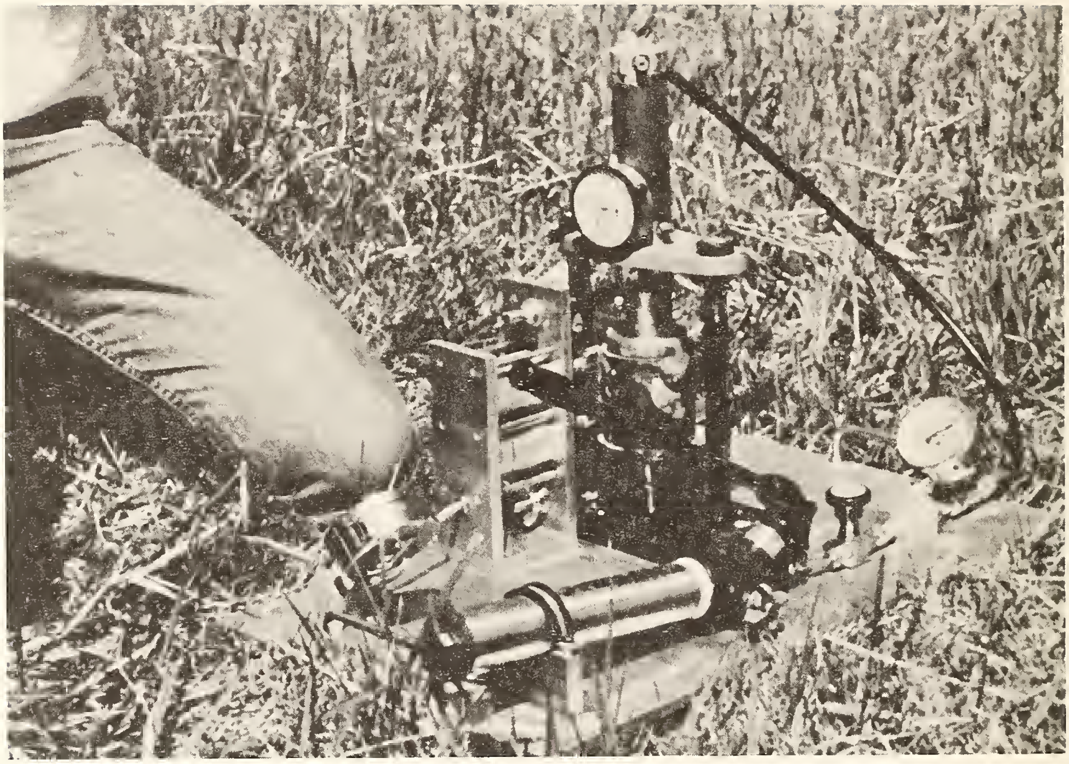


Fig. 33. Variable elasticity model K-Test (portable model).

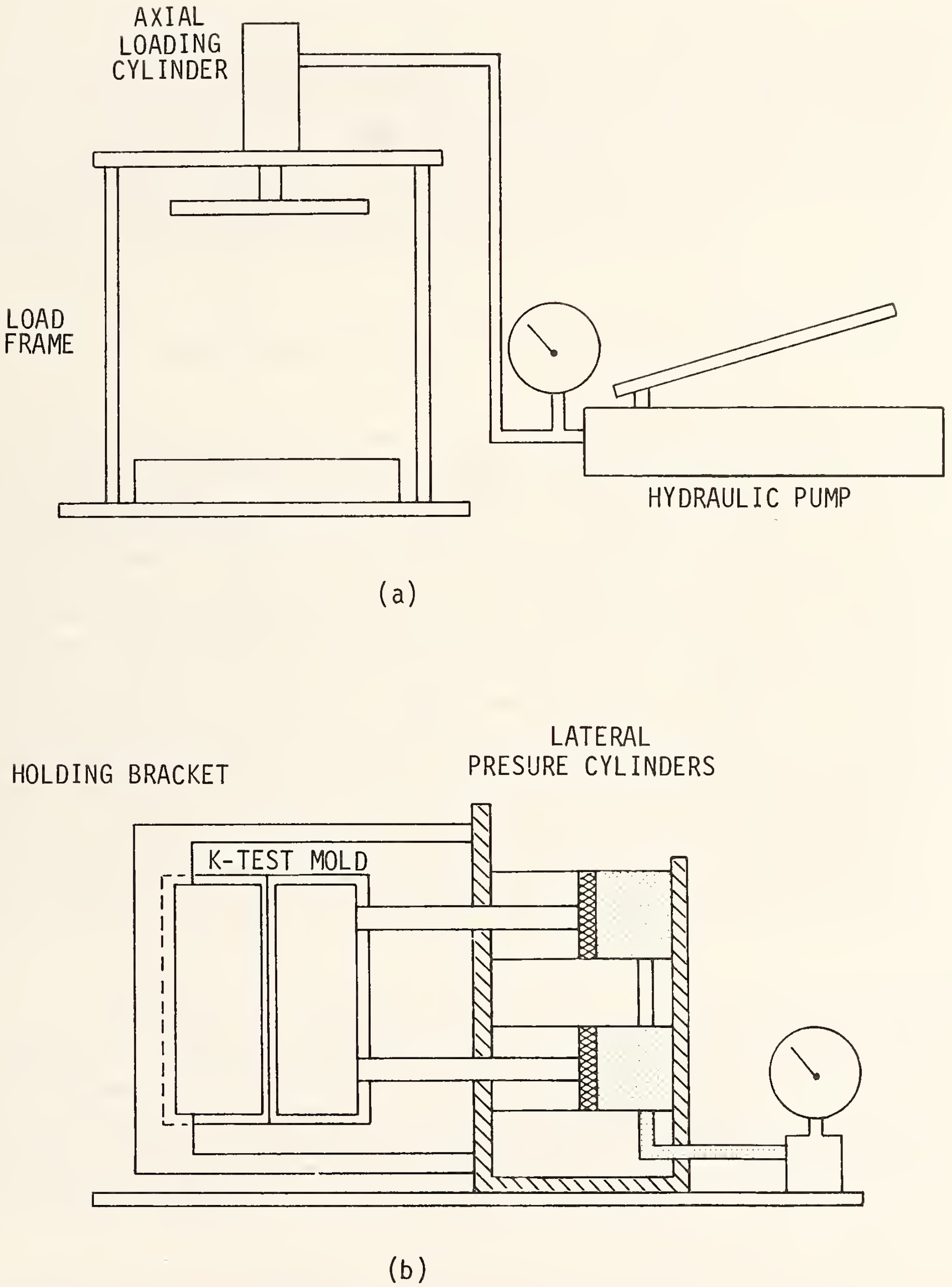


Fig. 34. Schematic of portable K-Test loading system (a) and lateral pressure monitoring system (b).

PHASE II - LABORATORY STUDY

The purpose of the Phase II - Laboratory Study was to determine the effects of the more promising Phase I chemical compaction aids on the moisture-density and other properties of a broader range of fine-grained soils. The eighteen soils selected for Phase II were representative of major U.S. soil types, having a variety of engineering characteristics and clay mineralogies. Properties of the eighteen soils were previously presented in Table 8.

Variations in Moisture-Density Test Procedure

Initially in this project, all moisture-density specimens of both treated and untreated soils were produced through the re-use procedure whereby compacted specimens were pulverized and remolded for successive points on the M-D curve. Without exception, the several products tried in this fashion produced no substantial changes in M-D curves. However, by using a freshly-mixed soil for each M-D specimen, significantly different M-D curves were often produced, some products showing definite effectiveness in M-D relationships where the M-D curves shifted to the left and up. An example of this, previously illustrated with the AASHO soil, Fig. 8, illustrated (a) substantially no variation in the M-D relation between the untreated and treated air-dried soil where re-use of specimens was permitted, and (b) distinct variation where only fresh air-dried specimens were used. It was suspected that much of the data obtained during the Literature Review (Vol. I, pp. 15-58) reflected the soil re-use procedure of M-D determination and may be the principal cause for some authors stating that the product they investigated showed no improvement in laboratory M-D testing.

The effect of re-use may be explained. Re-use of soil produces continued weakening of the structure, and less compaction energy is expended to break up aggregated particles. It is this energy that might plausibly be reduced by use of a chemical compaction aid. Furthermore, re-use, even if achieving higher density, may actually weaken the soil by destroying the aggregated structure. In some cases, re-use may give lower density by creating a poorer gradation of aggregate sizes.

One of the conceptual questions for the objectives of this project centered on whether or not present laboratory methods accurately represent normal field compaction procedures. In most instances, a base, subbase, or soil lift is either dried back to OMC or small amounts of water are added and mixed, and then the lift is compacted. It obviously is not cycled through air drying, pulverizing, remixing, and recompacting and repeated until the desired moisture and density are achieved.

Thus, to more closely discern the effect of chemical additives on compaction and to more closely analyze simulated field compaction procedures, a series of otherwise standard T-99 density tests was performed on the Phase II soils (Table 8) under the following conditions:

1. Soil fully air-dried and pulverized; re-use specimens for each M-D point: (ADR)*

2. Soil fully air-dried and pulverized; fresh soil specimens for each M-D point: (ADF)*

3. Soil undried** or only partially air-dried (to get below anticipated optimum moisture content), partially pulverized (to reduce clods to workable size); re-use specimens for each M-D point: (PADR)*

4. Soil undried or only partially air dried, partially pulverized; fresh soil specimens for each M-D point: (PADF)*

Each specimen thus molded was immediately utilized in the Iowa K-Test. Test Condition 4, above, was assumed as most closely simulating field compaction and, therefore, became the datum for comparison with Conditions 1-3. Table 29 summarizes the changes in untreated soil maximum density, optimum moisture content, lateral pressure ratio, and angle of internal friction, which occurred due to the variable conditions of drying, pulverizing, and soil usage (as compared to that of the PADF condition). It will be noted that these changes were significant: overall lab densities (γ_d) varied from +6.9 to -6.5 pcf, OMC's varied from -9.2 to +8.6%, and friction angles (ϕ) varied from +19° to - 17°, compared to that of the PADF specimens. Pressure ratio (K_i) values showed changes of +0.22 to -0.27, consistent with the changes in ϕ. Thus, significant variability in γ_d and OMC are obtainable between air-dried and partial air-dried conditions, as well as between using fresh specimens for each point of the untreated M-D curve and re-using a singly mixed and remolded specimen.

To further evaluate the above observations, a similar series of standard T-99 density tests were performed on selected Phase II soils

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*AD = air dried
PAD = partially air dried or no air drying
R = re-use of specimen
F = fresh specimens

**All phase II soil samples were field-sealed in plastic-lined sample bags. Upon laboratory arrival, the sample bags were mixed together as quickly as possible, then placed in sealed containers, in order to (1) maintain as near as possible the original moisture content, (2) provide uniformity of composite B/C horizon samples, and (3) maintain as near as possible the aggregated soil structure for all further M-D tests.

Table 29. Changes in untreated soil density optimum moisture content, pressure ratio, and friction values due to molding conditions.

Soil	Condition	Changes in Parameters			
		γ_d,pcf	OMC,%	K_i	ϕ,degrees
Altamont	PADF	(100.4)*	(19.9)	(0.52)	(18)
	PADR	-1.7	+1.4	-0.06	+5
	ADF	-2.2	+0.5	-0.02	+1
	ADR	0	+0.1	-0.07	+5
Houston Black	PADF	(99.5)	(22.7)	(0.51)	(20)
	PADR	-4.8	+3.3	+0.06	-4
	ADF	-5.2	+2.4	+0.02	-2
	ADR	+0.7	-1.1	-0.01	-1
Peavine	PADF	(74.8)	(43.4)	(0.36)	(28)
	PADR	+0.1	-1.7	-0.01	+1
	ADF	+3.5	-8.5	0	0
	ADR	+4.9	-9.2	-0.18	+16
Melbourne	PADF	(88.1)	(30.3)	(0.39)	(25)
	PADR	+1.3	-1.2	-0.15	+18
	ADF	+4.4	-4.8	-0.04	+4
	ADR	+6.9	-6.0	-0.10	+9
Marias	PADF	(99.9)	(23.4)	(0.55)	(23)
	PADR	+1.2	-1.4	+0.02	-8
	ADF	+0.4	-0.9	+0.09	-10
	ADR	-0.2	-1.1	0	-6
Buxton	PADF	(99.4)	(23.0)	(0.39)	(26)
	PADR	-0.8	+0.5	0	0
	ADF	+2.0	-1.4	-0.07	+6
	ADR	+1.4	-0.9	-0.05	+2
Vergennes	PADF	(99.9)	(22.2)	(0.36)	(28)
	PADR	+1.2	-1.3	+0.08	-5
	ADF	+5.1	-2.3	+0.05	-3
	ADR	+3.1	-3.4	-0.08	+6
Onoway	PADF	(127.5)	(9.7)	(0.42)	(25)
	PADR	+0.4	+0.1	+0.04	-5
	ADF	-6.5	+1.8	-0.02	+1
	ADR	-5.5	+2.8	+0.10	-6
Frederick	PADF	(92.8)	(27.6)	(0.35)	(29)
	PADR	+1.3	-0.5	+0.05	-3
	ADF	0	-3.2	-0.09	+7
	ADR	+0.2	-1.0	0	0
Persanti	PADF	(95.3)	(23.2)	(0.22)	(39)
	PADR	+3.5	+1.6	+0.22	-16
	ADF	+1.0	+1.5	+0.11	-7
	ADR	+0.3	+3.1	+0.18	-9
Bearden	PADF	(108.1)	(16.4)	(0.28)	(35)
	PADR	-0.1	+1.1	+0.02	-3
	ADF	-4.7	+4.3	+0.03	-6
	ADR	-5.4	+4.4	+0.14	-11
Rimrock	PADF	(99.5)	(22.2)	(0.55)	(18)
	PADR	+2.2	-0.8	-0.14	+6
	ADF	-1.0	+0.4	0	-1
	ADR	+3.0	-1.0	-0.08	+3
Ontonagon	PADF	(90.5)	(27.8)	(0.49)	(20)
	PADR	+1.7	-0.1	+0.09	-4
	ADF	+3.9	-5.5	-0.08	+12
	ADR	+4.1	-4.4	-0.13	+9
Nappannee	PADF	(105.7)	(20.0)	(0.52)	(19)
	PADR	+0.6	-1.3	-0.02	+1
	ADF	+0.9	-2.7	-0.12	+8
	ADR	-1.7	-3.0	-0.27	+19
Paulding	PADF	(85.9)	(27.3)	(0.25)	(40)
	PADR	+2.9	+1.7	+0.03	-5
	ADF	+4.5	+3.4	+0.12	-12
	ADR	+4.3	+8.6	+0.16	-17
Pierre	PADF	(89.5)	(27.4)	(0.60)	(15)
	PADR	-0.3	-2.7	-0.20	+9
	ADF	+0.3	-4.0	-0.16	+10
	ADR	+2.1	-0.1	-0.10	+5

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*Values in parentheses are actual values of γ_d, OMC, K_i, and ϕ.

treated with variable quantities of chemicals SA-1 and SC-518. Table 30 summarizes the changes in maximum density, optimum moisture content, lateral pressure ratio, and angle of internal friction, in both the untreated and treated soils, which occurred due to the variable conditions of drying, pulverizing, and test usage. However, changes in the parameters of Table 30 are presented (a) relative to the untreated soil compacted at OMC and maximum γ_d by the respective-condition method, and (b) relative to the untreated PADF condition only.

Analysis of Table 30 relative to each specific molding condition illustrates that whatever γ_d, OMC, K_i, or ϕ values, which an individual practioner may want to achieve through laboratory M-D testing of treated or untreated soils, may be obtained by merely varying the test process. For example, consider SA-1 treatment of the Nappannee series soil:

1. Through the PADR process, gains are obtainable with each of the four parameters.
2. Through the PADF process, combined moisture and density effectiveness would be considered nil, but significant improvement of lateral stability and shear resistance would be indicated through addition of SA-1, i.e., possible stabilization of the soil.
3. Application of the ADF condition would generally indicate detrimental M-D and stability effects due to chemical additive.
4. The ADR condition would show SA-1 totally detrimental if applied to this soil.

Variations of the above illustration may be noted with the other soils presented in Table 30 and, to a large extent, are attributable to the varying mineralogies.

If the PADF untreated condition is assumed as most closely simulating field compaction and is thus used as the datum for comparison with Conditions 1-3, it is noted that the changes in γ_d, OMC, K_i, and ϕ are once again significant: overall lab densities (γ_d) varied from +9.8 to -5.5 pcf, OMC varied from -5.6 to +8.6%, and friction angles (ϕ) from $+26^o$ to -24^o (compared to those of the PADF untreated specimens). Lateral pressure ratio values (K_i) showed changes of +0.39 to -0.35, again consistent with the changes in ϕ. Examining similar changes within each soil, using the respective untreated PADF as the datum for comparison, once again reflects the probability that variations of γ_d, OMC, K_i, and ϕ may be achieved due to variability of the M-D test process.

Standard specifications for moisture-density testing basically allow the four alternative conditions noted herein. Tables 29 and 30 indicate what may occur if one or more of these conditions of drying, preparation, and specimen-usage are interchanged, or even partially interchanged, by one technician or within one agency for

Table 30. Comparison of condition only vs. PADF condition for changes in untreated soil density, optimum moisture content, pressure ratio, and friction values.

Soil	Condition, Treatment, and Concentration	Changes in Parameters Relative to Condition Only				Changes in Parameters Relative to PADF Condition			
		γ_d, pcf	OMC, %	K_i	ϕ, degrees	γ_d, pcf	OMC, %	K_i	ϕ, degrees
Frederick	PADF - Water	(92.8)[*]	(27.6)	(0.35)	(29)	(92.8)	(27.6)	(0.35)	(29)
	PADF - SA-1 1/1000	+0.6	-3.5	+0.02	-4	+0.6	-3.5	+0.02	-4
	PADF - SA-1 10/1000	-0.3	01.7	+0.03	-2	-0.3	-1.7	+0.03	-2
	PADR - Water	(94.1)	(27.1)	(0.40)	(26)	+1.3	-0.5	+0.05	-3
	PADR - SA-1 1/1000	+0.3	-0.6	-0.10	+2	+1.6	-1.1	-0.05	-1
	PADR - SA-1 10/1000	+0.7	-2.4	-0.10	+4	+2.0	-1.9	-0.05	+1
	ADF - Water	(92.8)	(24.4)	(0.26)	(36)	0	-3.2	-0.09	+7
	ADF - SA-1 1/1000	+0.9	+2.3	+0.12	-14	+0.9	-1.5	+0.03	-7
	ADF - SA-1 10/1000	-1.1	+2.9	+0.26	-19	-1.1	-0.3	+0.17	-12
	ADR - Water	(93.0)	(26.6)	(0.35)	(29)	+0.2	-1.0	0	0
	ADR - SA-1 1/1000	-1.9	-2.1	-0.08	+5	-1.7	-3.1	-0.07	+5
	ADR - SA-1 10/1000	-0.2	+0.1	+0.25	-13	0	-0.9	+0.25	-13
Persanti	PADF - Water	(95.3)	(23.2)	(0.22)	(39)	(95.3)	(23.2)	(0.22)	(39)
	PADF - SC-518 1/1000	+0.3	+1.3	+0.13	-13	+0.3	+1.3	+0.13	-13
	PADF - SC-518 10/1000	+2.0	+2.3	+0.08	-9	+2.0	+2.3	+0.08	-9
	PADR - Water	(98.8)	(24.8)	(0.44)	(23)	+3.5	+1.6	+0.22	-16
	PADR - SC-518 1/1000	-0.8	-0.6	-0.11	+4	+2.7	+1.0	+0.11	-12
	PADR - SC-518 10/1000	-0.3	+0.1	-0.19	+11	+3.2	+1.7	+0.03	-5

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[*] Values in parentheses are actual values of γ_d, OMC, K, and ϕ.

Table 30. Comparison of condition only vs. PADF condition for changes in untreated soil density, optimum moisture content, pressure ratio, and friction values (continued).

Soil	Condition, Treatment, and Concentration	Changes in Parameters Relative to Condition Only				Changes in Parameters Relative to PADF Condition			
		γ_d, pcf	OMC, %	K_i	ϕ, degrees	γ_d, pcf	OMC, %	K_i	ϕ, degrees
Persanti	ADF - Water	(96.3)	(24.7)	(0.33)	(32)	+1.0	+1.5	+0.11	-7
	ADF - SA-1 1/1000	+0.1	+1.0	+0.22	-14	+1.1	+2.5	+0.33	-21
	ADF - SA-1 10/1000	+1.7	-0.4	+0.28	-17	+2.7	+1.1	+0.39	-24
	ADF - SC-518 1/1000	+2.1	-1.8	-0.02	-1	+3.1	-0.3	+0.09	-8
	ADF - SC-518 10/1000	+2.4	-2.5	-0.10	+8	+3.4	-1.0	+0.01	+1
	ADR - Water	(95.6)	(26.3)	(0.40)	(28)	+0.3	+3.1	+0.18	-9
	ADR - SA-1 1/1000	+2.2	-0.7	+0.10	-8	+2.5	+2.4	+0.28	-19
	ADR - SA-1 10/1000	+2.5	-2.7	+0.12	-10	+2.8	+0.4	+0.30	-21
	ADR - SC-518 1/1000	+1.3	-2.5	-0.05	0	+1.6	+0.6	+0.13	-11
	ADR - SC-518 10/1000	+1.7	-3.6	-0.15	+6	+2.0	-0.5	+0.03	-5
Bearden	PADF - Water	(108.1)	(16.4)	(0.28)	(35)	(108.1)	(16.4)	(0.28)	(35)
	PADF - SA-1 1/1000	-5.5	+3.4	+0.02	+3	-5.5	+3.4	+0.02	+3
	PADF - SA-1 10/1000	-5.3	+2.8	+0.12	-9	-5.3	+2.8	+0.12	-9
	PADF - SC-518 1/1000	-4.4	+2.9	+0.07	-5	-4.4	+2.9	+0.07	-5
	PADF - SC-518 10/1000	-4.2	+3.3	-0.03	+1	-4.2	+3.3	-0.03	+5
	PADR - Water	(108.0)	(17.5)	(0.30)	(32)	-0.1	+1.1	+0.02	-3
	PADR - SA-1 1/1000	-3.4	+1.1	+0.10	-2	-3.5	+2.2	+0.12	-5
	PADR - SA-1 10/1000	-1.5	+1.2	0.0	0	-1.6	+2.3	+0.02	-3
	PADR - SC-518 1/1000	-2.2	+1.0	0.0	0	-2.3	+2.1	+0.02	-3
	PADR - SC-518 10/1000	-1.0	+2.0	+0.10	-8	-1.1	+3.1	+0.12	-11
	ADF - Water	(103.4)	(20.7)	(0.31)	(29)	-4.7	+4.3	+0.03	-6
	ADF - SA-1 1/1000	+0.4	-0.3	+0.14	-7	-4.3	+4.0	+0.17	-13

Table 30. Comparison of condition only vs. PADF condition for changes in untreated soil density, optimum moisture content, pressure ratio, and friction values (continued).

Soil	Condition, Treatment, and Concentration	Changes in Parameters Relative to Condition Only				Changes in Parameters Relative to PADF Condition			
		γ_d, pcf	OMC, %	K_i	ϕ, degrees	γ_d, pcf	OMC, %	K_i	ϕ, degrees
Bearden	ADF - SA-1 10/1000	-0.6	-1.5	+0.08	-2	-5.3	+2.8	+0.11	-8
	ADF - SC-518 1/1000	-0.4	-1.8	+0.04	-1	-5.1	+2.5	+0.07	-7
	ADF - SC-518 10/1000	-0.1	-1.0	+0.02	+1	-4.8	+3.3	+0.05	-5
	ADR - Water	(102.7)	(20.8)	(0.42)	24	-5.4	+4.4	+0.14	-11
	ADR - SA-1 1/1000	0	+0.9	+0.20	-11	-5.4	+5.3	+0.34	-22
	ADR - SA-1 10/1000	+2.3	+0.7	+0.22	-12	-3.1	+5.1	+0.36	-23
	ADR - SC-518 10/1000	+1.9	-0.7	+0.13	-6	-3.5	+3.7	+0.27	-17
Rimrock	PADF - Water	(99.5)	(22.2)	(0.55)	(18)	(99.5)	(22.2)	(0.55)	(18)
	PADF - SA-1 1/1000	+2.0	-2.1	-0.29	+16	+2.0	-2.1	-0.29	+16
	PADF - SA-1 10/1000	-0.1	-1.3	-0.20	+12	-0.1	-1.3	-0.20	+12
	PADR - Water	(101.7)	(21.4)	(0.41)	(24)	+2.2	-0.8	-0.14	+6
	PADR - SA-1 1/1000	-0.8	-2.4	-0.13	+10	+1.4	-3.2	-0.27	+16
	PADR - SA-1 10/1000	-3.3	-0.3	-0.21	+16	-1.1	-1.1	-0.35	+26
	ADF - Water	(98.5)	(22.6)	(0.55)	(17)	-1.0	+0.4	0	-1
	ADF - SA-1 1/1000	-0.5	-0.1	-0.07	+4	-1.5	+0.3	-0.07	-4
	ADF - SA-1 10/1000	-0.7	-0.7	-0.05	+3	-1.7	-0.3	-0.05	+2
	ADR - Water	(102.5)	(21.2)	(0.47)	(21)	+3.0	-1.0	-0.08	+3
	ADR - SA-1 1/1000	-3.3	+2.0	+0.15	-7	-0.3	+1.0	+0.07	-4
	ADR - SA-1 10/1000	-2.8	+0.8	+0.03	-1	+0.2	+0.2	-0.05	+2

Table 30. Comparison of condition only vs. PADF condition for changes in untreated soil density, optimum moisture content, pressure ratio, and friction values (continued).

Soil	Condition, Treatment, and Concentration	Changes in Parameters Relative to Condition Only				Changes in Parameters Relative to PADF Condition			
		γ_d, pcf	OMC, %	K_i	ϕ, degrees	γ_d, pcf	OMC, %	K_i	ϕ, degrees
Ontonagon	PADF - Water	(90.5)	(27.8)	(0.49	(20)	(90.5)	(27.8)	(0.49)	(20)
	PADF - SC-518 1/1000	+1.7	-0.3	-0.13	+10	+1.7	-0.3	-0.13	+10
	PADF - SC-518 10/1000	+2.9	-3.9	-0.22	-12	+2.9	-3.9	-0.22	+12
	PADR - Water	(92.2)	(27.7)	(0.58)	(16)	+1.7	-0.1	+0.09	-4
	PADR - SC-518 1/1000	-0.2	-1.2	-0.17	+8	+1.5	-1.3	-0.08	+4
	PADR - SC-518 10/1000	+1.6	-1.6	-0.18	+10	+2.2	-1.7	-0.09	+6
	ADF - Water	(94.4)	(22.3)	(0.41)	(32)	+3.9	-5.5	-0.08	+12
	ADF - SC-518 1/1000	-0.3	+0.9	-0.15	+5	+3.6	-5.6	-0.23	+17
	ADF - SC-518 10/1000	+0.3	+0.7	-0.04	-5	+4.2	-4.8	-0.12	+7
	ADR - Water	(94.6)	(23.4)	(0.36	(29)	+4.1	-4.4	-0.13	+9
	ADR - SC-518 1/1000	-0.3	+0.6	0	-5	+3.8	-3.8	-0.13	+14
	ADR - SC-518 10/1000	+0.3	-1.1	+0.06	-7	+4.4	-5.5	-0.07	+2
Nappannee	PADF - Water	(105.7)	(20.0)	(0.52)	(19)	(105.7)	(20.0)	(0.52)	(19)
	PADF - SA-1 1/1000	+0.6	-2.4	-0.32	+26	+0.6	-2.4	-0.32	+26
	PADF - SA-1 10/1000	-3.7	+1.0	-0.23	+18	-3.7	+1.0	-0.23	+18
	PADR - Water	(106.3)	(18.7)	(0.50)	(20)	+0.6	-1.3	-0.02	+1
	PADR - SA-1 1/1000	+1.0	-1.1	-0.15	+9	+1.6	-2.4	-0.17	+10
	PADR - SA-1 10/1000	+2.0	-1.4	-0.10	+8	+2.0	-2.7	-0.12	+9

Table 30. Comparison of condition only vs. PADF condition for changes in untreated soil density, optimum moisture content, pressure ratio, and friction values (continued)

Soil	Condition, Treatment, and Concentration	Changes in Parameters Relative to Condition Only				Changes in Parameters Relative to PADF Condition			
		γ_d, pcf	OMC, %	K_i	ϕ degrees	γ_d, pcf	OMC, %	K_i	ϕ degrees
Nappannee	ADF - Water	(106.6)	(17.3)	(0.40)	(27)	+0.9	-2.7	-0.12	+8
	ADF - SA-1 1/1000	-4.8	+2.7	-0.04	0	-3.9	0	-0.16	+8
	ADF - SA-1 10/1000	-3.3	-0.5	-0.12	+5	-2.4	-3.2	-0.24	+13
	ADR - Water	(104.0)	(17.0)	(0.25)	(38)	-1.7	-3.0	-0.27	+19
	ADR - SA-1 1/1000	-0.8	+2.2	+0.08	-6	-2.5	-0.8	-0.19	+13
	ADR - SA-1 10/1000	-2.4	+1.9	+0.05	-6	-4.1	-1.1	-0.22	+13
Paulding	PADF - Water	(85.9)	(22.3)	(0.25)	(40)	(85.9)	(22.3)	(0.25)	(40)
	PADF - SC-518 1/1000	+2.5	+4.1	+0.21	-4	+2.5	+4.1	+0.21	-4
	PADF - SC-518 10/1000	+2.6	+3.8	+0.20	-7	+2.6	+3.8	+0.20	-7
	PADR - Water	(88.8)	(24.0)	(0.28)	(35)	+2.9	+1.7	+0.03	-5
	PADR - SC-518 1/1000	-0.6	+5.1	+0.16	-13	+2.3	+6.8	+0.17	-18
	ADF - Water	(90.4)	(25.7)	(0.37)	(28)	+4.5	+3.4	+0.12	-12
	ADF - SC-518 1/1000	+4.2	+1.0	+0.13	-9	+8.7	+4.4	+0.25	-21
	ADF - SC-518 10/1000	+5.3	-1.9	+0.12	-9	+9.8	+1.5	+0.24	-21
	ADR - Water	(90.2)	(30.9)	(0.41)	(23)	+4.3	+8.6	+0.16	-17
	ADR - SC-518 1/1000	+5.2	-5.8	+0.07	-2	+9.5	+2.8	+0.23	-19
	ADR - SC-518 10/1000	-0.7	-7.3	-0.11	+11	+3.6	+1.3	+0.05	-6

any given soil. Such potential occurrences can only indicate the necessity for a thorough re-evaluation of standard moisture-density test specifications for predominanatly fine-grained soils.

However, the purpose of this study was to ascertain a moisture-density test technique which would provide T-99 compactive effort yet optimize the potential for comparison of M-D and stability effectiveness of untreated vs. chemically treated fine-grained soils. On the basis of this study, we concluded that partial air drying coupled with fresh soil for each point of an M-D curve was the most logical basis for evaluation of effectiveness of chemical compaction aids in Phase II of this study. Figure 32 illustrates the moisture-density and other engineering parametric relationships attainable with the PADF process.

Additional Screening Tests

Several chemicals were listed in the Product Literature Review section of this report but were not included in the Phase I study. This occurred due to (a) the chemicals were not being promoted as commercial aids to compaction and/or (b) samples were not received prior to completion of the Phase I study. However, because of their potential moisture-density effectiveness, as indicated within the literature review, they were screened as a portion of the Phase II study for possible inclusion with the major chemicals selected from Phase I.

Specimen preparation was in accordance with the air-dried, pulverized fresh specimen (ADF) technique used in Phase I, with stability analyzed through the Iowa K-Test.

Several products investigated by Shirley[26] in a "Virginia clay" and a "Georgia silt" indicated a significant 8 to 10% increase in maximum density. In an effort to synthesize Shirley's results, three soils, Shelby, AASHO, and Cecil, were utilized for the screening tests as representative of montmorillonitic, illitic, and kaolinitic soils. A kaolinitic soil was considered essential for this study, since both the silt and clay used by Shirley appeared to be of predominantly kaolinitic mineralogy with some illite and quartz.

Tables 31, 32, and 33 present the changes in γ_d, OMC, K_i, ϕ, c, and E of the treated soils, compared to those of the untreated soils. Herein, it was assumed that a fully effective compaction aid must increase γ_d and reduce OMC, while at the same time maintaining or improving stability. The latter was evaluated through reduced K_i values, coupled with increased ϕ, c, and E parameters. Analyses of Tables 31, 32, and 33 provide the following evaluations of compaction effectiveness:

Table 31. Changes in moisture-density and K-test parameters due to treatment, Shelby Soil.

Treatment % Dry Soil Wt.	Maximum Dry Density, pcf	Optimum Moisture Content, %	K-Test Parameters at γ_d and OMC.			
			K_i	ϕ, degrees	c, psi	E($\times 10^3$), psi
Water	(100.4)*	(20.0)	(0.42)	(23)	(2.6)	(2.6)
Tergitol 15-S-9						
0.10	+0.6	-1.0	+0.02	0	-0.6	+0.4
0.50	0.0	-1.0	+0.02	+2	-1.6	-0.1
Aerosol OT-75%						
0.10	-0.7	+0.4	+0.02	-1	-1.6	-0.1
0.50	+0.1	0.0	+0.04	-1	-2.6	-0.1
Alkanol 189-S						
0.10	-0.6	+1.1	+0.04	+1	+0.2	+0.2
0.50	+0.9	-0.8	-0.02	+2	+0.6	+0.4
Poly-Tergent B-300						
0.10	-1.6	-0.3	+0.01	+2	+0.2	+0.2
0.50	+0.4	-3.0	-0.08	+7	+1.6	-0.1
Duponol WA Paste						
0.10	0.0	-2.7	-0.02	+3	+1.4	+0.4
0.50	-0.6	-1.2	-0.06	+4	+1.8	-0.1
Bio-Soft D-35X						
0.10	0.0	-0.2	+0.02	+1	+1.4	+1.0
0.50	+0.6	-0.6	-0.02	+2	-0.6	+0.4
Nacconol 40F						
0.10	-0.3	-1.8	+0.03	+2	+1.0	-0.2
0.50	-0.5	-1.3	+0.01	+3	+1.4	+0.6

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*Numbers in parentheses refer to actual, untreated values of the various parameters.

Table 32. Changes in moisture-density and K-test parameters due to treatment, AASHO Soil.

Treatment % Dry Soil Wt.	Maximum Dry Density, pcf	Optimum Moisture Content, %	K-Test Parameters at γ_d and OMC.			
			K_i	ϕ, degrees	c, psi	$E(\times 10^3)$, psi
Water	(116.0)*	(14.2)	(0.40)	(25)	(3.8)	(3.4)
Tergitol 15-S-9						
0.10	-2.2	-0.6	-0.06	+5	+4.6	-0.1
0.50	-1.8	+0.1	-0.02	+2	+0.8	-0.3
Aerosol OT-75%						
0.10	+0.1	-0.5	-0.06	+4	+2.2	+0.1
0.50	+0.4	+0.6	+0.14	-7	-3.2	-0.2
Alkanol 189-S						
0.10	+1.1	-0.3	+0.025	-1	-1.0	+0.7
0.50	+1.2	-0.3	-0.04	0	-2.6	-0.1
Poly-Tergent B-300						
0.10	-1.3	0.0	0.0	-2	0.0	-0.6
0.50	-2.3	+0.3	-0.06	-1	0.0	-0.6
Duponol WA Paste						
0.10	0.0	+0.1	+0.023	0	-0.2	+0.2
0.50	0.0	+0.1	+0.025	0	-0.2	+0.2

*Numbers in parentheses refer to actual, untreated values of the various parameters.

Table 33. Changes in moisture-density and K-test parameters due to treatment, Cecil Soil.

Treatment % Dry Soil Wt.	Maximum Dry Density, pcf	Optimum Moisture Content, %	K-Test Parameters at γ_d and OMC.			
			K_i	ϕ, degrees	c, psi	E($\times 10^3$), psi
Water	(98.4)*	(22.8)	(0.38)	(28)	(4.0)	(4.0)
Tergitol 15-S-9						
0.10	-1.4	-0.5	-0.08	+2	+3.6	-1.0
0.50	-0.1	-0.8	-0.10	+5	+1.4	-0.3
Aerosol OT-75%						
0.10	+2.6	-1.3	-0.04	+2	-1.2	-0.5
0.50	+0.7	-1.0	-0.04	0	+0.2	-0.7
Alkanol 189-S						
0.10	-0.8	-0.4	-0.04	+1	+0.2	-0.8
0.50	-0.2	-2.7	-0.08	+1	+5.8	-1.5
Poly-Tergent B-300						
0.10	-1.2	-1.0	-0.04	+2	+2.0	-0.6
0.50	0	-1.4	-0.06	+3	+2.0	-0.7
Duponol WA Paste						
0.10	+0.8	-1.8	-0.02	0	+0.4	-0.8
0.50	-0.8	-1.6	-0.03	+4	+4.8	-0.8
Nacconol 40F						
0.10	+0.9	-1.5	-0.02	+1	+2.0	-0.8
0.50	+2.7	-1.4	+0.02	-2	-1.4	-0.8

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*Numbers in parentheses refer to actual, untreated values of the various parameters.

Shelby series

1. Tergitol 15-S-9. Minor improvement due to reduced OMC only. Not effective.

2. Aerosol OT-75%. Not effective.

3. Alkanol 189-S. Slight improvement in all values at 0.50% dry soil weight. Partially effective but appears to require greater than 0.50% chemical, an arbitrary cutoff economically. Thus, not effective.

4. Poly-Tergent B-300. At 0.50%, improved OMC, K_i, ϕ, and c. Effective.

5. Duponol WA Paste. No improvement in γ_d only; improved all other factors. Effective.

6. Bio-Soft D-35X. Not effective.

7. Nacconol 40F. Reduced OMC, increased ϕ and c slightly. Partially effective, stability only.

AASHO Soil

1. Tergitol 15-S-9. At 0.1%, slightly improved OMC and K_i, improved ϕ and c. Significant reduction in γ_d. Net evaluation, not effective.

2. Aerosol OT-75%. Slightly improved OMC, K_i, ϕ, c, and E at 0.1%. No change in γ_d. Qualifiedly effective at low percentages.

3. Alkanol 189-S. Slightly improved γ_d only, plus E at 0.1%. Not effective.

4. Poly-Tergent B-300. Not effective.

5. Duponol WA Paste. Not effective.

Cecil Series

1. Tergitol 15-S-9. Reduced γ_d and E, improved all other values. Partially effective through stability only.

2. Aerosol OT-75%. Improved all properties except E. Effective.

3. Alkanol 189-S. Reduced γ_d and E, improved all other values. Partially effective through stability only.

4. Poly-Tergent B-300. Reduced γ_d and E, improved all other values. Partially effective through stability only.

5. Duponol WA Paste. Erratic. Partially effective through stability only.

6. Nacconol 40F. Increased γ_d, reduced OMC, variable K-test parameters. Partially effective.

From the above analyses, only the following products would be considered appropriate for further Phase II study: Poly-Tergent B-300 and Duponol WA Paste with the montmorillonitic soils; Aerosol OT-75% with illitic soils; Aerosol OT-75% and Nacconol 40F with kaolinitic soils.

Comparison of the data of Tables 31, 32, and 33 with the work by Shirley,[26] presents the obvious question of why Shirley achieved γ_d increases of 8-10% and we did not? The difference lies in the manner in which the two investigations were conducted.

First, in the investigation by Shirley, each soil was air-dried in such a manner that the moisture content was only about 2.0%. In fact, the clay was oven-dried at 100 °F for 48 hours prior to sieving. Each soil was then sieved through a No. 4 sieve "with the majority of the discarded material being hardened lumps and roots." In our study, air-drying was not so thorough, and only roots and rock fragments larger than 3/4 in. were removed.

Second, although Shirley ran an M-D curve for each soil, a maximum untreated density and moisture content were selected as standards for comparison with the treated soils. The selected γ_d and moisture content for the two soils was 102.6 pcf and 13.0% for the silt, and 89 pcf and 25% for the clay, even though the maximum γ_d of the untreated soils was about 2 pcf higher and the OMC was about 3% greater.

Third, the amounts of chemicals added to the soils were computed as a percent by weight of final moisture content. Thus, 0.25 to 3.0% by weight of moisture resulted in 0.06 to 0.75% by dry soil weight of the clay and 0.028 to 0.33% of the silt.

Let us examine analogous data from our study, analyzing by concepts similar to those of Shirley, by comparing the treated maximum γ_d with the untreated γ_d, both at treated OMC. Table 34 presents example comparisons, all data being from ADF specimens. On this basis, the increase in density ranges from less than 1 to greater than 7 pcf, a percentage change from +0.4 to +8.0%. Thus, from this examination of density alone, the products range from slightly effective to superior. Also, from the standpoint of change of engineering characteristics, it may be shown that the lowest percentage increase in density (AASHO soil) resulted in better K_i, ϕ, c, and E performance when compared to the untreated soil compacted at the same moisture content. Likewise, it may be shown that the highest percentage increase in density (Paulding series) resulted in lower K_i and ϕ performance than the untreated at

Table 34. Comparison of treated and untreated M-D and K-Test values at the treated optimum moisture content.

Soil	Condition and Treatment	γ_d, pcf	OMC, %	K_i	ϕ, degrees	C, psi	E(× 10^3), psi
Shelby	Poly-Tergent B-300, 0.50%	100.8	17.0	0.34	30	4.2	2.5
	untreated @ treated OMC	94.6	17.0	0.375	30	7.2	2.0
Shelby	Duponol WA Paste, 0.10%	100.4	17.3	0.40	26	4.0	3.0
	untreated @ treated OMC	95.6	17.3	0.38	29	6.8	2.1
AASHO	Aerosol OT-75% 0.10%	116.1	13.7	0.34	29	6.0	3.5
	untreated @ treated OMC	115.6	13.7	0.37	28	4.2	3.3
Cecil	Aerosol OT-75%, 0.10%	101.0	21.5	0.34	30	5.2	3.5
	untreated @ treated OMC	97.5	21.5	0.36	29	4.8	3.2
Cecil	Nacconol 40F, 0.50%	101.1	21.4	0.40	26	2.6	3.2
	untreated & treated OMC	97.5	21.4	0.36	29	4.8	3.2
Shelby	SC-518, 10/1000	102.2	18.4	0.40	27	-	-
	untreated @ treated OMC	98.9	18.4	0.39	29	-	-
Paulding	SC-518, 10/1000	95.7	23.8	0.49	19	-	-
	untreated @ treated OMC	88.6	23.8	0.31	32	-	-

the same moisture content. The SC-518 treated Paulding at OMC and γ_d, when compared with the untreated at OMC and γ_d, also shows reduction in the engineering parameters K_i and ϕ. Likewise, the Aerosol OT-75% treated AASHO at OMC and γ_d, when compared with the untreated at OMC and γ_d, shows improvement in the parameters K_i, ϕ, c, and E.

It may therefore be concluded that the Shirley[26] investigation, though limited only to changes in γ_d, and the present investigation differ mainly in the method of analyzing shifts of the treated M-D curves to the left and up from those of the untreated soils; the Shirley analysis, in effect, penalizes data from the untreated soil by inviting comparisons at less-than-optimum moisture contents. Since, in many cases, the same results could be achieved by adding more water in lieu of chemical, we believe the Shirley method to be invalid for realistic evaluations.

A proprietary chemical called Terra-Seal was shown by Squier[18] to improve density, and was described by the manufacturer as improving soil compaction and bearing capacity characteristics. Using the ADF techniques of Phase I, this product was evaluated with the Monona and Shelby series soils at four concentration levels ranging from 0.1/1000 to 5/1000. With each concentration level, soil density was reduced including up to 4.9 pcf reduction in the Monona. Optimum moisture contents were reduced up to 1.5% in the Monona but increased up to 1.5% in the Shelby when compared to the untreated soils. Friction angle was generally decreased in both soils, while K_i values showed only minor increases or reductions. Due to the significant reductions in density, no further testing of Terra-Seal was included in the Phase II study.

Moisture-Density and K-Tests

From the primary Phase I studies, six chemicals were selected for evaluation with the eighteen soils of Phase II. These chemicals were Petro-S, SC-518, Clapak, Claset, SA-1, and Coherex. Because of their Phase I showing, Thinwater and Reynolds Road Packer were selected for partial inclusion in Phase II but with a limited number of soils. As stated in the preceding section of this report, Duponol WA Paste, Polytergent B-300, Aerosol OT-75%, and Nacconol 40F were also selected for evaluation with a limited number of soils.

Table 35 presents changes in moisture-density (γ_d), optimum moisture content (OMC), lateral pressure ratio (K_i), angle of internal friction (ϕ), cohesion (c), and modulus of deformation (E) of the treated compared to those of the untreated soils. All K-Tests were performed immediately following soil specimen compaction.

All testing conducted within this portion of the study was on the basis of the partially air-dried, partially pulverized, fresh soil specimen (PADF) technique previously discussed. In addition, Phase I studies evaluated each chemical on a water concentration basis which, through the moisture density tests, resulted in increasing quantities of chemical with each increase in moisture when expressed as a percentage of the dry soil weight. Taking the Phase I chemical concentrations at their respective optimum moisture contents, calculations were conducted in order to approximate the appropriate low, middle, and high chemical contents used in the Phase I study, but on a percentage dry soil weight basis. Thus, within all remaining Phase II and Phase III studies, the quantity of chemical within each specimen of the moisture-density test was constant, and the mid-chemical contents, shown in Table 35 for example, are approximately those either recommended by the manufacturer/producer or assumed from our review of theirs or other literature.

Qualitative Analysis

As the first step in analysis of the moisture-density and K-Test data of Table 35, a qualitative evaluation was conducted. The criteria assumed that a fully effective chemical aid to compaction must increase density, reduce optimum moisture and lateral pressure ratio, and increase friction angle, cohesion, and modulus of deformation when compared to the same parameters of the untreated soil at its maximum density and optimum moisture content. If all but one of the six parameters showed improvement, the chemical was rated as fully to partially effective. If two to four of the parameters were improved, it was assumed that the chemical was partially effective; this condition often occurred where, due to the flocculation or dispersive properties of the chemical, either the stability parameters or the M-D parameters, respectively, were improved. The chemical was rated as ineffective when little or no parametric improvements were noted, and/or the product was obviously deleterious to several of the parameters. Where possible, effectiveness evaluations also included the most desirable chemical content as viewed not only from Table 35 but also as indicated from each parametric data plot similar to that illustrated in Fig. 32. Following are observations thus obtained through the qualitative analysis.

1. Montmorillonitic Soils.

Bearden Series

a) Clapak. Significant improvement in γ_d and OMC at each percentage treatment. Good to excellent improvement in K_i, ϕ, and c at 0.1 and 0.2% dry soil weight, but only minor improvement in E at 0.2% level. Effective.

b) Claset. Significant improvement in γ_d, OMC, and c at each percentage treatment. K_i, ϕ, and E values indicate near zero improvement to deleterious. Effective in compaction. Partially effective in stability.

Table 35. Changes in moisture-density and K-test parameters, phase II soil series.

Soil and Dominant Clay Mineral	Treatment	% Dry Soil Wt.	Maximum Dry Density, pcf	Optimum Moisture Content, %	K-Test Parameters at γ_d and OMC			
					K_i	ϕ, degrees	c, psi	E ($\times 10^3$), psi
Bearden (Montmorillonite)	Water	----	(100.0)*	(20.9)	(0.316)	(30)	(4.3)	(3.8)
	Clapak	0.01	+3.5	-1.8	+0.067	-8	+4.9	-1.0
		0.10	+4.0	-3.3	-0.072	+3	+6.7	0
		0.20	+2.6	-6.3	-0.110	+5	+9.4	+0.4
	Claset	0.01	+3.8	-3.4	-0.020	-4	+10.5	-0.4
		0.10	+4.3	-2.7	-0.006	-2	+3.1	-0.4
		0.20	+3.7	-2.5	+0.052	-8	+7.2	-0.8
	Duponol WA Paste	0.10	-2.6	+1.1	-0.025	-9	+4.1	-1.0
		0.50	-2.1	-0.8	-0.025	-8	+3.1	-1.0
	Polytergent B-300	0.10	-2.7	+2.8	0	-11	-0.4	-1.3
		0.50	-3.5	+0.7	-0.045	-8	-0.1	-1.1
	Coherex	0.70	+3.1	-0.6	-0.019	-1	+3.6	+0.1
		1.00	-0.3	-0.7	+0.048	-3	-1.3	-0.8
		1.75	-1.3	-0.7	-0.005	-1	+1.9	-0.8
	Petro-S	0.91	+1.5	-1.6	+0.031	-5	+3.5	-0.2
		1.82	+0.7	-1.8	-0.024	-1	+4.8	-0.8
		2.73	+5.1	-3.9	+0.106	-9	+1.6	-1.0
	Thinwater	0.0006	+2.8	-1.5	-0.035	+3	-1.1	+0.2
		0.0012	+2.1	-2.0	+0.023	-2	-1.3	+0.4
		0.007	+4.7	-2.2	+0.007	-2	+0.5	+0.5
Renohill (Montmorillonite)	Water	----	(97.9)	(21.0)	(0.447)	(9)	(21.3)	(1.6)
	SC-518	0.01	-1.8	+1.2	+0.025	+3	-7.3	+0.1
		0.04	-1.5	+1.8	-0.043	+7	-8.3	+0.5
		0.07	-1.1	+1.6	+0.021	+3	-6.0	+0.3
	Clapak	0.01	-0.2	+1.2	+0.035	+4	-8.9	+0.4
		0.07	-0.3	+0.6	+0.005	+5	-7.1	+0.5
		0.15	-0.9	+0.6	+0.034	+3	-7.5	0
	Claset	0.01	-1.0	+2.2	+0.060	+4	-12.0	+0.9
		0.07	-0.5	+1.5	+0.127	0	-12.2	+0.4
		0.15	-0.9	+1.8	+0.045	+4	-10.5	+0.5
	Coherex	0.70	-1.0	+1.4	+0.099	+3	-14.7	+0.4
		1.00	-0.7	+0.6	+0.115	+4	-15.7	+0.4
		1.75	-1.1	-0.3	+0.031	+5	- 9.6	+0.2
	Petro-S	0.91	+1.6	-3.1	-0.032	+2	+ 1.0	+0.1
		1.82	+2.1	-0.9	+0.017	+5	- 8.1	+0.6
		2.73	+2.0	-1.3	+0.020	+7	-12.5	+0.5
	Duponol WA Paste	0.10	-3.8	+3.8	+0.025	-3	+3.6	-1.5
		0.50	-5.1	+4.0	+0.050	-2	+3.0	-1.4
	Polytergent B-300	0.10	-8.0	+7.7	+0.150	-10	+1.2	-1.4
		0.50	-6.0	+5.5	+0.075	-5	+1.8	-1.2

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*Values in parentheses are actual values of γ_d, OMC, K_i, ϕ, c, and E.

Table 35. Changes in moisture-density and K-test parameters, phase II soil series (continued).

Soil and Dominant Clay Mineral	Treatment	% Dry Soil Wt.	Maximum Dry Density, pcf	Optimum Moisture Content, %	K-Test Parameters at γ_d and OMC			
					K_i	ϕ, degrees	c, psi	E ($\times 10^3$), psi
Pierre (Montmorillonite)	Water	----	(89.2)	(26.8)	(0.505)	(13)	(10.4)	(2.1)
	SC-518	0.01	+0.8	-0.1	-0.081	+5	+0.6	-0.2
		0.035	+1.3	+0.4	+0.012	0	-0.5	+0.1
		0.07	+1.4	-0.2	-0.053	+3	+0.6	+0.1
	Clapak	0.01	+0.2	0	+0.010	+2	-3.2	0
		0.07	-0.3	-1.2	-0.044	+2	+0.3	-0.3
		0.14	-0.1	-0.4	-0.045	+1	+2.6	-0.1
	Claset	0.01	+0.8	-2.7	-0.101	+8	-1.8	-0.2
		0.07	+0.5	-2.2	-0.082	+4	-0.7	-0.4
		0.14	+1.2	-1.3	-0.005	+2	-3.1	0
	Coherex	0.70	-0.7	+0.3	+0.050	-7	-7.2	-0.2
		1.00	+1.0	-1.6	-0.020	+4	-4.2	-0.4
		1.75	-0.5	-1.7	-0.083	+4	+1.9	0
	Petro-S	0.70	+0.5	-1.2	-0.051	+5	-2.7	0
		1.40	+1.4	-0.9	-0.047	+5	-4.1	+0.5
		2.10	+0.6	-0.5	+0.069	-1	-5.0	-0.2
	Road Packer	0.01	-1.3	+0.5	+0.031	0	-3.7	-0.3
		0.035	-1.2	+0.3	+0.025	-2	-1.1	-0.5
		0.07	-0.7	-0.1	+0.004	+1	-2.8	+0.1
	Duponol WA Paste	0.10	+1.4	+0.8	0	+2	-10.4	+0.1
		0.50	+0.2	+0.7	+0.020	+6	-6.4	+0.1
	Polytergent B-300	0.10	+0.6	+0.2	+0.020	+3	-8.4	-0.2
		0.50	+0.2	+0.5	+0.095	+2	-8.7	-0.1
Altamont (Montmorillonite)	Water	----	(98.7)	(20.3)	(0.497)	(15)	(7.5)	(2.3)
	Clapak	0.01	-1.6	+2.1	+0.008	-1	+1.3	0
		0.07	-1.2	+1.2	-0.076	+2	+5.8	+0.1
		0.14	+0.2	+0.7	+0.011	-2	+2.2	-0.1
	SC-518	0.01	-1.4	+2.2	+0.077	-5	+0.8	-0.2
		0.035	+0.2	-0.2	-0.092	+3	+5.8	+0.1
		0.07	-1.0	+0.4	-0.053	-3	+3.2	+0.1
	Claset	0.01	-0.2	+0.8	+0.031	-5	+3.6	-0.4
		0.07	-0.3	+0.5	-0.050	+3	+1.3	+0.2
		0.14	+0.7	+0.4	-0.017	-1	+1.6	0
	Coherex	0.70	+0.1	+1.5	+0.136	-6	-2.2	-0.1
		1.00	+0.2	+0.2	+0.019	-1	-1.1	-0.2
		1.75	-1.0	+0.7	-0.029	+1	+0.5	-0.3
	Petro-S	0.70	+0.4	+0.4	+0.001	0	-0.5	-0.2
		1.40	+0.5	+0.7	+0.022	0	-1.9	0
		2.10	+1.2	-0.8	-0.059	+3	+0.4	0
	Duponol WA Paste	0.10	+0.1	-3.1	+0.050	-5	+2.2	-0.5
		0.50	+0.2	-3.2	+0.025	-5	+4.1	-0.5
	Polytergent B-300	0.10	-1.6	+2.6	+0.200	-11	+0.2	+1.1
		0.50	-0.2	-0.4	+0.050	-5	+1.8	+0.2

Table 35. Changes in moisture-density and K-test parameters, phase II soil series (continued).

Soil and Dominant Clay Mineral	Treatment	% Dry Soil Wt.	Maximum Dry Density, pcf	Optimum Moisture Content, %	K-Test Parameters at γ_d and OMC			
					K_i	ϕ, degrees	c, psi	E ($\times 10^3$), psi
Rimrock (Montmorillonite)	Water	----	(95.2)	(22.7)	(0.454)	(17)	(9.2)	(2.2)
	Claset	0.01	-0.9	-0.6	-0.008	0	-0.1	-0.1
		0.07	+1.6	-3.6	-0.099	+6	+2.3	-0.1
		0.14	+1.5	-1.2	-0.001	-2	+2.8	-0.3
	Coherex	0.70	+0.7	-2.3	+0.003	-1	-0.5	-0.5
		1.00	+1.1	-3.7	-0.072	+6	-1.6	-0.4
		1.75	+1.4	-2.5	-0.018	0	+1.6	-0.2
	Clapak	0.01	+1.1	-2.6	-0.101	+5	+3.9	0
		0.07	+2.9	-3.7	-0.059	+5	-1.8	0
		0.14	+2.4	-2.1	-0.021	+2	-2.0	-0.1
	SC-518	0.01	+1.1	-2.7	-0.091	+5	+2.1	0
		0.035	+1.5	-2.7	-0.007	+1	-2.3	-0.2
		0.07	+0.9	-2.7	-0.002	0	-0.9	-0.4
	Petro-S	0.70	+1.8	-5.2	-0.123	+10	-1.5	+0.3
		1.40	+2.3	-4.8	-0.091	+7	-1.4	+0.2
		2.10	+2.4	-3.5	-0.108	+2	-2.4	-0.2
	Duponol WA Paste	0.10	-0.9	-0.7	+0.025	-1	+1.4	-0.1
		0.50	+0.5	-2.9	-0.025	0	+0.7	-0.1
	Polytergent B-300	0.10	-3.4	+0.3	+0.100	-6	-1.5	+0.5
		0.50	-2.4	-2.8	0	+2	+1.7	+0.5
Houston Black (Montmorillonite)	Water	----	(92.9)	(25.1)	(0.471)	(16)	(9.7)	(2.1)
	SC-518	0.01	+1.2	0	+0.040	-2	-2.3	+0.3
		0.035	+1.7	+0.1	+0.104	-4	-2.8	+0.3
		0.07	+4.3	-2.1	0	+2	-3.7	+0.6
	SA-1	0.01	+0.4	+0.4	+0.002	-4	-0.1	-0.1
		0.07	-0.2	+2.1	+0.110	-6	-1.2	+0.2
		0.14	0	+0.5	-0.020	0	+1.0	-0.3
	Duponol WA Paste	0.10	-2.1	-1.6	+0.225	-10	+0.8	-1.9
		0.50	-3.6	-4.9	0	0	+6.6	-2.2
	Polytergent B-300	0.10	-4.8	+2.1	+0.250	-13	0	-1.4
		0.50	-3.0	+0.3	+0.225	-11	+0.4	-1.6
	Clapak	0.01	+4.8	-1.5	+0.006	-1	-0.5	+0.9
		0.07	+2.0	+1.0	+0.079	-4	-3.1	+0.9
		0.14	+1.6	+0.8	+0.073	-4	-1.7	+0.4
	Claset	0.01	+1.9	-0.8	+0.015	-1	-1.5	-0.2
		0.07	+2.1	+0.6	+0.107	-5	-2.7	+0.4
		0.14	+3.2	-0.8	+0.125	-6	-2.7	+0.2
	Coherex	0.70	+4.0	-3.6	-0.021	-1	+3.2	+1.1
		1.000	+1.8	-0.6	+0.157	-8	-3.5	0
		1.75	+3.8	-3.1	-0.034	0	+3.9	-0.4
	Petro-S	0.70	+5.6	-4.0	-0.044	-2	+0.1	+0.5
		1.40	+3.3	-2.1	+0.037	-2	-1.1	-0.2
		2.10	+2.7	-1.0	+0.079	-6	+0.3	-0.1

Table 35. Changes in moisture-density and K-test parameters, phase II soil series (continued)

Soil and Dominant Clay Minerals	Treatment	% Dry Soil Wt.	Maximum Dry Density, pcf	Optimum Moisture Content, %	K-Test Parameters at γ_d and OMC			
					K_i	φ, degrees	c, psi	E (× 10^3), psi
Peavine (Montmorillonite)	Water	----	(73.0)	(45.7)	(0.430)	(19)	(8.1)	(2.3)
	SC-518	0.01	-0.1	-0.9	-0.040	+4	-2.2	+0.3
		0.035	+0.6	-3.0	-0.043	+4	-1.5	+0.6
		0.07	+1.2	-4.6	-0.110	+9	0	+0.9
	SA-1	0.01	+0.8	-2.2	-0.053	+4	-0.5	+0.6
		0.07	+0.8	-2.5	-0.066	+4	+1.0	+0.7
		0.14	+1.5	-3.7	-0.020	+2	-0.5	+0.4
	Clapak	0.01	+1.6	-2.0	-0.051	+4	-1.0	+1.1
		0.07	+2.7	-3.4	-0.095	+8	-1.1	+1.5
		0.14	+3.5	-2.2	+0.002	+2	-3.6	+0.8
	Duponol WA Paste	0.10	+0.1	-3.1	+0.050	-5	+2.2	-0.5
		0.50	+0.2	-3.2	+0.025	-5	+4.1	-0.5
	Polytergent B-300	0.10	-1.6	+2.6	+0.200	-11	+0.2	+1.1
		0.50	-0.2	-0.4	+0.050	-5	+1.8	+0.2
	Claset	0.01	-0.1	-0.7	-0.008	+1	-1.3	+0.1
		0.07	+0.3	-1.3	-0.045	+4	-2.4	+0.5
		0.14	+0.5	-1.8	-0.092	+3	+7.6	+0.6
	Coherex	0.70	+0.3	-1.4	-0.058	+4	+0.6	+0.8
		1.00	+3.2	-7.7	-0.045	+4	-1.9	+0.9
		1.75	+3.8	-4.4	-0.094	+6	+1.9	+0.5
	Petro-S	0.70	+2.6	-6.2	-0.050	+3	+1.8	+0.3
		1.40	+2.3	-4.2	-0.003	+1	-1.3	+0.3
		2.10	+2.4	-5.4	+0.003	+2	-2.2	+0.3
	Thinwater	0.0005	+2.7	-5.2	-0.028	+2	+0.2	+1.0
		0.001	+3.1	-5.7	-0.031	+2	+0.6	+0.6
		0.007	+3.4	-2.2	-0.111	+8	+1.4	+0.7
	Road Packer	0.01	+1.0	-2.2	-0.075	+6	+0.6	+1.2
		0.035	+0.6	-1.8	-0.085	+4	+5.0	+0.7
		0.07	+3.2	-4.0	-0.057	+4	0	+1.2
Marias (Montmorillonite)	Water	----	(94.7)	(26.2)	(0.587)	(9)	(9.0)	(1.9)
	SC-518	0.01	+2.0	-1.9	-0.152	+8	+1.8	+0.6
		0.035	+5.3	-6.2	-0.205	+11	+3.4	+0.2
		0.07	+5.3	-4.4	-0.149	+8	+1.5	+0.8
	SA-1	0.01	+5.6	-6.5	-0.179	+9	+2.1	+0.4
		0.07	+6.7	-5.8	-0.185	+8	+5.4	+0.8
		0.14	+2.6	-3.7	-0.222	+9	+3.5	+0.3
	Clapak	0.01	+1.4	-1.7	-0.093	+3	+3.5	+0.7
		0.07	+1.0	-2.7	-0.149	+7	+4.1	0
		0.14	+2.6	-3.7	-0.194	+10	+4.3	+0.8
	Claset	0.01	+0.7	-3.4	-0.222	+11	+5.8	+0.3
		0.07	+0.9	-3.7	-0.169	+8	+2.8	+0.2
		0.14	+2.8	-7.4	-0.274	+16	+5.7	+0.2
	Coherex	0.70	+2.6	-5.1	-0.093	+3	+3.4	-0.1
		1.00	+0.6	-3.1	-0.112	+8	-1.5	+0.4
		1.75	+0.9	-2.5	-0.120	+6	+1.7	+0.1

Table 35. Changes in moisture-density and K-test parameters, phase II soil series (continued).

Soil and Dominant Clay Minerals	Treatment	% Dry Soil Wt.	Maximum Dry Density, pcf	Optimum Moisture Content, %	K-Test Parameters at γ_d and OMC			
					K_i	ϕ, degrees	c, psi	E ($\times 10^3$), psi
Marias (Montmorillonite)	Petro-S	0.70	+2.5	-4.2	-0.161	+10	+0.3	+0.7
		1.40	+1.7	-4.2	-0.170	+10	+1.8	+0.2
		2.10	+2.1	-3.8	-0.102	+5	+0.3	+0.4
	Duponol WA Paste	0.10	-2.1	-0.6	+0.025	0	+1.8	+0.1
		0.50	-2.0	+0.4	+0.020	0	+1.6	+0.1
	Polytergent B-300	0.10	-3.8	+0.3	+0.080	-2	+0.6	-0.2
		0.50	-3.3	-0.8	-0.050	+2	+0.2	0
Ontonagon (Montmorillonite)	Water	----	(93.7)	(26.0)	(0.356)	(20)	(14.9)	(2.3)
	SA-1	0.01	-0.9	+1.5	+0.015	0	+1.0	-0.1
		0.07	-2.0	+3.1	+0.104	-5	-3.1	+0.4
		0.14	+0.3	+1.7	+0.074	-3	-2.3	+0.2
	Clapak	0.01	+0.1	+1.1	+0.037	0	-2.3	-0.2
		0.07	+1.0	+1.5	+0.155	-6	-6.1	-0.1
		0.14	+1.4	+1.0	+0.076	-3	-3.2	+0.4
	Duponol WA Paste	0.10	+4.1	-3.6	-0.050	+4	+2.2	-0.8
		0.50	+2.7	-4.6	-0.050	+5	+7.2	+0.7
	Polytergent 300	0.10	+3.7	-1.4	0	-3	+2.0	-0.5
		0.50	+5.2	-6.1	-0.025	+2	+5.8	-0.6
	Claset	0.01	+1.9	-1.6	-0.013	+3	-1.1	+0.3
		0.07	0	+0.6	+0.053	0	-4.2	-0.2
		0.14	-4.0	+2.2	+0.075	-3	-2.5	-0.2
	Coherex	0.70	-2.1	+3.1	+0.140	-9	-5.2	+0.1
		1.75	-2.8	-1.0	+0.052	-2	-3.2	-0.5
	Petro-S	0.70	-2.2	+2.2	+0.375	-14	-5.2	-0.3
		1.40	+3.5	-1.2	+0.229	-11	-2.3	+0.3
		2.10	+3.3	-1.8	-0.068	0	-3.8	+0.2
Frederick (Kaolinite)	Water	----	(94.1)	(26.2)	(0.390)	(20)	(8.0)	(3.8)
	SC-518	0.01	-1.4	-0.5	-0.040	+1	+3.0	-0.2
		0.05	-1.2	-0.4	-0.065	+2	+2.0	0
		0.10	-0.9	+0.8	-0.065	-2	+0.7	+0.2
	Clapak	0.01	-3.7	+1.5	-0.040	+3	+2.2	+0.2
		0.10	-1.9	+1.8	+0.060	-5	-2.0	-0.1
		0.20	+0.4	+0.1	+0.085	-5	-2.0	0
	Claset	0.01	-0.8	+0.1	-0.061	+9	-0.6	+0.1
		0.10	+0.1	0	-0.074	+6	-3.8	-0.6
		0.20	-2.2	-1.1	-0.051	+5	-3.8	-0.8
	Petro-S	0.91	-0.3	-2.0	-0.069	+7	-0.2	-0.3
		1.82	+0.8	-1.8	-0.042	+4	-1.9	0
		2.73	-0.6	-2.4	-0.026	+3	-2.3	-1.1
	Thinwater	0.0006	+1.5	+1.5	-0.065	+6	-0.6	-0.4
		0.0012	+1.0	+3.0	-0.005	+3	-3.4	-0.6
		0.007	-1.9	+2.1	-0.034	+2	-1.7	-0.4

Table 35. Changes in moisture-density and K-test parameters, phase II soil series (continued).

Soil and Dominant Clay Minerals	Treatment	% Dry Soil Wt.	Maximum Dry Density, pcf	Optimum Moisture Content, %	K-Test Parameters at γ_d and OMC			
					K_i	ϕ, degrees	c, psi	E ($\times 10^3$), psi
Frederick (Kaolinite)	Coherex	0.70	+4.1	-2.0	-0.061	+7	-2.0	-0.2
		1.00	+3.1	-0.7	-0.015	+2	-2.2	+0.1
		1.75	+1.9	-1.6	-0.065	+6	-1.6	-0.2
	SA-1	0.01	-0.8	+0.7	+0.019	-5	-1.0	-0.7
		0.14	+0.6	-1.0	+0.006	-4	+0.2	-0.9
	Road Packer	0.01	-0.6	+0.2	-0.028	-2	+0.3	-0.6
		0.07	-1.5	+1.5	+0.024	-5	+0.3	-0.7
	Aerosol OT-75%	0.10	+1.7	-2.1	+0.125	-5	+2.8	+0.8
		0.50	+0.9	-2.0	+0.025	0	+3.8	+0.8
	Nacconol 40F	0.10	+1.5	-2.2	0	+3	+7.9	+0.8
		0.50	+4.0	-2.6	+0.050	-4	+6.1	0
Persanti (Kaolinite)	Water	----	(95.1)	(25.3)	(0.353)	(26)	(5.8)	(3.0)
	Clapak	0.01	+0.9	+0.2	+0.107	-7	-2.1	-0.3
		0.10	+1.0	-0.6	+0.152	-9	-2.5	-0.6
		0.20	+1.7	-0.7	+0.004	-3	+5.1	-0.5
	Claset	0.01	+0.3	+0.7	+0.018	-4	+6.0	+0.4
		0.10	0	-0.1	-0.014	-1	+4.5	+0.1
		0.20	+1.1	-0.2	+0.006	-1	+1.0	0
	Coherex	0.07	0	+0.1	+0.016	-3	+3.7	-0.3
		1.00	+0.5	-1.0	+0.010	-5	+5.7	-0.5
		1.75	+0.3	-0.4	+0.048	-7	+4.7	0
	Petro-S	0.91	+1.6	-1.0	+0.006	-2	+2.1	0
		1.82	+1.2	-1.6	+0.038	-3	+0.4	-0.2
		2.73	+2.6	-1.8	+0.026	-5	+5.3	-0.4
	Thinwater	0.0006	-1.1	+1.7	+0.079	-8	+4.5	-0.3
		0.0012	-1.9	+1.9	+0.070	-7	+3.3	0
		0.007	-1.0	-1.4	-0.063	+3	+4.9	-0.2
	Aerosol OT-75%	0.10	-1.2	-0.5	+0.025	0	+7.0	-0.1
		0.50	+2.3	-1.3	+0.050	-2	+5.0	-0.4
	Nacconol 40F	0.10	+1.2	-0.2	+0.050	-2	+10.2	+0.6
		0.50	+2.3	+0.5	+0.200	-12	-3.0	+0.5
Melbourne (Vermiculite)	Water	----	(85.6)	(33.0)	(0.428)	(21)	(5.4)	(3.0)
	SC-518	0.01	+0.2	-0.8	+0.012	0	-2.6	-0.6
		0.035	+1.4	-1.5	-0.048	+3	+0.6	+0.4
		0.07	+0.6	-0.7	-0.006	0	-0.3	-0.1
	SA-1	0.01	+1.8	-2.8	-0.039	+2	+0.6	0
		0.07	+7.4	-8.9	-0.094	+8	-3.5	-0.1
		0.14	+5.9	-8.9	-0.114	+8	+0.7	-0.6
	Aerosol OT-75%	0.10	+2.2	-3.1	+0.100	-2	+3.8	-0.8
		0.50	+2.3	-2.1	+0.025	-6	+4.4	0
	Nacconol 40F	0.10	-1.4	+0.5	+0.025	+2	+8.6	0
		0.50	-0.5	-1.1	+0.010	0	+7.8	+0.5

Table 35. Changes in moisture-density and K-test parameters, phase II soil series (continued).

Soil and Dominant Clay Minerals	Treatment	% Dry Soil Wt.	Maximum Dry Density, pcf	Optimum Moisture Content, %	K-Test Parameters at γ_d and OMC			
					K_i	ϕ, degrees	c, psi	E ($\times 10^3$), psi
Melbourne (Vermiculite)	Clapak	0.01	+5.7	-7.2	-0.080	+8	-0.3	-0.2
		0.07	-0.3	-1.2	-0.001	-2	+2.1	-0.5
		0.14	+0.7	-2.2	-0.020	-1	+3.5	-0.4
	Claset	0.01	+0.2	-1.1	-0.078	+3	+4.8	-0.2
		0.07	+0.1	-2.3	-0.076	0	+7.2	-0.7
		0.14	+6.5	-7.0	-0.083	+5	+3.4	-0.2
	Coherex	0.70	+5.3	-7.3	-0.015	+2	-2.8	-0.4
		1.00	+5.5	-7.0	-0.088	+4	+4.2	-0.5
		1.75	+6.2	-9.1	-0.055	+9	+6.8	-0.7
	Petro-S	0.70	+4.0	-5.3	-0.079	+2	+5.8	-0.2
		1.40	+2.9	-4.2	-0.039	+1	+1.7	-0.7
		2.10	+4.1	-5.2	-0.067	+1	+5.7	-0.4
Buxton (Vermiculite-Illite)	Water	----	(98.7)	(24.5)	(0.358)	(25)	(8.2)	(3.7)
	SC-518	0.01	-0.6	-1.2	-0.050	+2	+2.8	+0.4
		0.035	+1.0	-1.4	-0.043	+4	-3.7	+0.8
		0.07	0	-1.5	-0.061	+3	+5.9	+0.7
	SA-1	0.01	-2.0	-1.9	-0.096	+7	+1.2	-0.5
		0.07	-1.8	-1.9	-0.058	+3	+1.3	-0.7
		0.14	+0.2	-1.1	-0.011	+1	-1.4	-0.7
	Clapak	0.01	+0.5	-1.8	+0.017	0	-0.9	+0.2
		0.07	-2.9	+0.5	-0.021	0	+2.9	-1.1
		0.14	-2.7	+0.3	-0.046	+2	+1.0	-0.7
	Claset	0.01	-1.8	+0.1	-0.035	+2	+1.3	-0.4
		0.07	-1.0	+0.5	+0.092	-5	-2.4	-0.3
		0.14	-2.3	+0.8	-0.015	+1	+0.6	0
	Coherex	0.70	-0.8	-1.4	-0.053	+1	+6.1	-0.6
		1.00	-1.1	-1.5	-0.048	+2	+1.6	-0.6
		1.75	-1.4	-1.1	-0.031	+1	+1.3	-0.8
	Petro-S	0.70	+0.3	-0.6	+0.056	-7	+4.1	-0.7
		1.40	+0.7	-0.8	+0.050	-9	+10.2	-0.7
		2.10	+1.9	-2.3	+0.024	-2	+0.3	-0.8
	Aerosol OT-75%	0.10	+0.7	+0.1	+0.175	-4	+1.6	-0.1
		0.50	+1.3	-0.8	+0.200	-9	+3.3	-0.3
	Nacconol 40F	0.10	-1.8	+2.9	+0.300	-13	+4.3	-0.2
		0.50	-1.0	+2.6	+0.200	-6	+7.1	-1.1
Vergennes (Vermiculite-Illite)	Water	----	(100.7)	(22.3)	(0.399)	(22)	(7.1)	(2.5)
	SC-518	0.01	-1.1	-0.1	-0.068	+4	+2.2	+0.8
		0.035	+1.4	-1.3	-0.106	+7	+3.0	+1.1
		0.07	+1.4	-0.2	-0.017	+3	-2.3	+0.9
	Clapak	0.01	+1.7	0	+0.080	-4	-0.7	+0.8
		0.07	+1.1	+0.5	-0.007	-1	+3.9	+0.7
		0.14	+2.4	+0.1	+0.024	-1	+1.5	+0.9
	SA-1	0.01	-0.3	+0.2	-0.124	-1	+6.4	+0.9
		0.07	+1.0	-1.9	-0.194	+13	+3.3	+2.0
		0.14	+1.6	-0.5	+0.002	-3	+5.1	+0.9

Table 35. Changes in moisture-density and K-test parameters, phase II soil series (continued).

Soil and Dominant Clay Minerals	Treatment	% Dry Soil Wt.	Maximum Dry Density, pcf	Optimum Moisture Content, %	K-Test Parameters at γ_d and OMC			
					K_i	ϕ, degrees	c, psi	E ($\times 10^3$), psi
Vergennes (Vermiculite-Illite)	Coherex	0.70	+1.1	-0.9	-0.078	+5	+1.5	+1.2
		1.00	+1.1	-0.5	-0.049	+1	+6.2	+1.2
		1.75	+2.5	-0.8	-0.128	+7	+6.8	+1.8
	Petro-S	0.70	+2.3	-0.5	-0.054	+4	+1.1	+1.3
		1.40	+3.5	-1.6	-0.087	+5	+3.0	+1.9
		2.10	+3.1	-1.7	-0.068	+4	+2.5	+1.3
	Aerosol OT-75%	0.10	+1.1	-0.2	-0.075	+7	+7.0	+0.8
		0.50	+0.7	-0.1	-0.025	+1	+5.0	+1.0
	Nacconol 40F	0.10	+0.4	+0.5	0	+2	+3.6	+1.9
		0.50	+0.3	-0.4	-0.050	+8	+9.2	+0.9
	Thinwater	0.0006	+0.4	-0.3	-0.034	+4	-1.1	+1.0
		0.007	+1.5	-2.0	-0.124	+8	+4.0	+1.3
	Road Packer	0.01	+0.2	-0.7	+0.177	-13	+3.7	0
		0.07	+0.5	+0.6	-0.014	+2	-0.8	+0.9
Nappanee (Vermiculite-Illite)	Water	----	(108.2)	(17.5)	(0.367)	(19)	(17.5)	(2.6)
	SC-518	0.01	-0.7	-0.1	-0.056	+5	-2.3	-0.2
		0.035	-0.1	+1.2	+0.023	-1	-3.2	-0.1
		0.07	-0.7	+1.9	+0.028	+1	-5.2	+0.2
	Clapak	0.01	-0.1	+1.8	+0.041	-1	-3.6	+0.2
		0.07	0	-1.9	-0.118	+7	+5.3	+0.4
		0.14	-5.1	+2.4	+0.013	+4	-10.0	-0.6
	Claset	0.01	-5.1	+2.9	+0.028	+1	-7.0	+0.1
		0.07	-4.6	+2.1	+0.009	+2	-5.1	+0.2
		0.14	-2.1	+2.5	+0.127	-4	-11.7	+0.5
	Coherex	0.70	-1.1	+2.6	+0.139	-5	-9.2	+1.0
		1.00	-0.6	+0.2	+0.091	-2	-9.1	+0.2
		1.75	-1.9	+1.0	+0.138	-4	-10.5	-0.1
	Petro-S	0.70	-6.1	+2.5	+0.203	-11	-4.8	-0.9
		1.40	-5.6	+2.9	+0.357	-10	-10.3	+0.2
		2.10	-2.0	+1.3	+0.060	-2	-4.0	-0.2
	Aerosol OT-75%	0.10	0	-0.7	-0.030	0	+3.1	-0.4
		0.50	+1.0	-1.7	-0.030	+1	+3.5	-0.1
Paulding (Vermiculite-Illite)	Water	----	(92.3)	(27.3)	(0.516)	(15)	(6.3)	(2.2)
	Coherex	0.70	+1.4	-1.8	+0.044	6	+5.0	-0.1
		1.00	+0.4	-1.0	+0.250	-15	+8.5	+0.3
		1.75	+0.7	-0.8	+0.243	-15	+8.8	+0.4
	Petro-S	0.70	-1.2	-0.3	-0.009	-3	+4.8	-0.2
		1.40	-1.7	-1.1	+0.095	-13	+9.9	+0.2
		2.10	0	-1.5	-0.061	-2	+8.1	+0.1
	Claset	0.01	-0.2	+0.8	-0.005	-2	+3.9	-0.2
		0.07	-0.5	-3.2	-0.074	+2	+4.0	-0.4
		0.14	+1.7	-0.8	-0.159	+7	+10.8	-0.4
	SC-518	0.01	+1.4	-0.6	+0.060	-3	+3.6	+0.1
		0.035	+0.1	-2.9	+0.091	-12	+10.0	+0.7
		0.07	+1.9	-2.1	+0.201	-13	+4.4	+0.4

Table 35. Changes in moisture-density and K-test parameters, phase II soil series (continued).

Soil and Dominant Clay Minerals	Treatment	% Dry Soil Wt.	Maximum Dry Density, pcf	Optimum Moisture Content, %	K-Test Parameters at γ_d and OMC			
					K_i	ϕ, degrees	c, psi	E (× 10^3), psi
Paulding (Vermiculite-Illite)	SA-1	0.01	+4.9	-3.2	+0.394	-12	+1.5	+0.9
		0.07	+5.8	-3.1	-0.074	-2	+10.6	0
		0.14	+4.8	-3.0	+0.024	-9	+9.6	+0.1
	Clapak	0.01	+4.6	-2.8	-0.087	-2	+12.1	-0.1
		0.07	+4.5	-3.0	-0.075	-2	+9.9	-0.3
		0.14	+0.4	-1.9	+0.275	-2	+9.3	+0.2
	Aerosol OT-75%	0.10	+9.2	+3.2	+0.175	-17	+2.4	-0.8
		0.50	+9.6	+1.2	+0.175	-17	+7.7	-0.3
Fannin (Biotite-Vermiculite)	Water	----	(103.8)	(20.8)	(0.285)	(31)	(5.7)	(3.2)
	Clapak	0.007	-5.8	-0.3	+0.044	-3	-0.1	0
		0.07	-6.2	+0.9	+0.069	-5	-1.0	-0.2
		0.14	-4.4	-0.4	+0.057	-5	+2.2	-0.3
	Claset	0.007	-2.9	+1.1	+0.051	-6	+4.9	+1.2
		0.07	-2.5	+1.1	+0.136	-8	-2.0	+0.4
		0.14	-2.7	+0.4	+0.284	-1	+1.8	+0.1
	Aerosol OT-75%	0.10	-1.5	0	-0.010	+2	+7.6	+1.4
		0.50	+0.1	-1.7	-0.350	+7	+7.2	+1.2
	Coherex	0.70	-3.4	+1.0	+0.037	0	-4.4	+0.1
		1.00	-3.3	+0.7	+0.093	-7	+3.0	-0.3
		1.75	-3.5	+1.2	+0.108	-6	-2.7	-0.4
	Petro-S	0.70	-3.4	+0.4	+0.032	-4	+3.2	-0.2
		1.40	-2.3	0	+0.051	-4	0	-0.1
		2.10	-2.7	-0.6	+0.078	-5	-0.5	-0.5
Onoway (Mixed)	Water	----	(121.9)	(11.4)	(0.234)	(34)	(8.2)	(5.7)
	SC-518	0.01	-2.5	+0.5	+0.294	-20	-3.7	-1.1
		0.035	-1.0	+1.3	+0.066	-4	-3.1	-0.6
		0.07	+0.4	+0.9	+0.168	-16	-8.2	-2.5
	SA-1	0.01	-9.9	+3.3	+0.027	-4	+3.5	-3.1
		0.07	+2.1	-0.8	+0.001	-1	+3.2	-0.7
		0.14	-9.9	+3.8	+0.024	-5	+0.4	-2.2
	Clapak	0.01	-10.2	+3.8	-0.001	-1	+1.7	+1.6
		0.07	-8.6	+3.9	+0.079	-5	+0.3	-1.5
		0.14	+2.0	+0.1	+0.039	-3	+1.2	-0.3
	Claset	0.01	-9.1	+3.5	+0.007	-1	+2.7	-1.6
		0.07	-10.3	+4.8	+0.130	-9	-2.8	-1.9
		0.14	-2.6	-0.8	+0.087	-6	-2.0	-0.6
	Coherex	0.70	+4.6	-2.5	-0.077	+8	+2.0	+1.8
		1.00	+3.0	-1.1	+0.085	-5	-1.6	-0.7
		1.75	+3.3	-2.4	-0.009	+2	+2.3	+0.5
	Petro-S	0.70	+2.0	-1.3	+0.020	-1	-0.8	+0.5
		1.40	+0.9	-0.3	+0.050	-3	-1.5	-0.6
		2.10	-0.6	-0.8	+0.032	-3	+2.2	-0.6

c) Coherex. Some improvement in γ_d, OMC, and c at 0.70% dry soil weight only. Not effective. Lowering of treatment levels may be indicated.

d) Petro-S. Improvement in γ_d, OMC, and c at all treatment levels. K_i, ϕ, and E changes of little consequence to deleterious. Effective in compaction. Partially effective in stability.

e) Thinwater. Good to excellent improvement in γ_d and OMC, and slight improvement in E at each percentage treatment. No net improvement in combined K_i, ϕ, and c values. Partially effective.

f) Duponal WA Paste. Improved c only. Not effective.

g) Polytergent B-300. Not effective.

Renohill Series

a) SC-518. Increased ϕ and E, but dominantly deleterious to all other parameters regardless of treatment level. Not effective.

b) Clapak. Increased ϕ at each treatment, and increased E at 0.01 and 0.07% treatment only. Other parameters show moderately deleterious effects. Not effective.

c) Claset. Moderate increase in ϕ and E at 0.01 and 0.15% treatment. Moderate increase in E, coupled with significant reduction in c at all treatments. Other changes moderately deleterious. Not effective.

d) Coherex. Significant decrease in c at all treatments. Moderate improvement in ϕ and E only. Not effective.

e) Petro-S. Good to excellent improvement in γ_d and OMC at all treatment levels. Minor improvement in K_i, ϕ, c, and E at 0.91% dry soil weight. Significantly reduced c at higher percent treatments. Partially effective at low concentrations.

f) Duponol WA Paste. Improved c only. Not effective.

g) Polytergent B-300. Not effective.

Pierre Series

a) SC-518. Some improvement in γ_d at each percentage treatment and in ϕ and K_i at low and high treatments. No basic improvement in OMC, c, and E. Partially effective.

b) Clapak. Slight improvement in OMC, K_i, ϕ, and c at mid to high treatment levels. No change to somewhat deleterious effects with γ_d and E. Not effective.

c) Claset. Slight to good improvement in γ_d, OMC, K_i, and ϕ. No improvement to deleterious effects with c and E. Partially effective.

d) Coherex. Good improvement in OMC, K_i, and ϕ at mid to high percentages of product. Slight improvement to deleterious effects with γ_d, c, and E. Partially effective.

e) Petro-S. Slight to good improvement in γ_d, OMC, K_i, and ϕ at low to mid percentages. Not effective, however, due to significant lowering of cohesion.

f) Road Packer. Not effective.

g) Duponol WA Paste. Significant decrease in c at both levels of treatment. Limited improvement in γ_d and ϕ only. Not effective.

h) Poly-Tergent B-300. Significant decrease in c, and some increase in ϕ at both treatment levels. Other parameters show basically no change to deleterious effects. Not effective.

<u>Altamont Series</u>

a) Clapak. Improved cohesion at each level of treatment. Improved K_i and ϕ at 0.07% dry soil weight only. All other parameters show basically no change to deleterious effects. Not effective.

b) SC-518. Shear parameters c and ϕ are improved at 0.035% dry soil weight. Cohesion, only, improved at 0.07%. All other parameters show no effect to deleterious effects. Not effective.

c) Claset. Some improvement in c at all treatment levels, with improved K_i and ϕ at 0.07% only. Other parameters show no effect to deleterious effects. Not effective.

d) Coherex. Regardless of percentage treatment, not effective.

e) Petro-S. Slight improvement in γ_d, OMC, K_i, ϕ, and c at 2.10% dry soil weight only. This treatment level was considered uneconomical. Not effective.

f) Duponol WA Paste. Good to slight improvement in OMC and c only. Not effective.

g) Poly-Tergent B-300. Improved E at 0.10% only. Not effective.

Rimrock Series

a) Claset. Improved γ_d, OMC, K_i, ϕ, and c at 0.07% dry soil weight. Improved γ_d, OMC and c at 0.14% level. Partially effective.

b) Coherex. Moderate to good improvement in γ_d and OMC at each treatment level. Moderate to good improvement in K_i and c at 1.00%, and c at 1.75%. Partially effective.

c) Clapak. Good improvement in γ_d, OMC, K_i, and ϕ at each percentage treatment. Also improved c at 0.01%. E and c degenerated with increased treatment. Fully to partially effective.

d) SC-518. Moderate to good improvement in γ_d and OMC at each percentage treatment. Effectiveness with K_i, ϕ, c, and E decreased to deleterious state with increased treatment levels. Partially effective.

e) Petro-S. Good to significant effectiveness with γ_d, OMC, K_i, and ϕ at each treatment. Minor improvement to deleterious effects with E, while c decreased with increased percentages of chemical. Fully to partially effective.

f) Duponol WA Paste. Some reduction in OMC only. Not effective.

g) Poly-Tergent B-300. Some reduction in OMC at 0.50%, but γ_d was reduced at each treatment level. Not effective.

Houston Black Series

a) SC-518. Good to significant improvement in γ_d and E with increasing treatment percentages. Improved OMC and ϕ at 0.07%. No change to deleterious effects for OMC, K_i, ϕ, and c at 0.01 and 0.035%. Partially effective.

b) SA-1. Basically little improvement to deleterious effects regardless of percentage treatment. Not effective.

c) Clapak. Significant to good improvement in γ_d and E with increased percentage treatment. Improved OMC at lowest treatment, 0.01%. Other parameters show insignificant improvement to deleterious effect. Partially effective.

d) Claset. Good improvement in γ_d only. All other parameters show insignificant improvement to deleterious effects. Not effective.

e) Coherex. Good to significant improvement in γ_d and OMC with each treatment. Improved K_i and c at low and high treatment levels of 0.70 and 1.75%. Significant improvement in E at 0.70% only. Partially effective.

f) Petro-S. Significant to good effectiveness in γ_d and OMC with increasing levels of treatment. All other parameters show slight improvement to deleterious effects. Partially effective.

g) Duponol WA Paste. Good reduction in OMC plus increased c with increasing percentage of chemical. Other parameters show no effect. Not effective.

h) Poly-Tergent B-300. Not effective.

Peavine Series

a) SC-518. Increased effectiveness in γ_d, OMC, K_i, ϕ, and E with each increase in level of treatment. Significantly improved OMC, K, ϕ, and E at highest treatment of 0.07%. Cohesion improved from deleterious to no change in effectiveness from 0.01 to 0.07% dry soil weight. Fully to partially effective at relatively high treatment levels.

b) SA-1. Each treatment level improved γ_d, OMC, K_i, ϕ, and E. Slight plus-or-minus changes in c. Fully to partially effective.

c) Clapak. Each treatment improved γ_d, OMC, ϕ, and E. K_i was improved at low and mid percentages of 0.01 and 0.07. Cohesion was somewhat reduced. Fully to partially effective.

d) Claset. Slight to good improvement in γ_d, OMC, K_i, ϕ, and E at mid to high levels of 0.07 and 0.14% dry soil weight. Significantly improved c at 0.14%. Partially effective.

e) Coherex. Good to significant improvements in γ_d, OMC, K_i, ϕ, and E with each percentage chemical. Some improvement in c at low and high treatments of 0.70 and 1.75%. Fully to partially effective.

f) Petro-S. Good to significant improvement in γ_d and OMC with each chemical level of treatment. Partially improved ϕ and E at each percentage level, while c was improved at 0.70% only. K_i showed no basic change to some improvement. Partially effective through compaction only.

g) Thinwater. Good to significantly improved effectiveness in γ_d and OMC regardless of level of treatment. Variability of improved effectiveness with all other parameters, ranging from slight to significant. Fully effective.

h) Road Packer. Moderate to significant improvement in all parameters with all levels of treatment. Fully to partially effective.

i) Duponol WA Paste. Good improvement only in OMC and c with increasing chemical content. Other parameters not effective to deleterious. Not effective.

j) Poly-Tergent B-300. Improved only E at 0.1% and c at 0.50%. Not effective.

Marias Series

a) SC-518. Good to significant improvement in all parameters at each level of treatment. Fully effective.

b) SA-1. Good to significant improvement in all parameters at each level of treatment. Fully effective.

c) Clapak. Fair to good improvement in all parameters at 0.01 and 0.07% dry soil weight. Good to significant improvement in each parameter at highest treatment level of 0.14%. Fully to partially effective.

d) Claset. Some improvement in γ_d at mid and low percentages of chemical. Slight improvement in E at all treatment levels. All other parameters good to significant improvement, including a 16^o increase in ϕ at 0.14% chemical. Fully to partially effective.

e) Coherex. Good to significant improvement in all parameters, except E, at lowest percentage treatment. Slightly improved γ_d and E and good improvement in OMC, K_i, and ϕ at mid and high treatments. Cohesion reduced to slightly improved at mid and high treatments, respectively. Partially effective.

f) Petro-S. Fair to significant improvement in all parameters at all levels of treatment, though best at low and mid chemical percentages. Fully to partially effective.

g) Duponol WA Paste. Not effective.

h) Poly-Tergent B-300. Not effective.

Ontonagon Series

a) SA-1. Not effective, regardless of treatment level.

b) Clapak. Increased γ_d with increasing percentage of chemical. All other parameters indicate detrimental results. Not effective.

c) Claset. Except for cohesion, 0.01% treatment indicates fair to good parameter improvements. Mid and high chemical concentrations indicated detrimental chemical effects. Partially effective at low concentrations only.

d) Coherex. Except for a minor decrease in OMC at the highest treatment level, all changes were detrimental to compaction/ stability effectiveness. Not effective.

e) Petro-S. Good improvement in γ_d and OMC only at mid and high treatment levels. Low treatment levels and all other parameter changes were poor to deleterious. Not effective.

f) Duponol WA Paste. General improvement in all parameters except E. Most effective at 0.5%.

g) Poly-Tergent B-300. Improved all parameters except E. Most effective at 0.5% with significant reduction in OMC and increased γ_d.

2. Kaolinitic Soils.

Frederick Series

a) SC-518. Minor improvement in K_i, ϕ, and c at lower concentrations only. Not effective.

b) Clapak. Minor improvement in K_i, ϕ, c, and E at 0.01% only. Partially effective through stability improvement, low concentrations only.

c) Claset. Improved K_i and ϕ at each percentage treatment, and OMC at 0.20% only. Not effective.

d) Petro-S. Improved OMC, K_i, and ϕ at each treatment. Minor improvement in γ_d at 1.82% dry soil weight. Partly effective at lower concentration.

e) Thinwater. Improved γ_d, K_i, and ϕ. Increased OMC by 1.5 to 3.0% moisture and reduced c and E. Not effective.

f) Coherex. Significant improvement in γ_d and good to excellent benefits in OMC, K_i, and ϕ at low concentrations. Effective in compaction, partially effective in stability.

g) Aerosol OT-75%. Some improvement in γ_d, OMC, c, and E. K_i and ϕ showed no improvement to detrimental affects. Partially effective.

h) Nacconol 40F. Improved γ_d, OMC, and c. Partially effective.

i) SA-1. Parameter changes were generally zero to deleterious. Not effective.

j) Road Packer. Not effective.

Persanti Series

a) Clapak. Moderate improvement in γ_d, OMC, and c at 0.20% treatment only. Other parameters and treatment levels indicate general ineffectiveness. Partially effective for compaction only.

b) Claset. Moderate to good improvement in c at lower treatment levels only, and in γ_d at highest treatment only. Other parameter changes were insignificant to partially deleterious. Not effective.

c) Coherex. Minor improvements in γ_d and OMC occurred at 1.00 and 1.75% dry soil treatments while c was improved at all levels. Deleterious in other parameters. Not effective.

d) Petro-S. Good to excellent improvement in γ_d and OMC, with poor to good improvement in c occurring at all three treatments. Other parameters not effective. Partially effective in M-D only.

e) Thinwater. Improvement in OMC, K_i, ϕ, and c at highest treatment. Moderate improvement in c only at two lower treatments. Partially effective at high concentrations.

f) Aerosol OT-75%. Some improvement in γ_d, OMC, and c particularly at 0.50%, but offset by detrimental K_i, ϕ, and E changes. Not effective.

g) Nacconol 40F. Improved γ_d, c, and E at each percentage level. Ineffective for OMC, K_i, and ϕ. Overall rating: ineffective.

3. Vermiculite Soils.

Melbourne Series

a) SC-518. Good improvement in all parameters at the mid-treatment level of 0.035%. Low and high percentage treatments were slightly effective to deleterious for parameters. Partially effective.

b) SA-1. Significantly improved effectiveness with increasing chemical percentage for γ_d, OMC, K_i, and ϕ. Cohesion and E showed very slight improvement to somewhat deleterious effects. Fully to partially effective.

c) Clapak. Good to significant improvement in γ_d, OMC, K_i, and ϕ at 0.01% dry soil weight only. Good improvement in OMC and c only, at 0.07 and 0.14%. Partially effective.

d) Claset. Minor to significantly effective with parameters γ_d, OMC, K_i, ϕ, and c at all applied percentages of chemical. Some reduction in E at each percentage. Fully to partially effective.

e) Coherex. Good to significant improvement in γ_d, OMC, K_i, and ϕ at each treatment level. Significant improvement in c at mid to high percentages 1.00 and 1.75. Definite reduction in E at each percentage treatment. Fully to partially effective.

f) Petro-S. Good to significant improvement in all parameters, except E, at all treatment levels. Fully to partially effective.

g) Aerosol OT-75%. Improved γ_d, OMC, and c. Offset by high K_i and low E. Not effective.

h) Nacconol 40F. Good improvement in c only, primarily at low 0.1% level. For other parameters--not effective.

4. Vermiculite - Illite Soils.

<u>Buxton Series</u>

a) SC-518. Minor to good improvement in OMC, K_i, ϕ, c, and E, with exception of c at 0.035% (mid) level. Minor improvement in γ_d at 0.035% treatment only. Partially effective.

b) SA-1. Minor to good improvement in OMC, K_i, and ϕ at each level of treatment. Minor improvement in c but reduced γ_d at low and mid treatments. Deleterious effects with E at all treatment levels. Partially effective.

c) Clapak. Minor improvement to detrimental effects in all parameters at all treatment levels. Not effective.

d) Claset. Generally ineffective, though very slightly improved ϕ and c at low and high chemical concentrations only. Not effective.

e) Coherex. Minor to fair improvement in OMC, K_i, ϕ, and c at all treatments. Increased reduction in γ_d with increasing percentages of chemical coupled with reduced E. Partially effective.

f) Petro-S. Minor to significant improvement in γ_d, OMC, and c over range of treatments. Significantly increased c at mid treatment level, but offset by a major reduction in ϕ. Ineffective to detrimental with K_i, ϕ, and E. Not effective.

g) Aerosol OT-75%. Slight improvement in γ_d and c with increasing chemical content. Generally ineffective.

h) Nacconol 40F. Improved c only with increasing chemical content. Not effective.

Vergennes Series

a) SC-518. Minor to good improvement in OMC, K_i, ϕ, and E. Fair improvement in γ_d at mid to high treatment and in c at low to mid treatment levels. Partially effective.

b) Clapak. Minor to good improvement in γ_d, ϕ, and E. Randomly detrimental to improved OMC, K_i, and c parameters. Partially effective.

c) SA-1. Fair to significant improvement in all parameters at mid treatment level of 0.07%. Random effectiveness at low and high treatments. Good to significant improvement in c and E at each treatment level. Partially effective.

d) Coherex. Fair to significant improvement in all parameters over full range of treatment with a generalized trend of effectiveness increasing with increased percentages of chemical. Fully to partially effective.

e) Petro-S. Partial to significant improvement in all parameters regardless of level of treatment. Fully to partially effective.

f) Aerosol OT-75%. Slight improvement in γ_d, K_i, and E. Good improvement in ϕ and c at only 0.1%. Insignificant change in OMC. Partially effective.

g) Nacconol 40F. Generally effective in stability only.

h) Thinwater. Increased γ_d, ϕ, c, and E with increased percent chemical and decreased OMC and K_i. Generally effective at the higher treatment level of 0.007%.

i) Road Packer. Most parameters showed only slight plus or minus changes from untreated. Not effective.

Nappanee Series

a) SC-518. In general, detrimental effects increased with increasing percentage of chemical. Not effective.

b) Clapak. No effect to significant improvement in all parameters at 0.07% (mid) treatment only. Low and high levels of added chemical dominantly detrimental. Partially effective at mid treatment percentage only.

c) Claset. Significant reductions in γ_d and c coupled with increased OMC and K_i. Not effective.

d) Coherex. No effect to significantly detrimental with all percentages of chemical. Not effective.

e) Petro-S. Significant reductions in γ_d, ϕ, and c, and increased OMC and K. Not effective.

f) Aerosol OT-75%. Slight improvement in all parameters except E at 0.50%. Partially effective.

<u>Paulding Series</u>

a) Coherex. Minor M-D effectiveness decreased with increased percentages of chemical. Excellent improvement in c, but increased K_i and significantly reduced ϕ. Not effective.

b) Petro-S. Minor to good improvement in OMC and c at all treatment levels. All other changes in parameters showed little effect to significantly detrimental effects. Not effective.

c) Claset. Improved γ_d at highest treatment level only. Parameters OMC, K_i, ϕ, and c improved with mid to high treatments of 0.07 and 0.14% only. Minor reduction in E at all percentages of chemical. Partially effective.

d) SA-1. Good to significant effectiveness with γ_d, OMC, and c at all levels of treatment. Random minor improvements to significantly detrimental effects with K_i, ϕ, and E. Fully to partially effective at mid-range concentration of 0.07% only.

e) SC-518. Minor to good improvement in γ_d, OMC, c, and E at all chemical percentages. Increasing detrimental effects with K_i and ϕ due to increased percentages of chemical. Not effective.

f) Clapak. Minor to significant improvement in γ_d, OMC, and c for all treatments. Good improvement in K_i at low to mid treatment. Regardless of percentage of chemical, ϕ was slightly reduced. Minor plus and minus changes in E. Partially effective at low to mid levels of treatment only.

g) Aerosol OT-75%. Significant improvement in γ_d, but significant decrease in ϕ and increased OMC. Not effective.

5. Biotite-Vermiculite Soil.

Fannin Series

a) Clapak. Other than a partially improved OMC at 0.07% treatment, and c at 0.14% treatment, Clapak is not effective. Significant reduction in γ_d occurred at all treatment levels.

b) Claset. Partial improvement occurred only with c and E. Not effective.

c) Coherex. Slight improvement in c only at 1.00% dry weight treatment. Other parameters indicates no change to deleterious effects. Not effective.

d) Petro-S. Slight improvement in c only at 0.70% dry soil weight. All other parameters indicates no change to deleterious effects. Not effective.

e) Aerosol OT-75%. Good improvement in stability parameters and OMC at 0.50%. Basically no change in γ_d. Generally effective.

6. Mixed Soil/Clay Mineralogy.

Onoway Series

a) SC-518. No improvement to significantly detrimental effects in all parameters regardless of percentage of chemical. Not effective.

b) SA-1. Partial improvement to significantly detrimental effects at all levels of treatment and parameters. Not effective.

c) Clapak. Partial improvement to significantly detrimental effects at all levels of treatment and parameters. Not effective.

d) Claset. Partial improvement to highly detrimental effects at all levels of treatment and parameters. Not effective.

e) Coherex. Good improvement in γ_d and OMC at each percentage of chemical. Fair to excellent improvement in K_i, ϕ, c, and E at low and high treatments only, while deleterious to these parameters at the mid-treatment level. Partially effective.

f) Petro-S. Generally ineffective over all levels of treatment since parameters show only minor improvements to minor detrimental effects. Not effective.

Table 36 presents a simplified summation of the above observations. Of the nearly 140 combinations of soils and chemicals evaluated at their maximum γ_d and OMC, only 26 showed favorable M-D and stability effectiveness.

Table 36. Summary of moisture-density and K-test product effectiveness at maximum γ_d and OMC.

Soil Series and Dominant Clay Mineral*	Products**											
	Clapak	Claset	Coherex	Petro-S	Thin-water	SC-518	SA-1	Road Packer	Duponol WA Paste	Poly-tergent B-300	Aerosol OT-75%	Nacconol 40F
Bearden (M)	+	+	-	+	0	N/D	N/D	N/D	-	-	N/D	N/D
Renohill (M)	-	-	-	0	N/D	-	N/D	N/D	-	-	N/D	N/D
Pierre (M)	-	0	0	-	N/D	0	N/D	-	-	-	N/D	N/D
Altamont (M)	-	-	-	-	N/D	-	N/D	N/D	-	-	N/D	N/D
Rimrock (M)	+	0	0	+	N/D	0	N/D	N/D	-	-	N/D	N/D
Houston Black (M)	0	-	0	0	N/D	0	-	N/D	-	-	N/D	N/D
Peavine (M)	+	0	+	0	++	+	+	+	-	-	N/D	N/D
Marias (M)	+	+	0	+	N/D	++	++	N/D	-	-	N/D	N/D
Ontonagon (M)	-	-	-	-	N/D	N/D	-	N/D	+	0	N/D	N/D
Frederick (K)	0	-	+	+	-	-	-	-	N/D	N/D	0	0
Persanti (K)	0	-	-	0	0	N/D	N/D	N/D	N/D	N/D	-	-
Melbourne (V)	0	+	+	+	N/D	0	+	N/D	N/D	N/D	-	-
Buxton (V-I)	-	-	0	-	N/D	0	0	N/D	N/D	N/D	-	-
Vergennes (V-I)	0	N/D	+	+	+	0	0	-	N/D	N/D	0	0
Nappannee (V-I)	-	-	-	-	N/D	-	N/D	N/D	N/D	N/D	0	N/D
Paulding (V-I)	0	0	-	-	N/D	-	0	N/D	N/D	N/D	-	N/D
Fannin (B-V)	-	-	-	-	N/D	N/D	N/D	N/D	N/D	N/D	0	N/D
Onoway (MX)	-	-	0	-	N/D	-	-	N/D	N/D	N/D	N/D	N/D

*Soil Series and Dominant Clay Mineral

M = Montmorillonitic
K = Kaolinitic
V = Vermiculite
V-I = Vermiculite-Illite
B-V = Biotite-Vermiculite
MX = Mixed

**Products

++ = Fully effective
\+ = Fully to partially effective
0 = Partially effective
\- = Not effective
N/D = Not determined

Of these 26 combinations, only 3 are noted as fully effective (++), while 23 are fully to partially effective (+). Thirty-eight of the combinations are only partially effective (0), generally in M-D or in stability parameters only, but rarely both. All remaining combinations are ineffective (-) in terms of both M-D and stability evaluations; at least 50% of all soil-chemical treatment combinations provided no increase in density, decrease in OMC, or increased stability when compared to the untreated soil at their individual maximum γ_d and OMC.

Of the 26 favorable combinations shown in Table 36, the following summary can be made relative to the individual chemicals:

1. Clapak. Fully to partially effective (+) in four of the nine montmorillonitic soils only.

2. Claset. Fully to partially effective (+) in two of the nine montmorillonitic soils, and in one of the five mica groupings (V, V-I, and B-V) within which it was tested.

3. Coherex. Fully to partially effective in one of the nine montmorillonitic soils, one of the two kaolinitics, and two of the six micaceous groupings.

4. Petro-S. Fully to partially effective in three of the nine montmorillonitics, one of the two kaolinites, and two of the six mica groups.

5. Thinwater. Of the two montmorillonitic soils treated with this product, Thinwater was fully effective (++) in the Peavine series only. Tested in but one of the micaceous series, Thinwater was fully to partially effective (+).

6. SC-518. This product was fully to partially effective (++ and/or +) in two of the seven montmorillonitic soils only.

7. SA-1. Fully to partially effective (++ and/or +) in two of the four treated montmorillonitic series, and one of the four treated micaceous groups.

8. Road Packer. This product was 50% fully to partially effective within two treated montmorillonitics.

9. Duponol WA Paste. Fully to partially effective in one of the nine montmorillonitic series.

Poly-Tergent B-300, Aerosol OT-75%, and Nacconol 40F produced no favorable M-D/strength effectiveness in any of the soils treated with these products as analyzed at maximum γ_d and OMC.

Within the 26 favorable combinations, Clapak was the most effective in the montmorillonitic group, followed in a somewhat decreasing order by Petro-S, SC-518, SA-1, Claset, Thinwater, Road Packer, Coherex, and Duponol WA Paste. Coherex and Petro-S were the only favorable chemicals with the kaolinitic group. Within the micaceous grouping of soils, Coherex and Petro-S were the most effective, followed in somewhat decreasing order by SA-1, Claset, and Thinwater. Within the mixed mineralogy soil, no chemical produced favorable M-D stability effectiveness.

Evaluative Analysis

From the preceding qualitative analysis it was not know for certain if any real chemical effects were obtained from the moisture-density and K-Test study since results were obviously mixed, potentially ranging from highly effective to totally deleterious. Statistical theory and methods were employed in an effort to scrutinize, clarify, and summarize the test processes and data, with the expectation that such methods would provide a more substantive evaluation of effects of chemical treatments on moisture-density and stability relationships.

An initial goal of the statistical program was to determine whether or not dependable parametric relations existed. A correlation matrix of variables for each of the eight Phase I soils was therefore produced, not only to serve as a possible additional guide for the Phase II study but also to serve as a check on the dependability of the Phase I parameters. A typical matrix is shown in Fig. 35 where each entry represents the correlation between the two variables heading the row and column of that entry. Significance of the relationships were determined according to the student's-t-distribution at the 0.05 level of significance (a 5% chance of the relationship being due to chance alone).

A blank entry represents a correlation coefficient that is not significant at the 0.05 level; a plus sign (+) indicates a significant positive correlation coefficient, and minus sign (-) indicates a significant negative correlation coefficient.

Results from the eight matrices were assembled into a "master matrix" (Fig. 36) in which each entry indicates the number of soils having significant correlation coefficients of similar sign for that pair of variables associated with the entry. For example, the relationship between moisture content and spherical bearing value (SBV) was significant and direct in five of the eight soils, while the relationship between dry density and SBV was significant and inverse in three of the eight soils. Three entries were found to have contradications in sign and are indicated by a zero in the matrix. It was felt these contradictions were due to "weak" tests, i.e., tests of probability with fewer than ten data points.

	OPTIMUM MOISTURE CONTENT	MAXIMUM DRY DENSITY	CONCENTRATION	LIQUID LIMIT	PLASTIC LIMIT	COHESION	ANGLE OF INTERNAL FRICTION	SPHERICAL BEARING VALUE	SURFACE TENSION OF SOLUTION	SURFACE TENSION OF LEACHATE
OPTIMUM MOISTURE CONTENT		-	-	+		-	+	+		+
MAXIMUM DRY DENSITY				-	-		-	-		
CONCENTRATION				-			-	-		-
LIQUID LIMIT					+			+		
PLASTIC LIMIT										
COHESION							-	-		
ANGLE OF INTERNAL FRICTION								+		
SPHERICAL BEARING VALUE										+
SURFACE TENSION OF SOLUTION										+
SURFACE TENSION OF LEACHATE										

Fig. 35. Product-moment correlation matrix for Decatur series.

	OPTIMUM MOISTURE CONTENT	MAXIMUM DRY DENSITY	CONCENTRATION	pH OF SOLUTION	LIQUID LIMIT	PLASTIC LIMIT	COHESION	ANGLE OF INTERNAL FRICTION	SPHERICAL BEARING VALUE	SURFACE TENSION OF SOLUTION	SURFACE TENSION OF LEACHATE
OPTIMUM MOISTURE CONTENT		-4	-6	-1	+2		-3	+2	+5		+3
MAXIMUM DRY DENSITY			-1	+1	-1	-2		0	-3	0	
CONCENTRATION				+3	-2		+2	-2	-7	-3	-3
pH OF SOLUTION										-5	
LIQUID LIMIT						+2			+1		
PLASTIC LIMIT											
COHESION								-1	-2		
ANGLE OF INTERNAL FRICTION									+2	0	
SPHERICAL BEARING VALUE											+1
SURFACE TENSION OF SOLUTION											+4
SURFACE TENSION OF LEACHATE											

Fig. 36. Master Matrix.

Statistically significant relationship, found to exist between some of the parameters, for the most part were previously recognized relationships, i.e., cohesion (c) is inversely related to the angle of internal friction (ϕ). Such results tended to validate test data but did not provide answers to questions concerning soil-chemical interactions. Suspected "causative" factors, such as chemical concentration, pH, surface tension of solution, and surface tension of leachate, were therefore examined in greater detail. Only surface tension of leachate indicated potential significance in the matrix analysis. Plots of optimum moisture content and maximum dry density versus surface tension of leachate were made for each soil series; examples are shown in Figs. 37 and 38. Although correlation coefficients associated with these variables often were not significant at the 0.05 level, the plots suggested that a relationship exists. Therefore, additional surface tension testing of leachates appeared prudent with all Phase II soils and chemicals.

Interpretation of Moisture-Density and K-Test Results. An important part of the evaluations was the precision of measurements and determinations (for example, of the optimum moisture content and maximum density). The compaction test used throughout this study was the well known, standard Proctor test. Less standardized is the test interpretation. The classic Proctor curve is roughly parabolic in shape with the "wet" side in close proximity and roughly parallel to the zero air voids curve. Interpretation of the test generally consists of drawing a smooth, parabolic curve through the data points and reading optimum moisture content and maximum dry density at an arbitrary peak of the curve.

Winterkorn and Fang,[78] in a discussion of work by Lee and Suedkamp,[79] elaborated on the shape of Proctor curves, recognizing four categories of shapes considered to be determined by the liquid limit of the soil. Shape "A" is the classic parabolic curve, shape "B" has two peaks, shape "C" has a peak and a trough, and shape "D" is a broad curve with no distinc peak. Aberrations within "B" and "C" are considered to be due to changes in soil structure brought about by drying, while shapes "A" and "B" can be thought of as representing two extremes of soil structure. The classic parabolic curve was reported associated with soils having liquid limits in the range of 30 to 70%, which very nearly encompasses the total range of liquid limits of the untreated soils used in the study herein (Table 8, Vol. I).

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[78] H. F. Winterkorn and H.-Y. Fang, Foundation Engineering Handbook. New York: Van Nostrand-Reinhold, 1975.

[79] D. Y. Lee and R. J. Suedkamp, "Characteristics of Irregularly Shaped Compaction Curves of Soils," High. Res. Rec., No. 381, (1972), pp. 1-9.

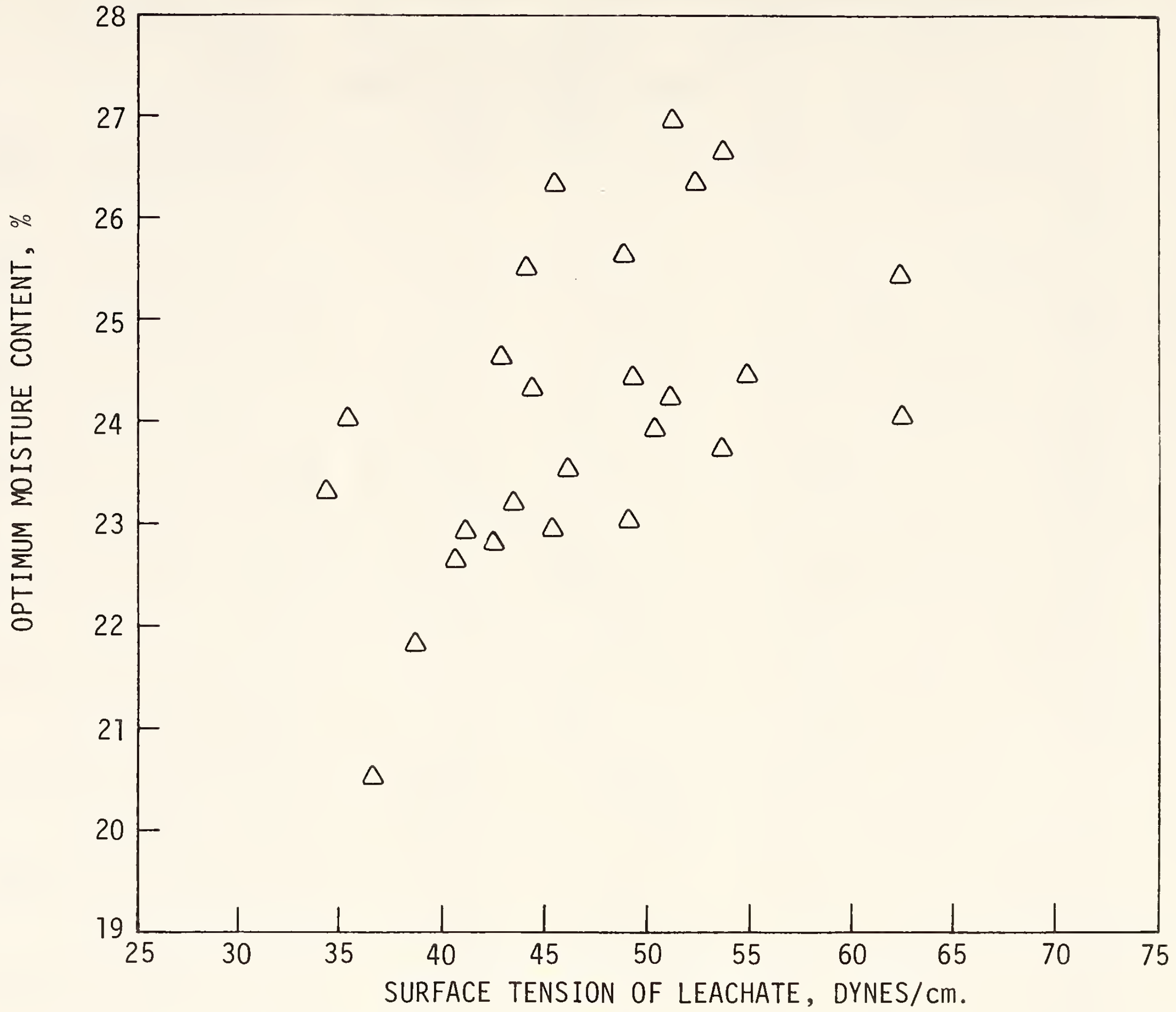

Fig. 37. Surface tension of leachate vs. optimum moisture content, Decatur soil.

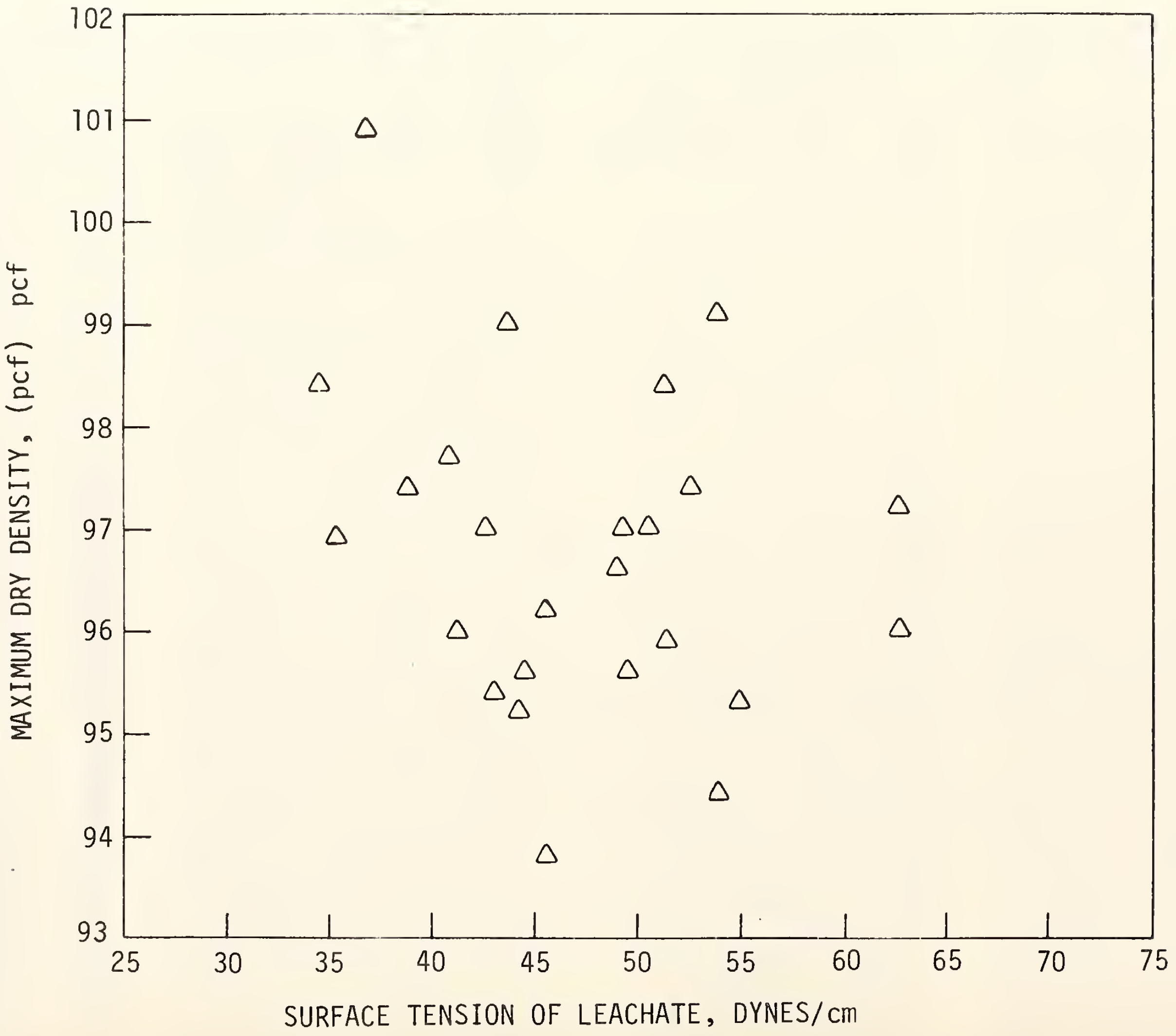

Fig. 38. Surface tension of leachate vs. maximum dry density, Decatur soil.

One consequence of aberrations in Proctor curves is that considerable subjective evaluation is made in interpretation of γ_d and OMC test data. Another is the possibility of reading from only one peak (of a two-humped curve) in one test, and from the other hump in another test. A third consequence is that it is difficult to read a precise value of optimum moisture content from a broad curve. Thus, interpretation of test data was visualized as a potential source of error.

As measured by standard deviation, reproducibility in laboratory compaction test results is often quoted as 1.0% for optimum moisture content, and 2 lb/cu ft for maximum dry density. In Highway Research Board Special Report 66, Shook and Fang[80] report on a study conducted as part of the AASHO Road Test. One purpose of their study was to obtain an estimate of variance to be anticipated in compaction test results. Samples of carefully prepared, completely air-dried and pulverized soil were shipped to more than sixty agencies to be tested according to the AASHTO T-99 procedure. Tabulation of the resulting data produced standard deviations of 1.0% moisture content and 2.2 lb/cu ft. These values appear reasonable when considering possible errors within the test procedure as utilized by a significant number of agencies.

Due to the selection process of the Phase II soils, physical, engineering, and chemical responses would vary, allowing possible grouping of the soils according to response as well as common factor(s) among them. The factor(s) could lead to potential mechanism(s) explaining the soils' response to chemical treatment.

Chemical properties and rates of application varied greatly. Three rates of application of each chemical were used throughout this study; the middle rate approximating that deciphered from the producer's literature, with lesser and greater amounts of the chemicals applied and tested to ascertain effect of treatment level.

Use of the automatic, programmable, rammer-type compactor, minimizing the human element involved in specimen compaction, was considered essential for obtaining statistically reliable data and was frequently calibrated in order to insure constancy of compactive effort. Specimens were compacted within about one hour after incorporation of water and chemical into the soil. This deviation from the standard test procedure was adopted to more closely simulate field conditions where compaction soon follows incorporation of water and chemical into the soil.

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[80] J. F. Shook and H.-Y. Fang, "Cooperative Materials Testing Program at the AASHO Road Test." High. Res. Board Special Report, No. 66, (1961), pp. 59-102.

Soil samples were transported in moisture-proof bags at time of collection; hence, the soil was usually very near the natural moisture content prior to the start of the compaction test. Sufficient soil was spread out and allowed to air dry until the moisture content had been reduced several percentage points below estimated optimum moisture content. Twenty-one hundred (2100) grams of this partially-air-dried soil was then placed in each of four or five sealed containers until it was to be used. The partially-air-dried condition of the soil was also assumed to more closely simulate field conditions. Each of the sealed samples of soil was at essentially the same moisture content; therefore, each container held essentially the same weight of oven-dry soil.

The procedure by which a chemical was incorporated into the soil was determined by the need to maintain a constant level of chemical in each test specimen even though a variable amount of water was added. This was met by placing the required amount of chemical in a graduated cylinder and adding sufficient tap water to create a solution of specified volume. The amount of chemical added and the volume of the resulting solution was recorded in all cases; the volume of solution being varied from specimen to specimen to produce the M-D curve. Thus, chemical concentration of the solution varied from specimen to specimen, but amount of chemical, expressed as a percentage of dry soil weight, remained constant.

Chemical solution was added to the soil while the soil was being mixed in a Hobart mechanical, three-speed mixer with side-bowl scraper. Occasional hand mixing was also used in order to obtain a more homogeneous mix. Some problems were presented by the very tough, highly plastic soils in that it was difficult to evenly incorporate solution into the soil. Since the same problem exists in the field, no more than a little extra effort in hand mixing was used to alleviate difficult mixing problems.

Raw data generated by the compaction test consisted of a wet weight of soil and three moisture content determinations for each test specimen. Two moisture samples were obtained from the loose soil prior to compaction, while a third was taken from the specimen after completion of the K-Test. Soil wet unit weight was determined by dividing the wet weight by the volume of the specimen (1/30 cu ft). Soil dry unit weight was calculated using the average of the three moisture contents.

Though impractical to control the level of partial-air-drying to some specified value for each soil, a good estimate of initial, partially-air-dried soil moisture content was obtained through use of the constant weight of partially-air-dried soil and the amount of chemical solution added. The following calculations serve to illustrate determination of this estimate, hereafter referred to as the "initial moisture content":

$$\begin{array}{rl} 2100 & \text{g partially-air-dried soil} \\ +\ \underline{150} & \text{g (ml) water or chemical solution added} \\ 2250 & \text{g of wet soil @ 21.2\% moisture content} \end{array}$$

$$\frac{2250}{1.212} = 1856.4 \text{ g of dry soil}$$

$$2250 - 1856.4 - 393.6 \text{ g of total water}$$

$$393.6 - 150.0 = 243.6 \text{ g of water in soil initially}$$

$$\text{Initial moisture content} = \frac{243.6}{1856.4} \times 100 = 13.1\%$$

This method treated the chemical solution as if it were pure water, but worst-case comparisons indicated the assumption to be sufficiently accurate for present purposes. An estimate of the initial moisture content was made for each specimen molded, and the average for each compaction tests series was taken as the initial moisture content for the series. The estimates of initial moisture content for a single test series normally were quite close to one another. Occasional check specimens prepared the next day might show a variation in initial moisture content.

A graph was produced for each soil and soil-chemical combination to portray the moisture-density relationships. Each datum point was produced with the aid of the Hewlett-Packard Model 9100B programmable calculator and Model 9125A X-Y plotter which also plotted the calculated zero air-voids curve of the soil; the latter served as a frame of reference for hand-drawn M-D curves and also provided an estimate of the slope of the Proctor curve wet of optimum when data points were not advantageously positioned. Each graph was then interpreted for optimum moisture content and maximum dry density for each treatment level.

The Iowa K-Test, used to evaluate stability of the treated and untreated soils, provided a second use for 1/30 cu ft specimens that would otherwise have been discarded, and it gave added confidence in statistical correlations due to the paired data. There also is a theoretical basis for the test which is not only appealing in itself but presents arguments similar to those of a triaxial test procedure for settlement analysis, known as Lambe's stress-path method.

The K-Test apparatus can be described as a cylindrical proving ring which applies a lateral confining stress in response to lateral soil movement. Material properties of the apparatus are constant, and the testing procedures is simple; therefore, soil properties are the primary test variables. Because stability parameters obtained from K-Tests differ as a results of changes in soil properties, the test is an excellent means for determining changes in soil properties as a result of chemical treatment. Precision and reproducibility of the test results made it an invaluable tool for the statistical study.

Initially, the specimen diameter is smaller than the inside diameter of the K-Test apparatus. This allows the specimen to be tested in unconfined compression until it deforms sufficiently to contact the sides of the apparatus. During unconfined compression, the stress path rises with a slope of one. The height of this initial rise is a function of the cohesive strength properties of the soil and provides a means of quantifying these properties. After full contact between soil and the mold has been attained, confining stress gradually develops as the apparatus is forced open, and the stress-path rises less rapidly and is slightly curved through this portion of the test. Departure of the stress-paths from linearity was small and was ignored so far as quantification of stability data was concerned. Simple linear regression techniques were applied to the test data to characterize soil stability in terms of slope and intercept of the stress-path.

The stress-path slope is primarily a function of frictional strength of soil, i.e., the angle of internal friction. Internal friction supports a portion of the vertical load during the K-Test, reducing lateral stress and increasing deviatoric stress. Thus, variations in the frictional strength of a soil can be detected by a change in slope of the stress-path obtained from the K-Test.

Soil strength is generally factored into two components--cohesion and internal friction--and expressed through the Coulomb equation[9]:

$$\tau = c + \sigma \tan \phi$$

where

τ = soil shear strength
c = cohesion
ϕ = angle of internal friction
σ = normal stress

This expression for soil strength is well suited for design but was inappropriate for statistically evaluating the laboratory tests because cohesion and internal friction are inversely related.

One alternative was to use the coefficient of lateral earth pressure (K_i). This ratio is a function of both cohesion and internal friction, thus representing a "pooled" measure of strength in which low values of K_i correspond to higher values of soil strength and stability. The parameter K_i was monitored throughout the stability test and typically behaves in a fashion where it approaches, then becomes asymptotic to, some maximum value when plotted against σ_1. The largest value was therefore selected for use in both the qualitative and subsequent statistical or quantitative analyses.

Vertical deflection of a specimen was measured throughout the K-test, allowing evaluation of a fourth stability parameter, the deformation modulus, E. This modulus is actually a pseudo-elastic modulus analogous to Young's modulus. Early in the laboratory testing program, plots were made of stress versus strain for a number of specimens from different soils. It was observed that a nearly linear relationship existed between stress and strain after the first three data points in all tests. All but the first three data pairs of vertical stress and strain were then included in a single linear regression in order to quantify compressibility characteristics of the soil. It was recognized that effect of the relatively rigid K-Test apparatus was very much a part of the stress-strain relationship but was considered to be a constant. Changes in the value of deformation modulus, E, were thus attributable to changes in compressibility of the soil.

Each standard Proctor test normally consisted of four or more K-Tests, each K-Test producing a set of four stability parameters. The vast quantity of data generated by the K-Tests prompted development of methods of data reduction into a form that could be assimilated by computer and analyzed with existing statistical programs. For all four stability parameters, data reduction was accomplished using numerical techniques, the Hewlett-Packard 9100B programmable calculator, and analogies drawn from familiar soil engineering concepts.

The statistical analyses required that comparisons be made of stability parameters from Proctor tests, which presented a problem in that a moisture content datum was required in order to make "just" comparisons. The optimum moisture content was selected as the datum for these analyses; however, one problem was that, in most cases, no sample was prepared at this moisture content. Studies of numerous plots of the stability parameters vs. both moisture content and dry density for each M-D series revealed that reasonably consistent relationships existed between the parameters and the respective moisture contents, as illustrated in Fig. 39. These relationships allowed the use of linear regressions to provide a prediction equation for each stability parameter in terms of moisture content, from which could be evaluated the parameter values at optimum.

Other means could have been used to evaluate stability parameters at optimum moisture content. One method would have been to interpolate between the two values of stability parameters corresponding to moisture contents bracketing optimum, as was done in the qualitative analysis. It was observed from the plots, however, that the greatest fluctuation in parameters "c" and "ϕ" often occurred in the immediate vicinity of optimum moisture content. Such fluctuations may be associated with changes in soil structure and particle orientation occurring near the optimum moisture content during compaction. For purposes of statistical analyses, this method would have been much more difficult to implement on a computer.

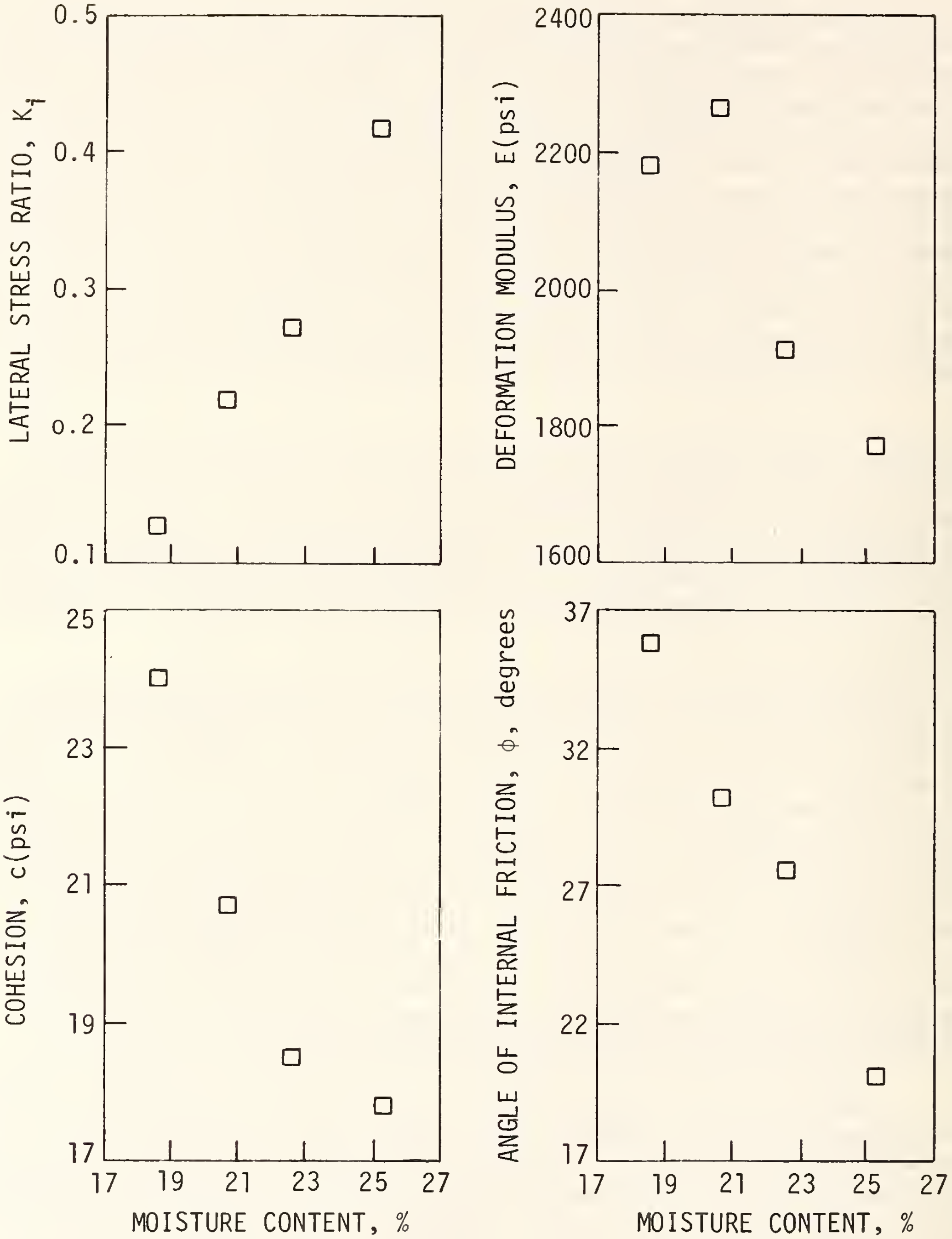

Fig. 39. Iowa K-Test parameters vs. moisture content.

A second method might have been to "eye ball" the stability parameter from each plot. This method was compared to the method using regression by analyzing the same data set with both techniques. It was found that where strong relationships existed, as was generally the case, the difference in predicted values was very small. When the relationship was weak, differences occurred, but there was no way of determining which value was more correct. Hence, the method using statistical regression was considered to be the equal of even the most laborious manual technique.

The first step in the analysis, therefore, was to reduce raw K-Test data into the four stability parameters, c, ϕ, K_i, and E and to tabulate the moisture-density test results. These data were placed on computer cards, each card representing a single K-Test. Second, the stability parameters were normalized to the optimum moisture content datum.

Effect of Initial Moisture Content. Optimum moisture content and maximum dry density were the fundamental, dependent variables of this Phase II study. Variation in these parameters had to be properly attributed to the independent variables before consideration could be extended to analyses of stability parameters, since the latter are, in part, functions of the moisture content and dry density.

A data set for a particular soil usually consisted of the results of sixteen to nineteen compaction tests. These included several sets with chemicals, each set consisting of three different treatment levels plus an untreated control set.

Statistical analyses could begin only after a fair sized portion of the laboratory work had been completed. Variations in maximum dry density on the order of 8-10 lb/cu ft were being observed within individual soil data sets, and an estimate of error in these measurements was needed to test whether or not such differences were due to chemical treatment.

A brief experiment was conducted with untreated Altamont soil to determine if such variations could be attributed to random error. The compaction test procedure was not altered in any way, with the exception that a constant amount of water was added to the soil. Six Proctor specimens were produced, each supposedly at optimum moisture content and maximum dry density. Little variation in test results occurred, as the range in dry density and moisture content was 1.1 lb/cu ft and 1.5%, respectively. It was concluded that poor laboratory procedures and techniques were not the cause of any large variation in the test results.

The entire compaction test procedure was then scrutinized in an attempt to find out if an unrecognized factor might be present. The initial moisture content of the soil used in the compaction test was back-calculated by the procedure previously outlined, since it had not been measured. Two possible effects from variation in initial moisture content are (a) utilization of partially-air-dried soil might allow the chemicals to act more or less effectively, or (b) part of the variation in moisture-density results might be directly attributable to variations in the level of the initial moisture content.

To a large extent, initial moisture content is a completely random variable, though bounded by two conditions: (1) moisture contents less than zero are not possible, and (2) the level of initial moisture content must not exceed optimum moisture content of the soil. The range of initial moisture content within a single soil set was occasionally as much as 10%, particulary when check specimens were molded on succeeding days.

Linear regression plots of optimum moisture content and maximum dry density versus calculated initial moisture content for each soil were then examined (Figs. 40-57). Apparent relationships were tested by applying student's t-test to the correlation coefficients (r) from simple linear regressions, Table 37. It is noted that the relationship between optimum and initial moisture contents was found to be statistically significant at the 5% level in 12 of the 18 soils, and significant at the 1% level in 11 of these 12. The relationship between maximum dry density and initial moisture content was found to be significant in 9 of the 18 soils at the 5% level.

As a check of the possibility that these relationships were due to the chemical, a series of untreated compaction tests were conducted with initial moisture content purposely varied. This series was conducted with the Peavine soil because of its high natural moisture content, about 42%. Results are presented in Fig. 58, together with results with chemical treatments. This plot indicates that drying prior to compaction may indeed alter moisture-density relationships and potentially could alter some M-D relations as much or more than the chemical treatments. Certainly the effect of initial moisture content cannot be ignored in an evaluation of the effectiveness of chemicals.

Results of a similar study of drying effects were briefly reported by Grady,[81] in a study in which initial moisture contents were varied and monitored. Grady's results are presented in Fig. 59. All points represent tests for which partially air-dried, fresh soil specimens were used, with the exception of an oven-dried soil specimen (0% initial moisture content) used for one test. If the test using oven-dried soil is ignored, a model equation of the remaining data can be based upon the natural logarithm of initial moisture content and is noted in Fig. 59 as the curved line. Similar curves are drawn in Figs. 40 through 57. Consideration of all data presented in Fig. 59 leads to credible linear relationships as well.

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[81] J. D. Grady, High. Res. Board Proc., 29, (1949), pp. 488-490.

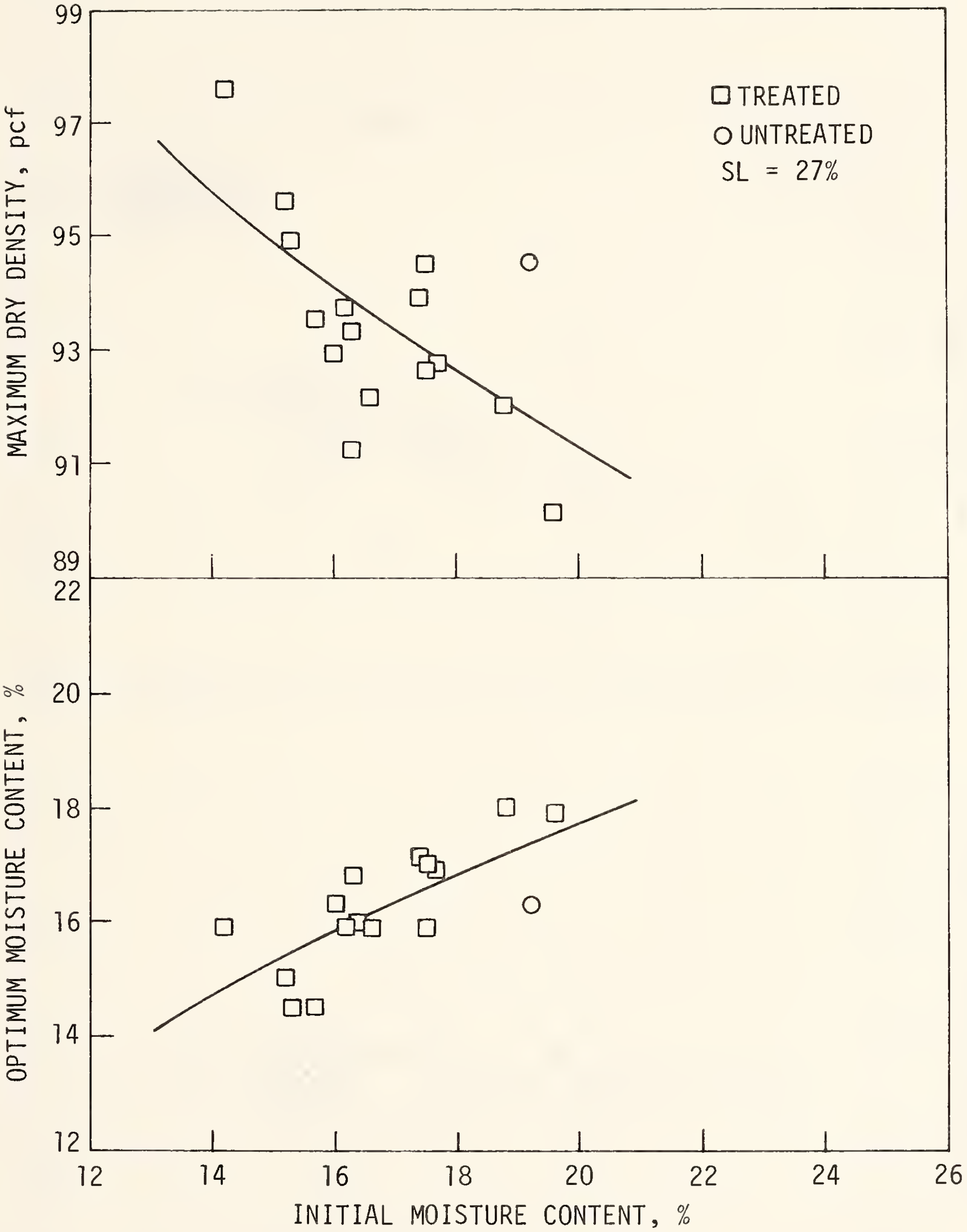

Fig. 40. Relationship between maximum dry density and optimum moisture content, Frederick series.

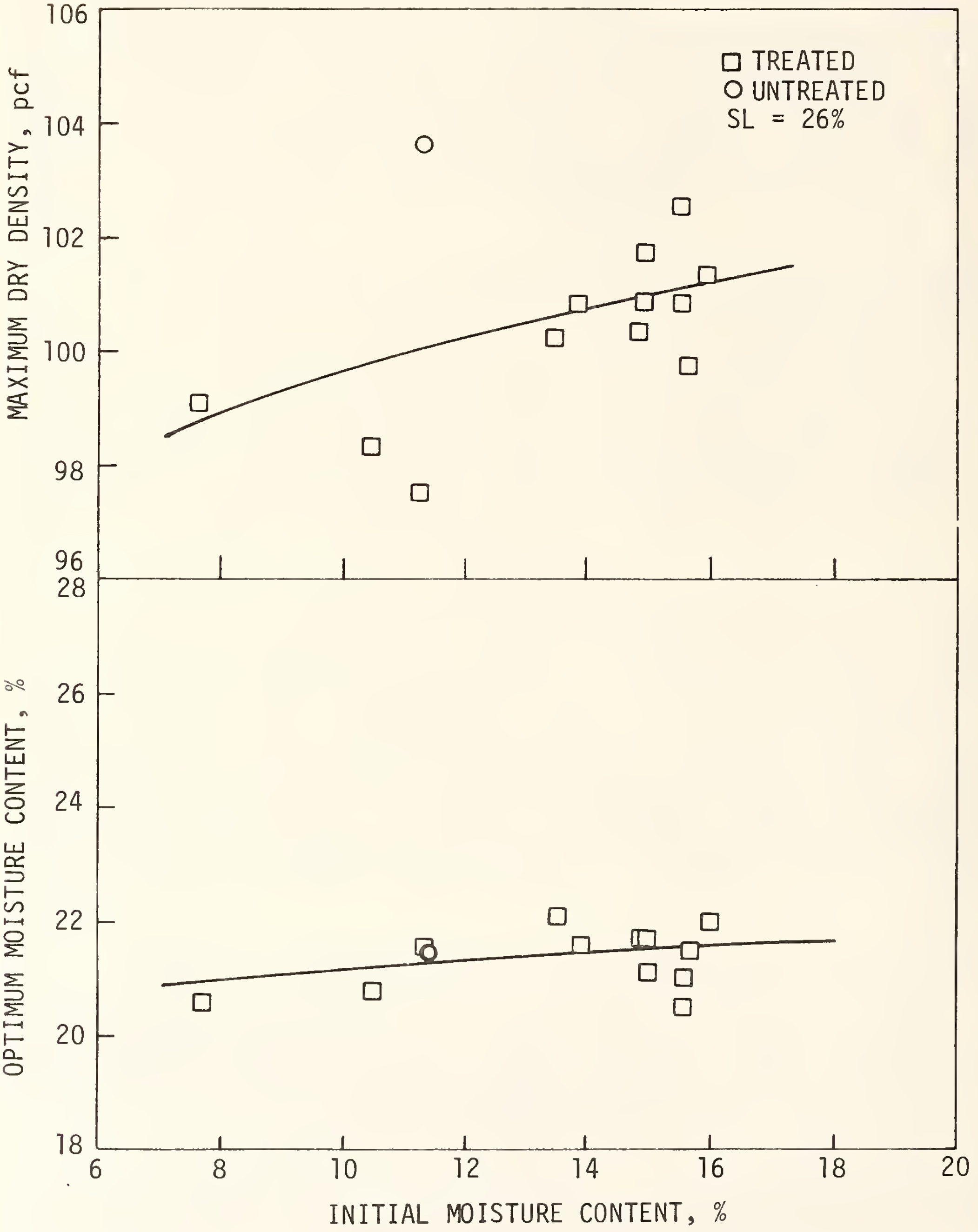

Fig. 41. Relationship between maximum dry density and optimum moisture content, Fannin series

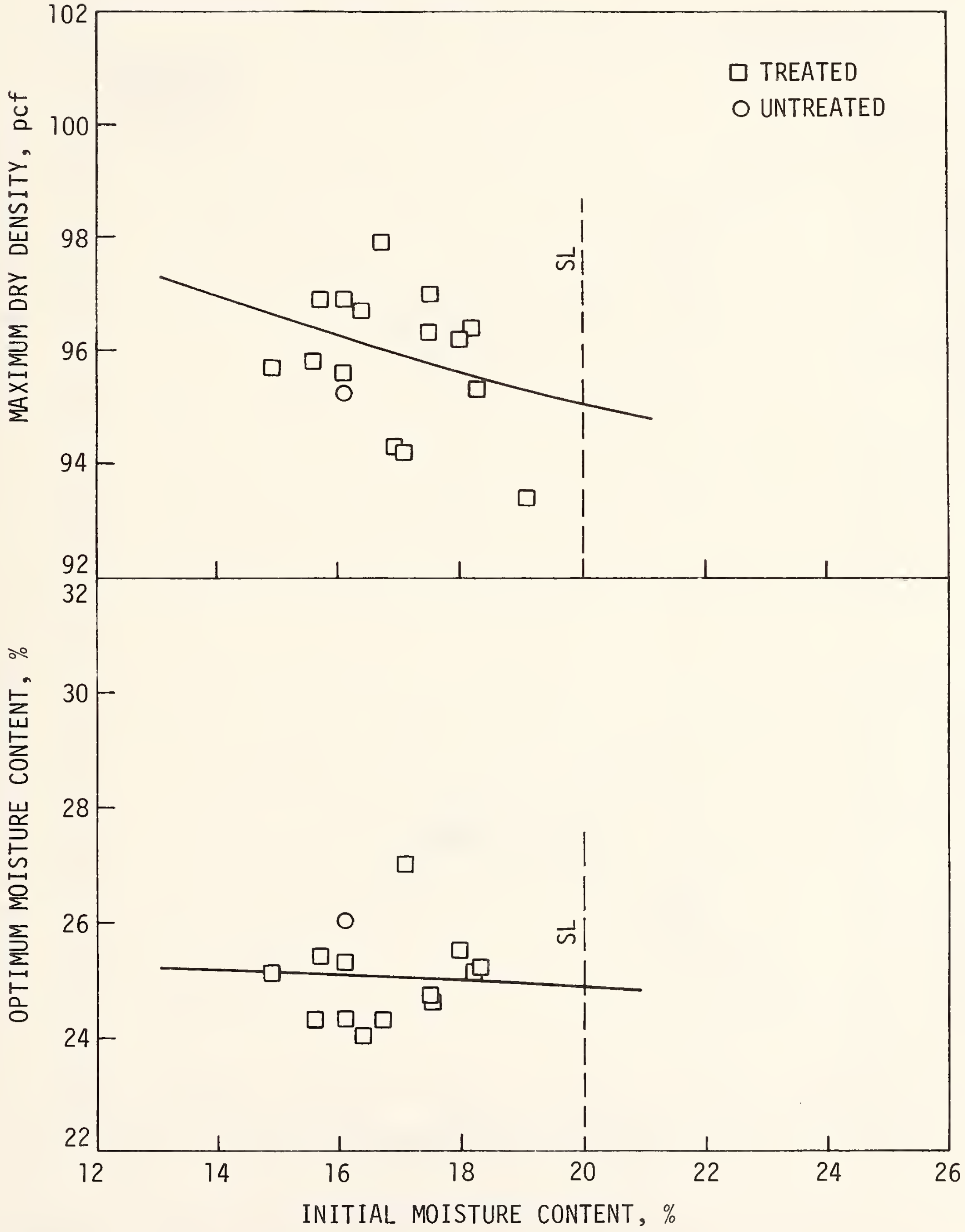

Fig. 42. Relationship between maximum dry density and optimum moisture content, Persanti series

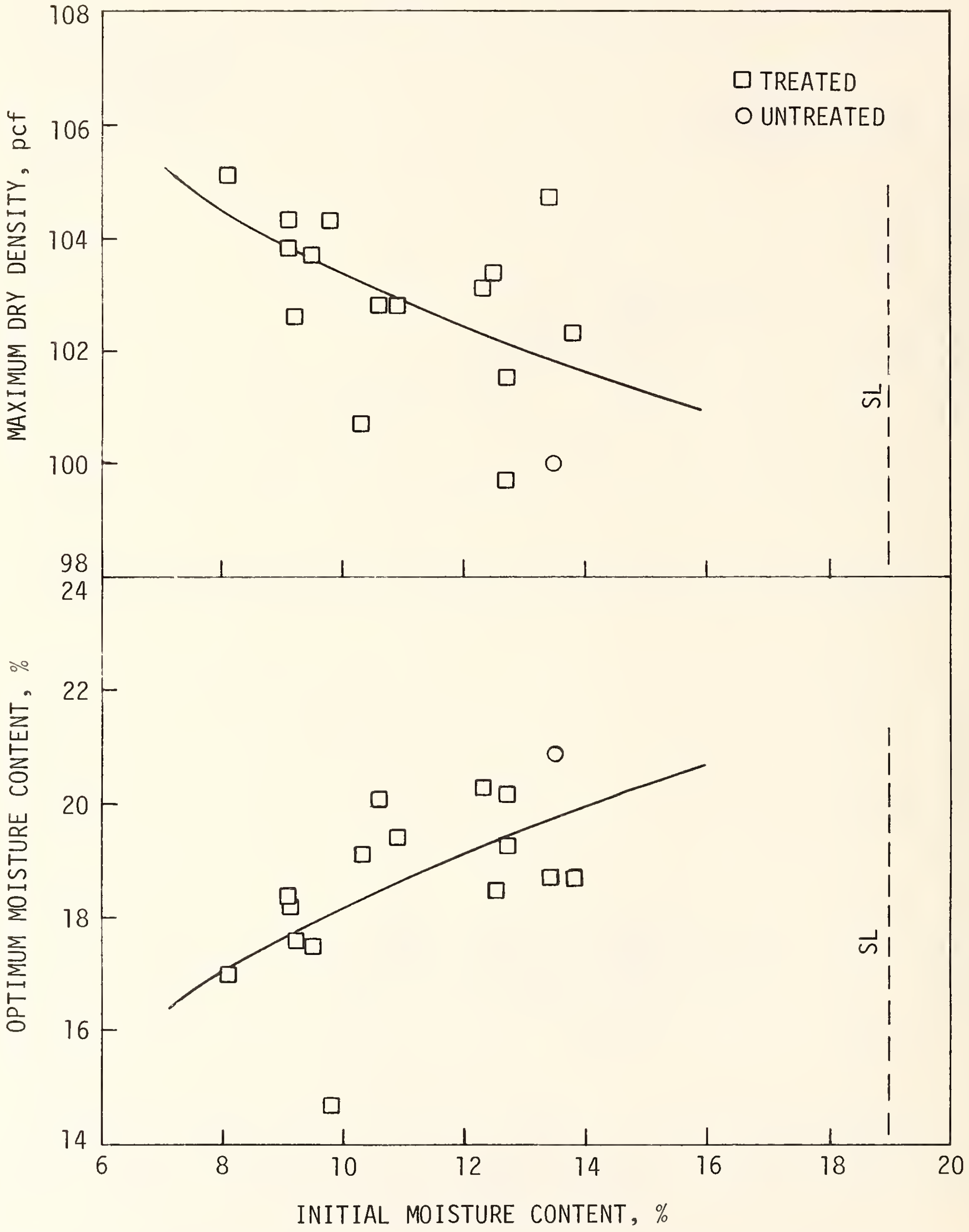

Fig. 43. Relationship between maximum dry density and optimum moisture content, Bearden series.

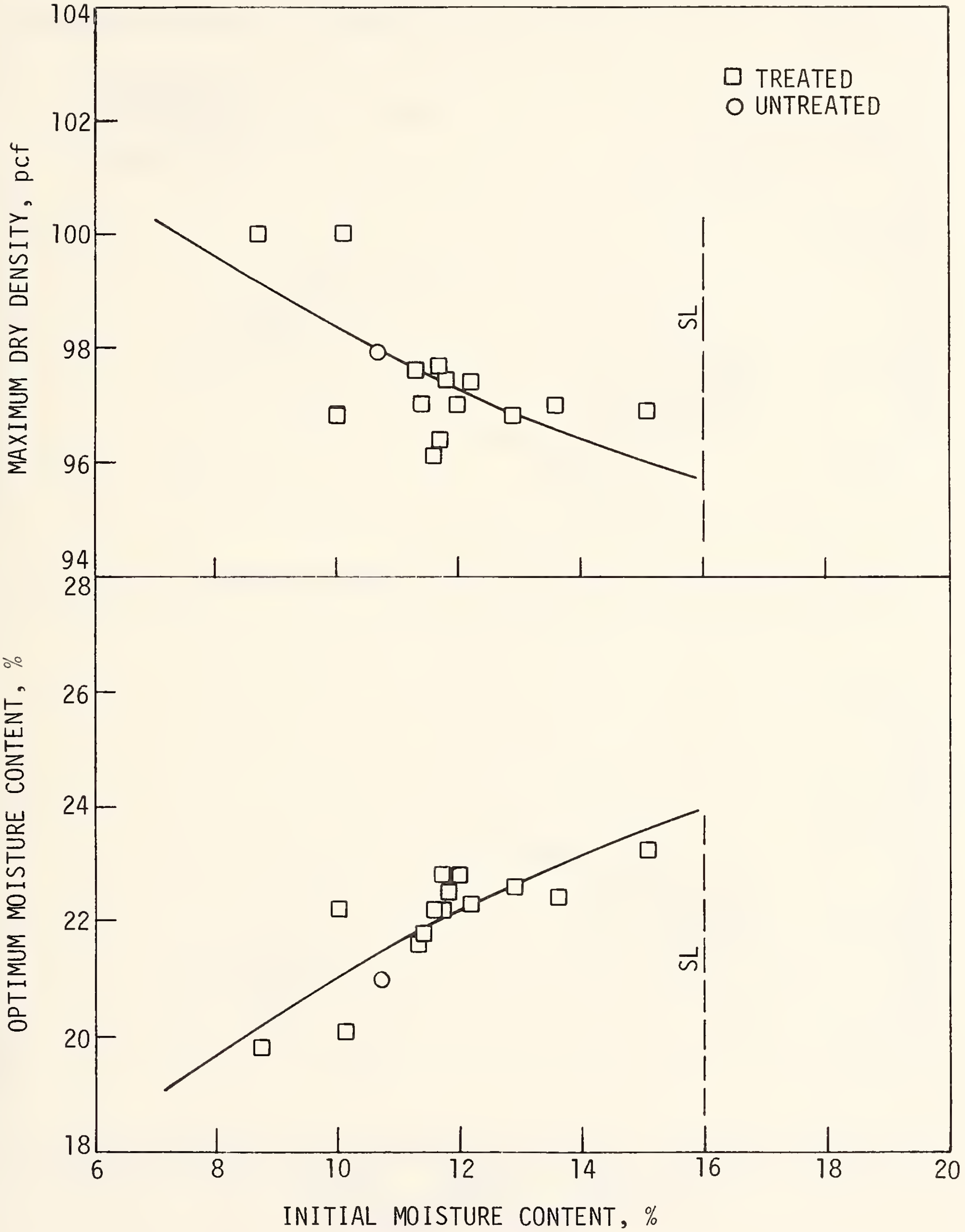

Fig. 44. Relationship between maximum dry density and optimum moisture content, Renohill series.

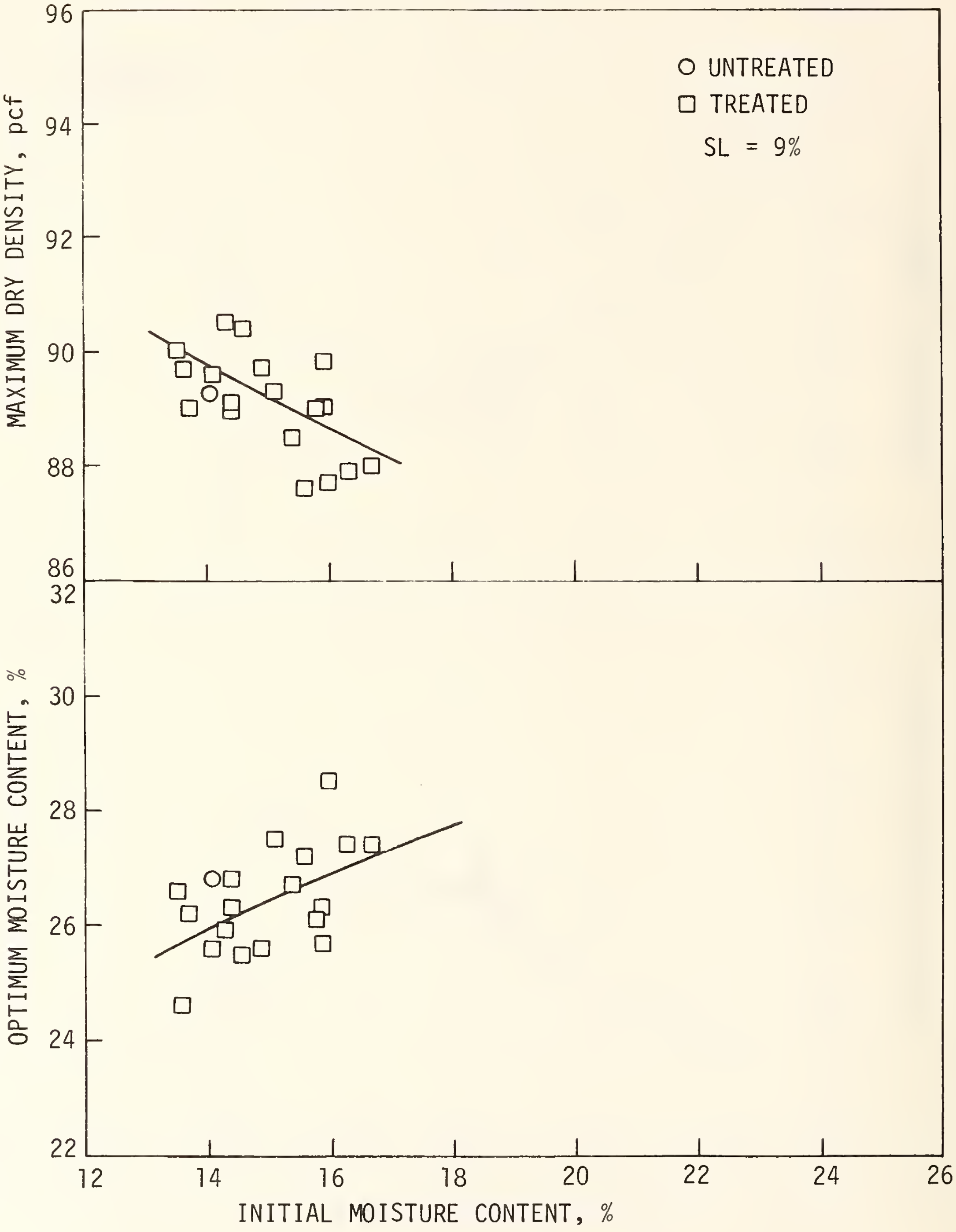

Fig. 45. Relationship between maximum dry density and optimum moisture content, Pierre series.

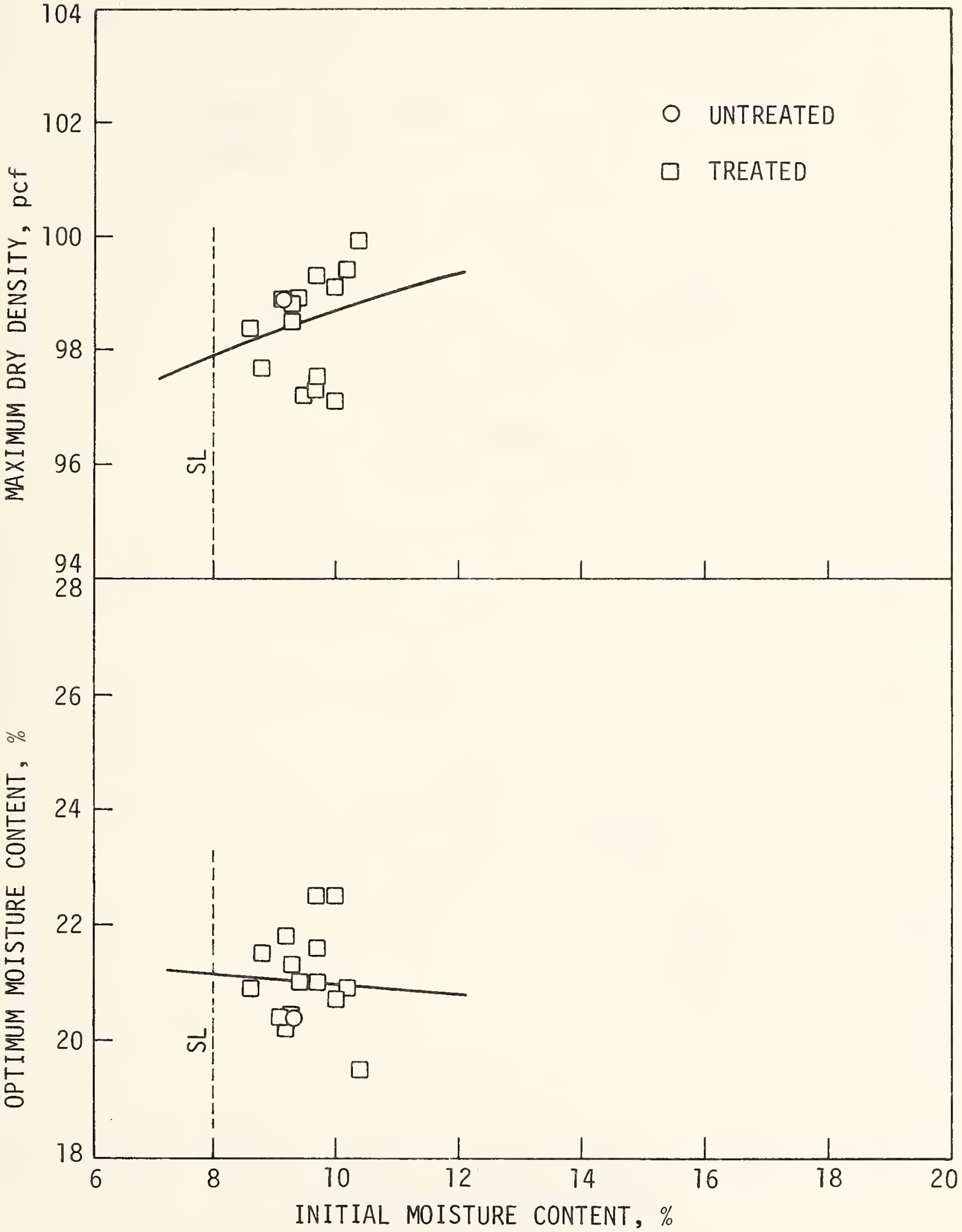

Fig. 46. Relationship between maximum dry density and optimum moisture content, Altamont series.

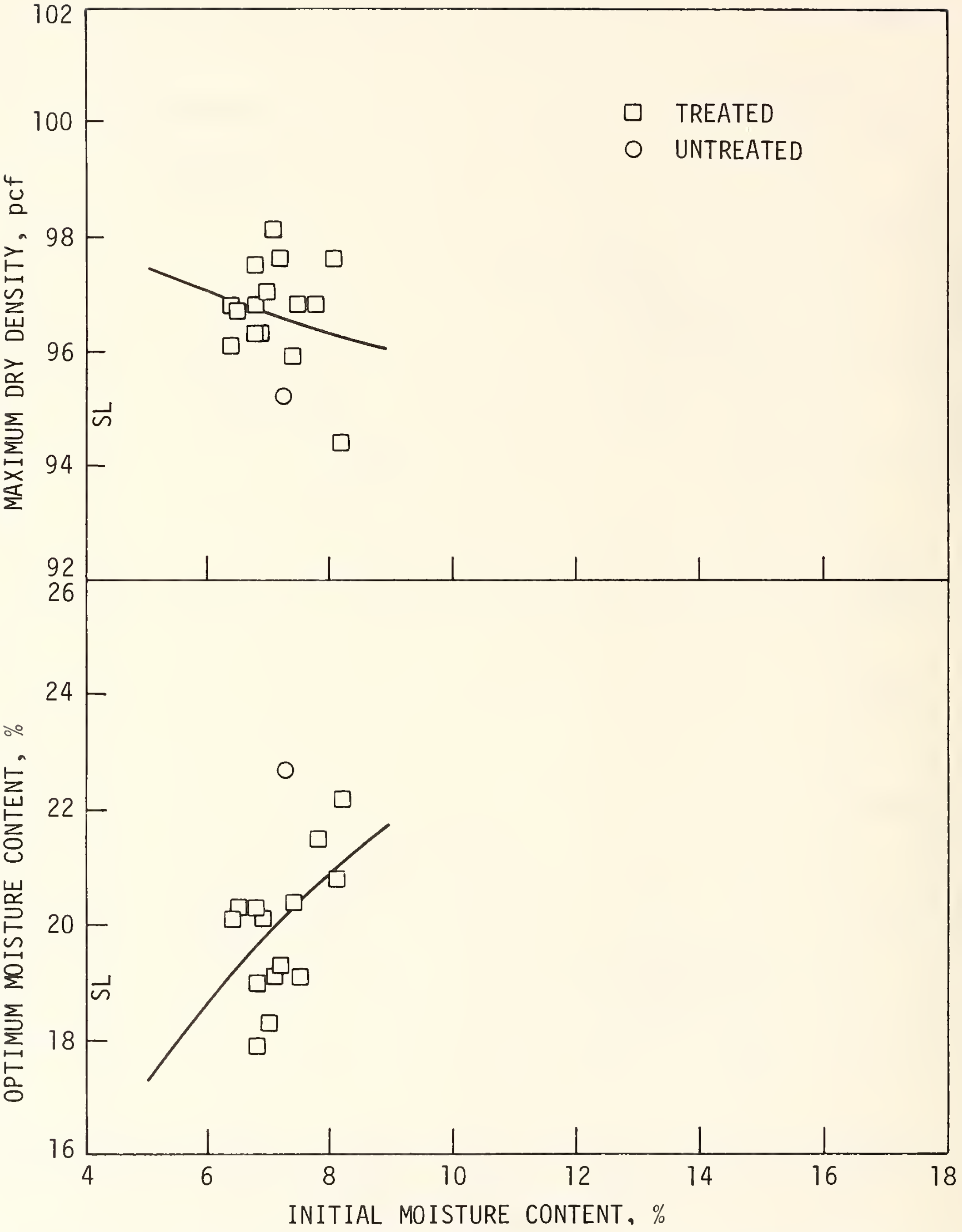

Fig. 47. Relationship between maximum dry density and optimum moisture content, Rimrock series.

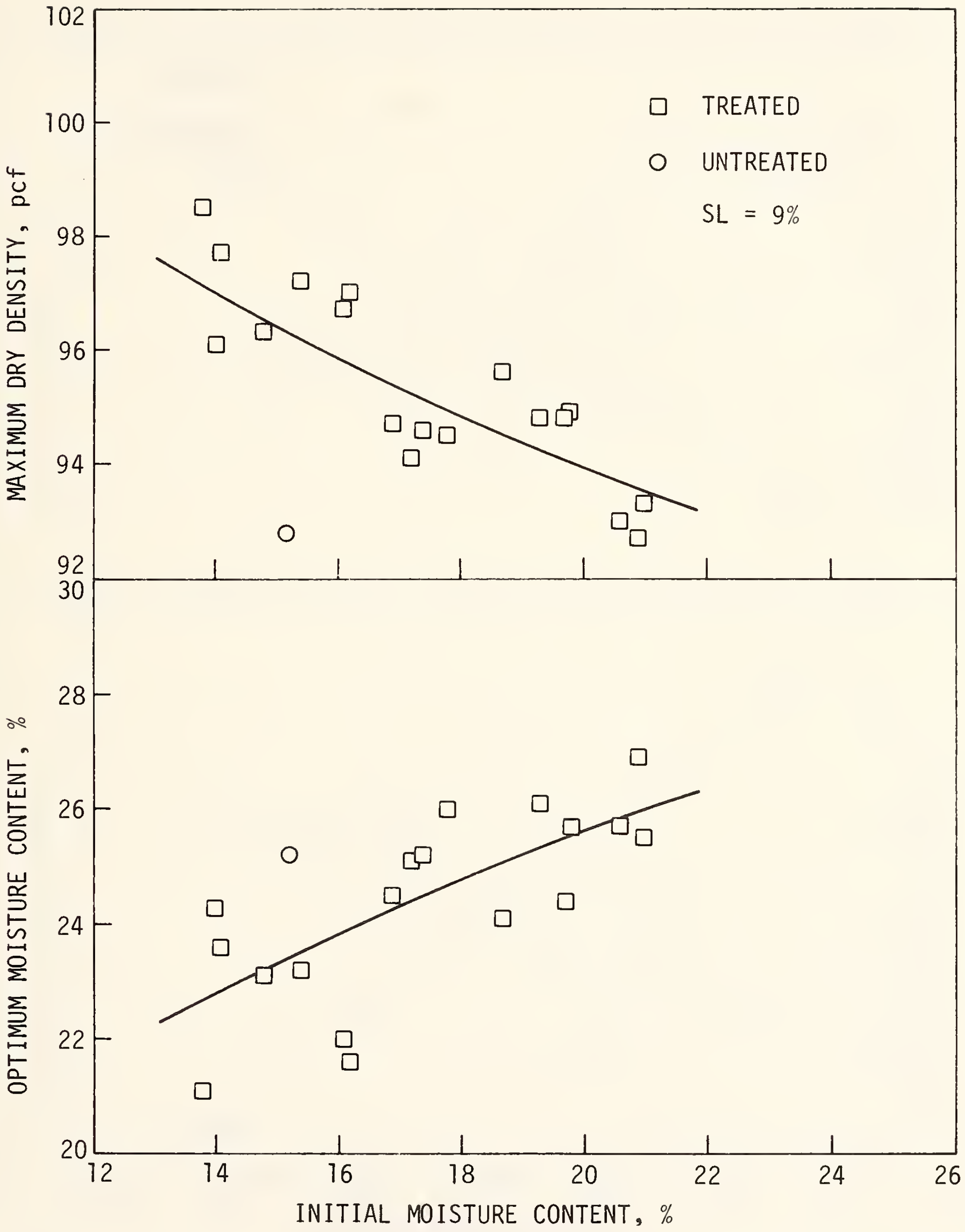

Fig. 48. Relationship between maximum dry density and optimum moisture content, Houston Black series.

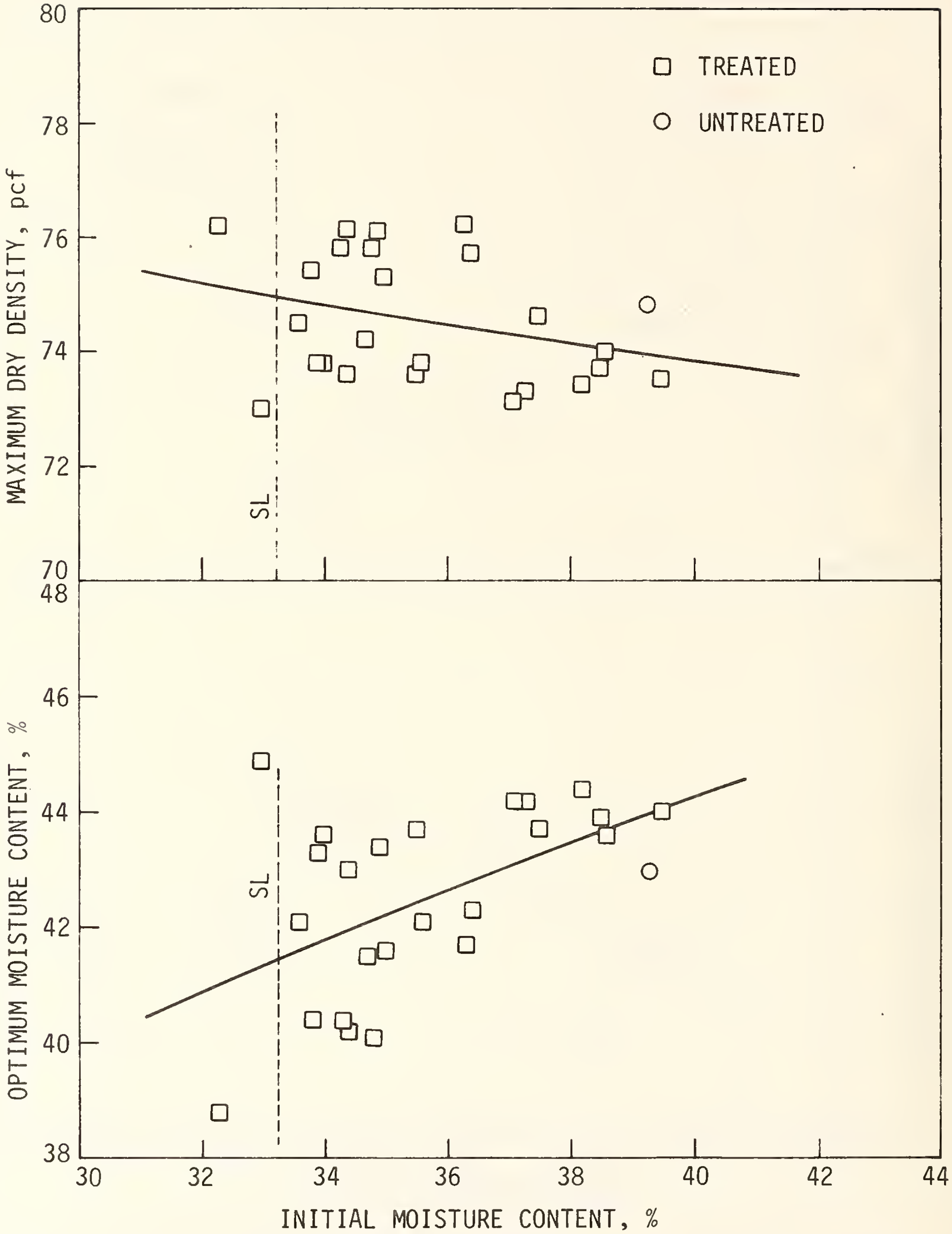

Fig. 49. Relationship between maximum dry density and optimum moisture content, Peavine series.

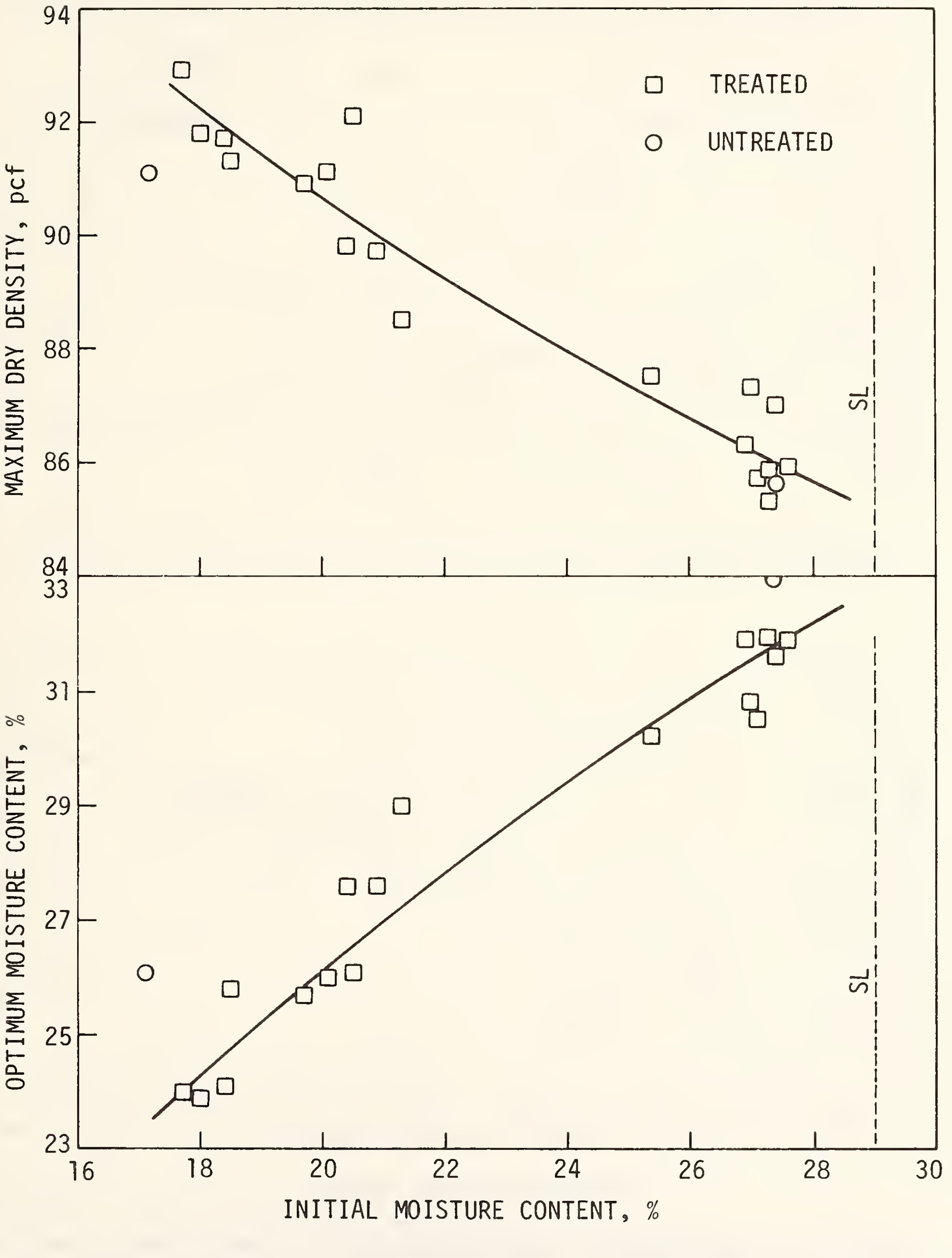

Fig. 50. Relationship between maximum dry density and optimum moisture content, Melbourne series.

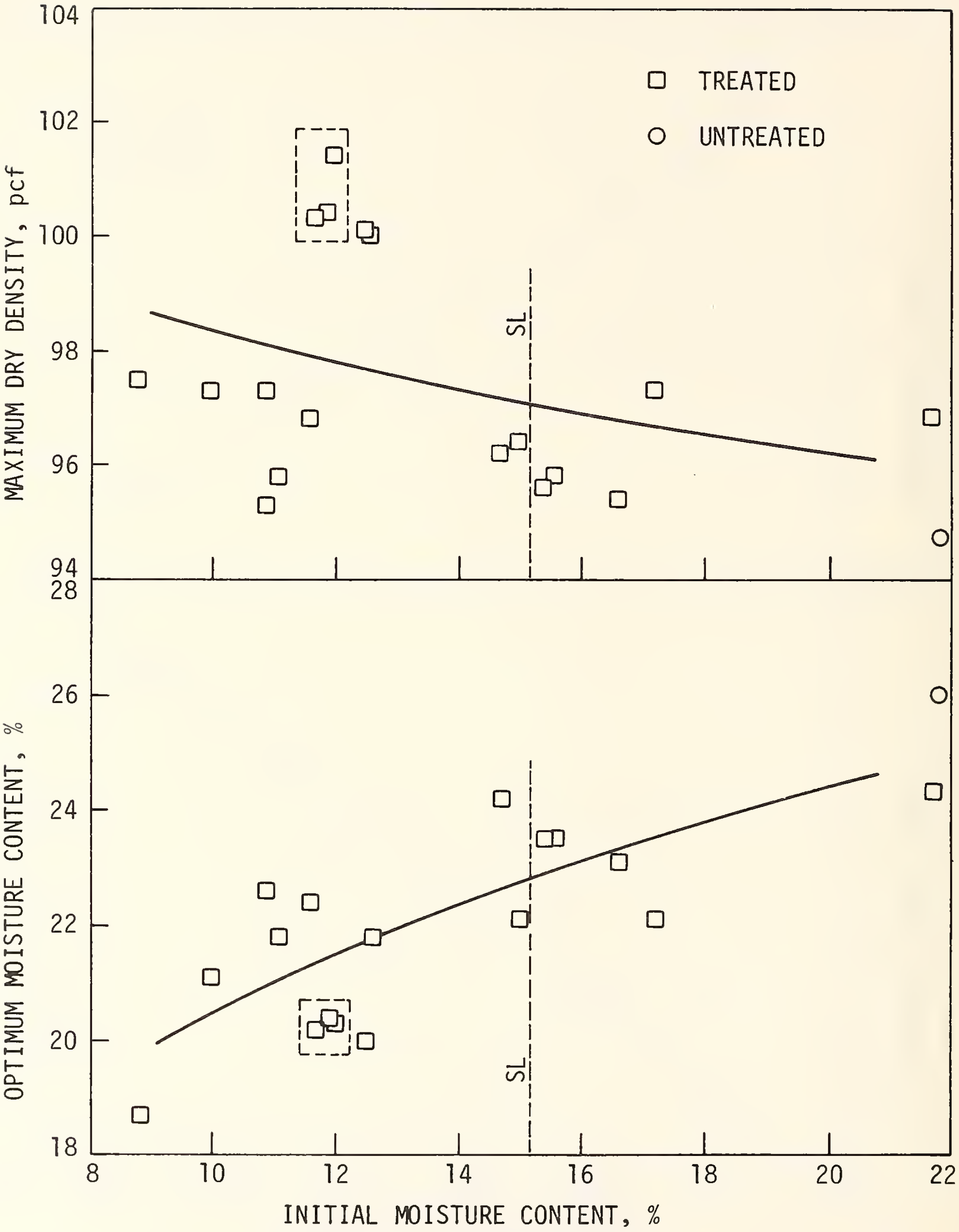

Fig. 51. Relationship between maximum dry density and optimum moisture content, Marias series.

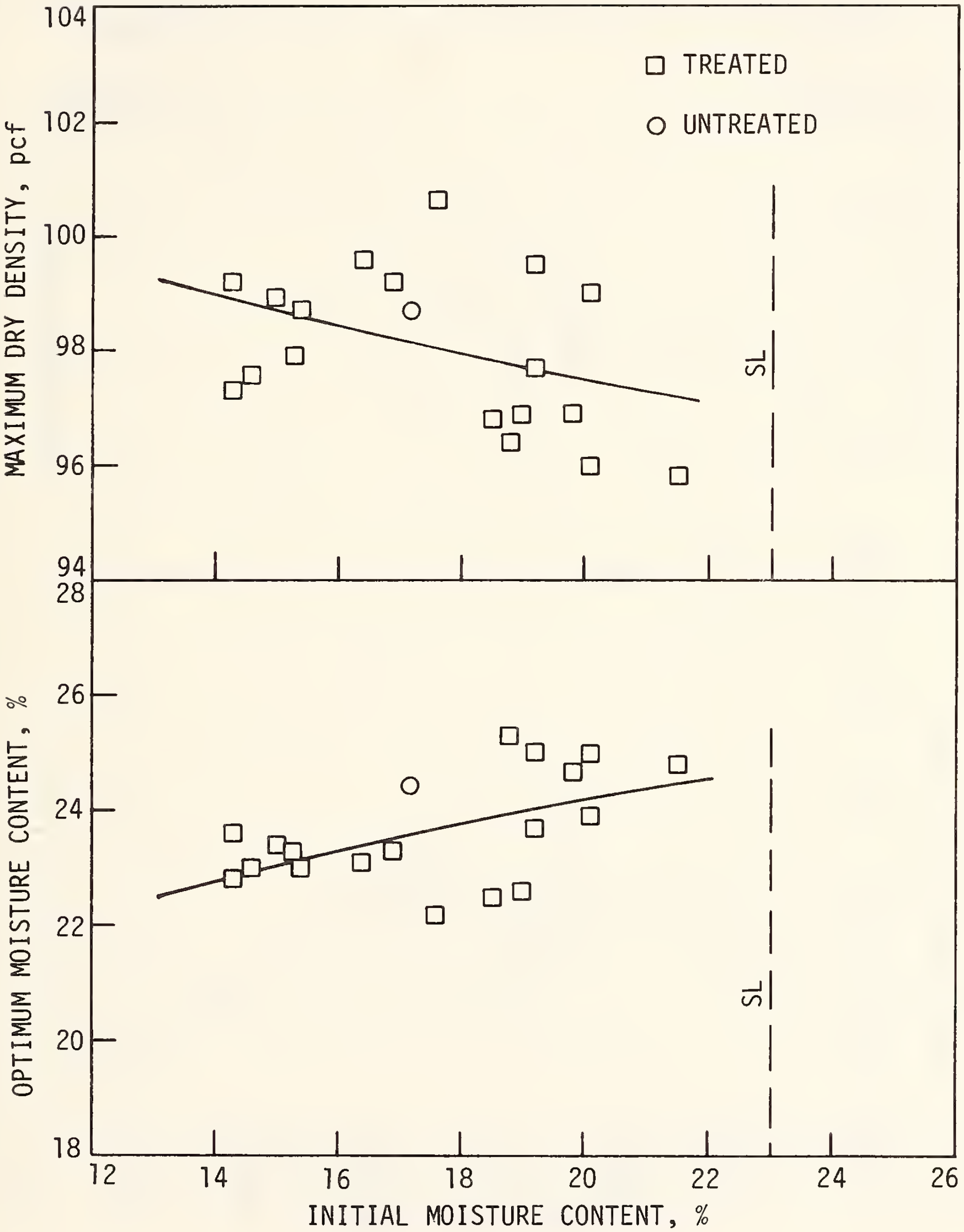

Fig. 52. Relationship between maximum dry density and optimum moisture content, Buxton series.

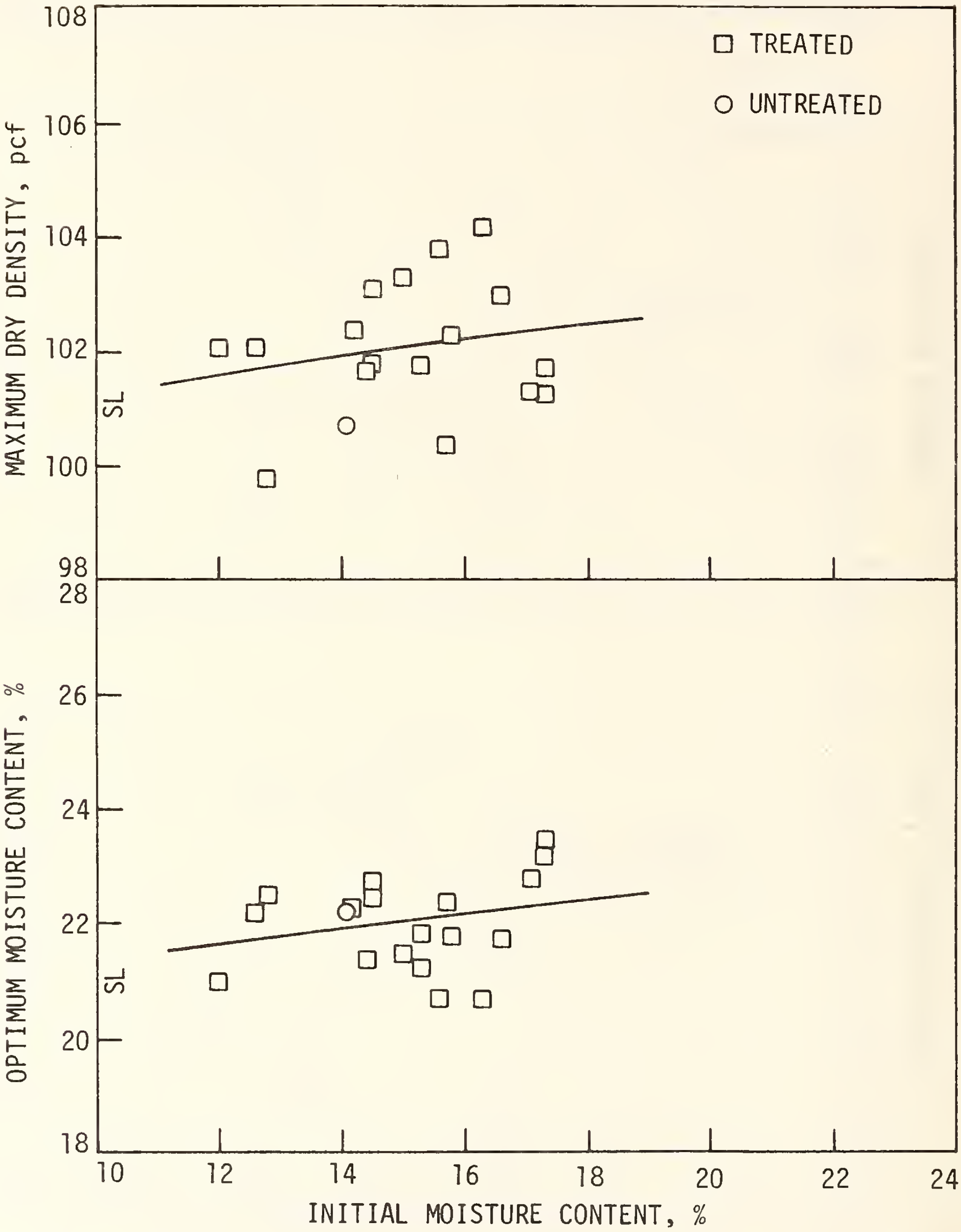

Fig. 53. Relationship between maximum dry density and optimum moisture content, Vergennes series.

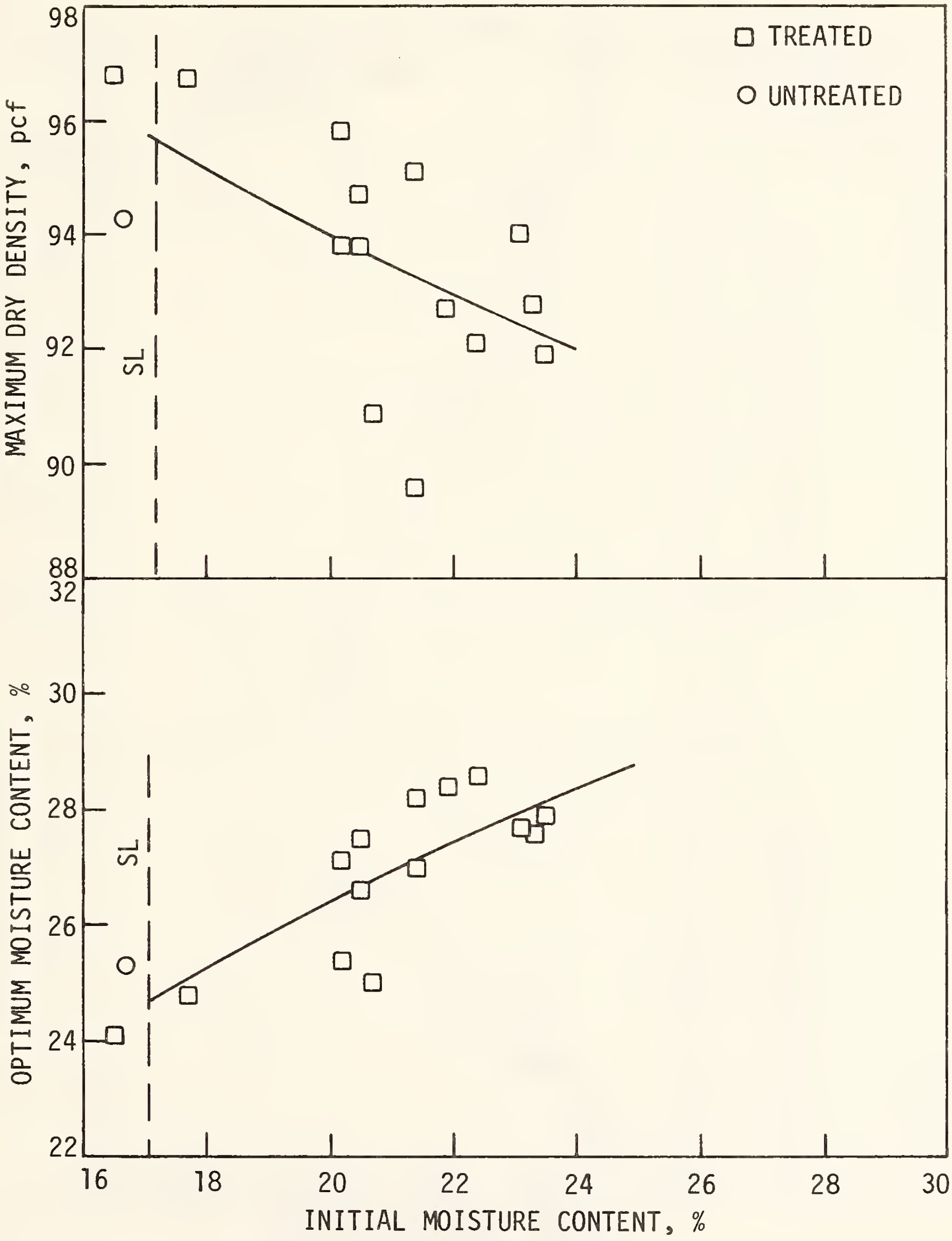

Fig. 54. Relationship between maximum dry density and optimum moisture content, Ontonagon series.

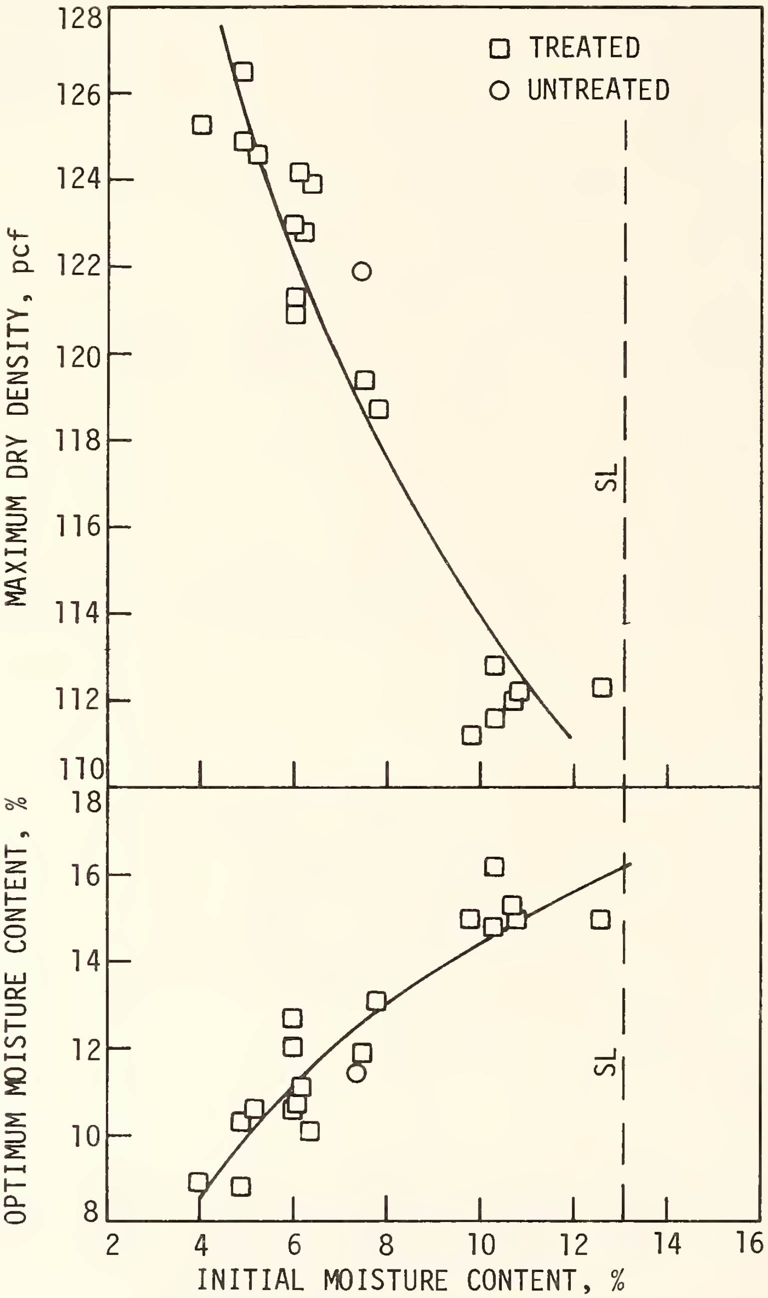

Fig. 55. Relationship between maximum dry density and optimum moisture content, Onoway series.

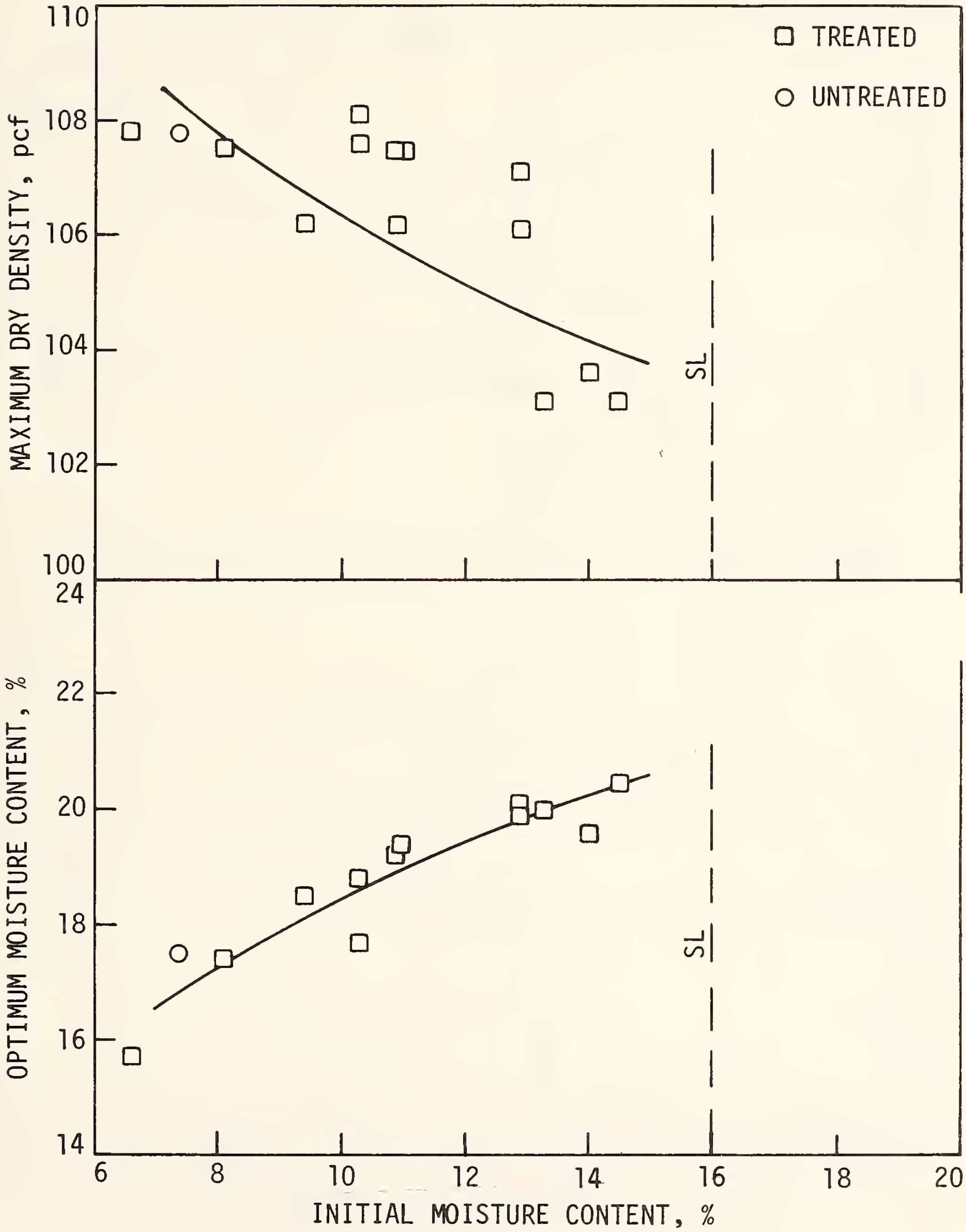

Fig. 56. Relationship between maximum dry density and optimum moisture content, Nappanee series.

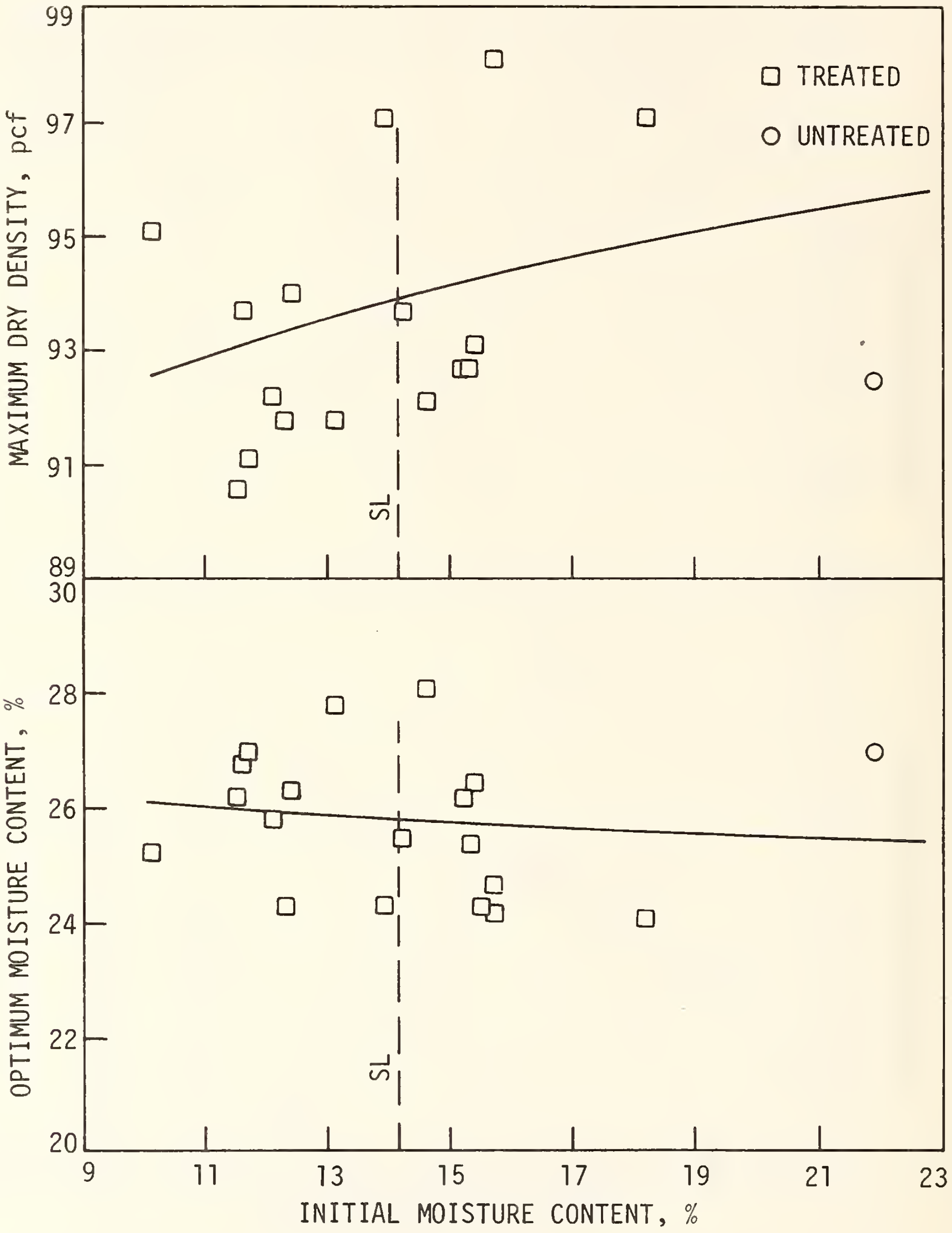

Fig. 57. Relationship between maximum dry density and optimum moisture content, Paulding series.

Table 37. Statistical regression data of initial moisture content vs. optimum moisture content and maximum dry density.

Soil	Initial moisture content vs. optimum moisture			Initial moisture content vs. maximum dry density		
	Correlation Coefficient	Slope	Intercept	Correlation Coefficient	Slope	Intercept
Frederick	0.73**	0.50	17.7	-0.61*	-0.73	105.7
Fannin	0.33	0.07	20.4	0.43	0.28	96.7
Persanti	-0.08	-0.06	25.9	-0.31	-0.32	101.3
Bearden	0.59*	0.48	13.4	-0.52*	-0.45	107.8
Renohill	0.79**	0.50	16.1	-0.60*	-0.44	102.7
Pierre	0.52**	0.48	19.2	-0.63**	-0.56	97.4
Altamont	-0.06	-0.10	22.0	0.22	0.38	94.8
Rimrock	0.47	1.10	12.2	-0.21	-0.36	99.2
Houston Black	0.69**	0.46	16.5	-0.72**	-0.50	103.9
Peavine	0.53**	0.42	27.6	-0.32	-0.17	80.7
Melbourne	0.97**	0.76	10.9	-0.96**	-0.64	103.5
Marias	0.77**	0.38	16.9	-0.41	-0.23	100.5
Buxton	0.54**	0.23	19.7	-0.42	-0.25	102.5
Vergennes	0.25	0.13	20.0	0.18	0.13	100.1
Ontonagon	0.82**	0.54	15.6	-0.60*	-0.56	105.1
Onoway	0.92**	0.86	5.8	-0.95**	-2.12	135.4
Nappannee	0.92**	0.52	13.2	-0.71*	-0.66	113.1
Paulding	-0.09	-0.04	26.4	0.29	0.24	90.4

*Correlation coefficient significant at the 5% level.

**Correlation coefficient significant at the 1% level.

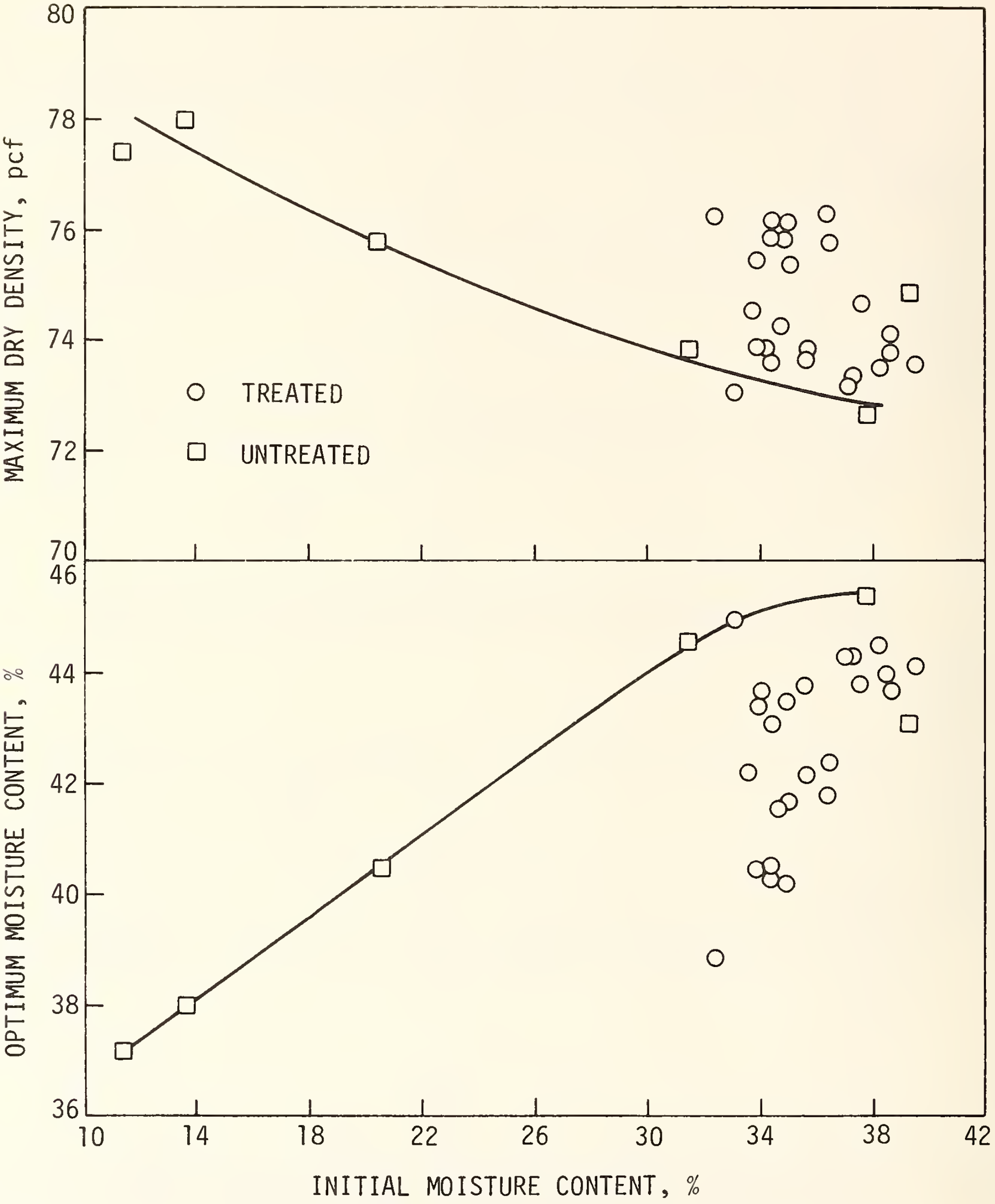

Fig. 58. Effect of initial moisture content on moisture-density relations, Peavine series.

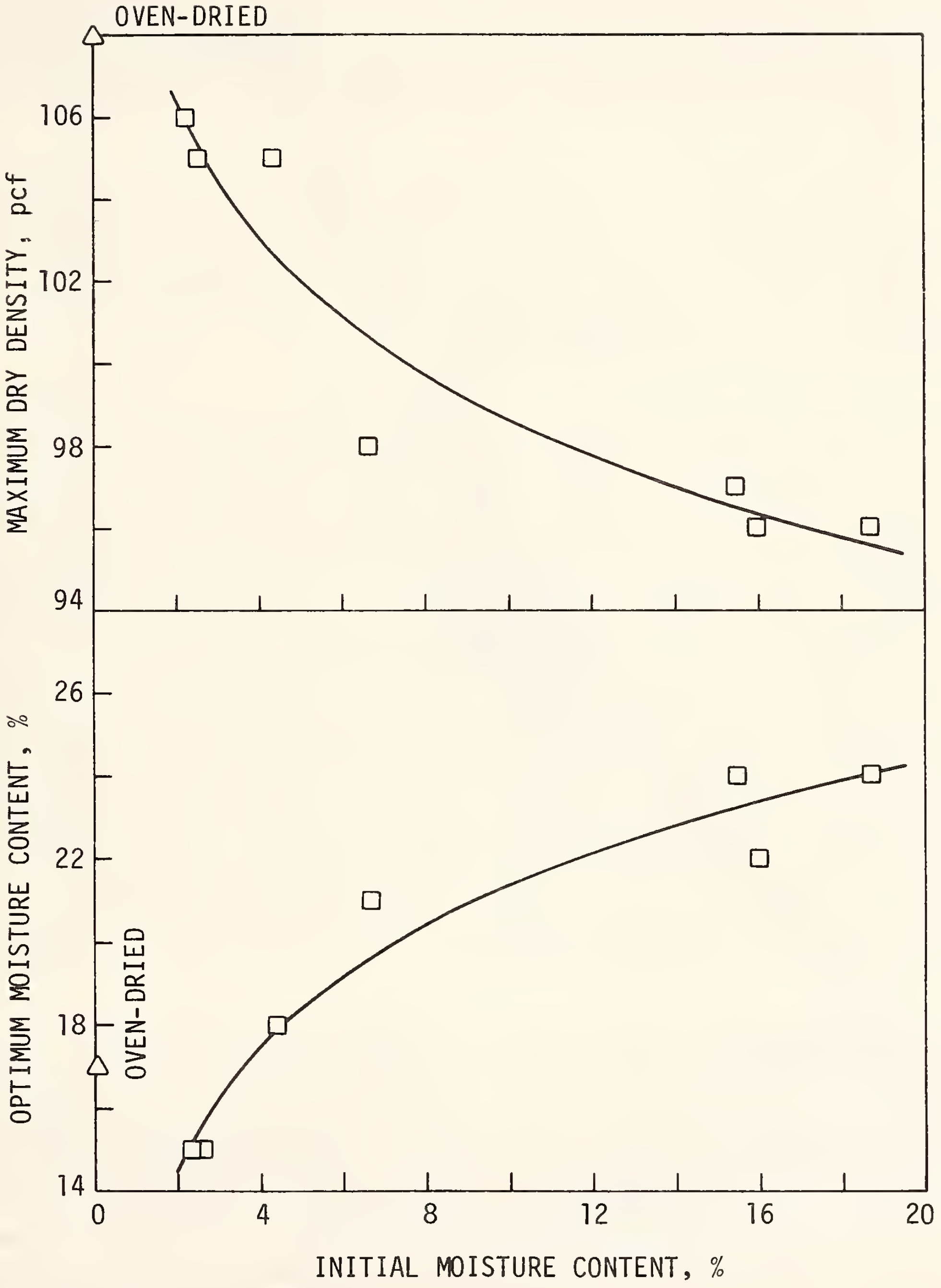

Fig. 59. Effect of drying on moisture-density relations by Grady (81).

These studies thus indicated that moisture-density relationships can be affected by the level of initial moisture content, even in the absence of chemical treatment. It must be recognized, however, that such relationships may be affected by soil type, particle size distribution, mineralogy, and possible other soil parameters. In addition, the surface physico-chemical changes involving soil particles, wrought by addition of most of these chemicals, are to a large extent unknown factors.

In the case of the Peavine series illustrated in Fig. 58, it is evident that some of the chemical treatments show a positive moisture-density effectiveness regardless of initial moisture content. Similar potential positive and/or negative M-D effectiveness is also illustrated in Figs. 40 through 57, even though not always recognized by the linear regression analyses of Table 37.

It has been hypothesized that upon drying, an initially saturated soil should reduce in volume 1 cu cm/g of weight loss until the soil particles come into intimate contact with one another, after which no further reduction in volume should occur.[9] The moisture content corresponding to this condition is referred to as the shrinkage limit (SL), originally proposed by Atterburg. Shrinkage limits obtained by a standard test procedure (ASTM D427-6) for the minus 40 sieve fraction of the untreated soils are presented in Figs. 40 through 57. Partial air-drying above a shrinkage limit, therefore, might cause densification which, for the short times between adding water and final compaction, is irreversible. If this is true, one would expect soils with a shrinkage limit well below the test moisture content range to show the largest densification and reduction in OMC by partial air drying. Observation of Figs. 40 though 57 do not support this hypothesis. Furthermore, regression analyses show little or no relationship between OMC, γ_d, SL, and initial moisture content. The lack of a relation to SL may be attributable to the presence of chemicals, to the fact that the SL was determined on air-dry minus 40 sieve fraction of the soil, or to other factors.

Moisture-density data from 271 compaction tests of the 18 treated and untreated soils are presented in Figs. 60, 61, and 62. Figure 60 indicates that the loci of data parallel the family of zero air-voids curves corresponding to specific gravities of 2.65, 2.70, and 2.75. Such parallelism would be anticipated. Figure 61 presents the relationship between optimum and initial moisture contents. The minimum boundary of this relationship would be a 45° line indicative of points of equal optimum and initial moisture contents. Figure 62 presents the relationship between maximum dry densities and initial moisture contents. In general, the data once again parallel the zero-air voids curve but are shifted to the left by a quantity of initial moisture indicative of the relationship in Fig. 61. As in Fig. 59, a model curve based on initial moisture content could be fitted to each data set (Figs. 61 and 62). Such curve fitting, however, could be misleading since it might be erroneously presumed that, through a knowledge of initial moisture content, both the optimum moisture and maximum dry density could be predicted. This fallacy would arise out of lack of consideration of the slope of a predictive model equation for each

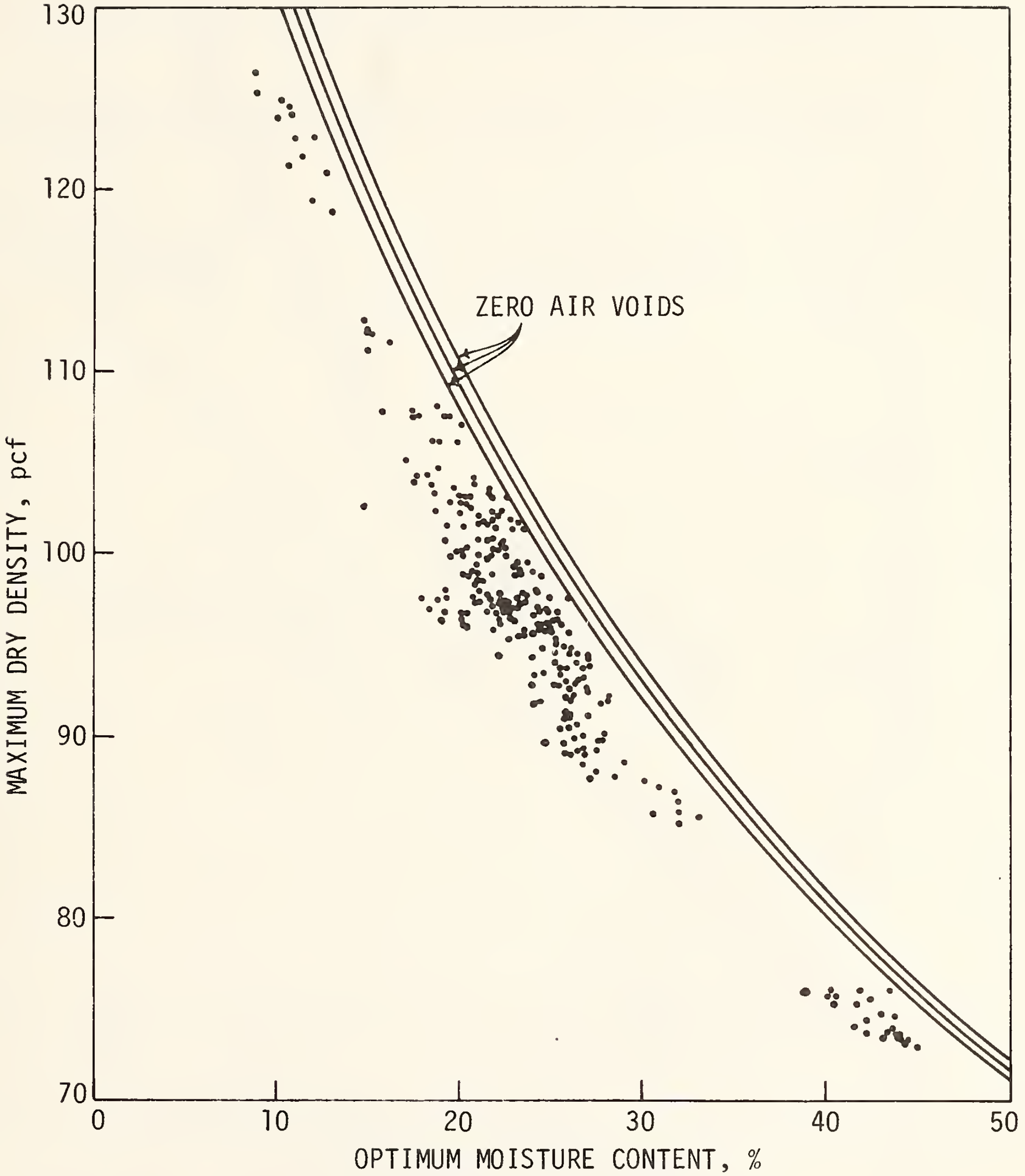

Fig. 60. Relationship of optimum moisture content and maximum dry density, Phase II treated and untreated soils.

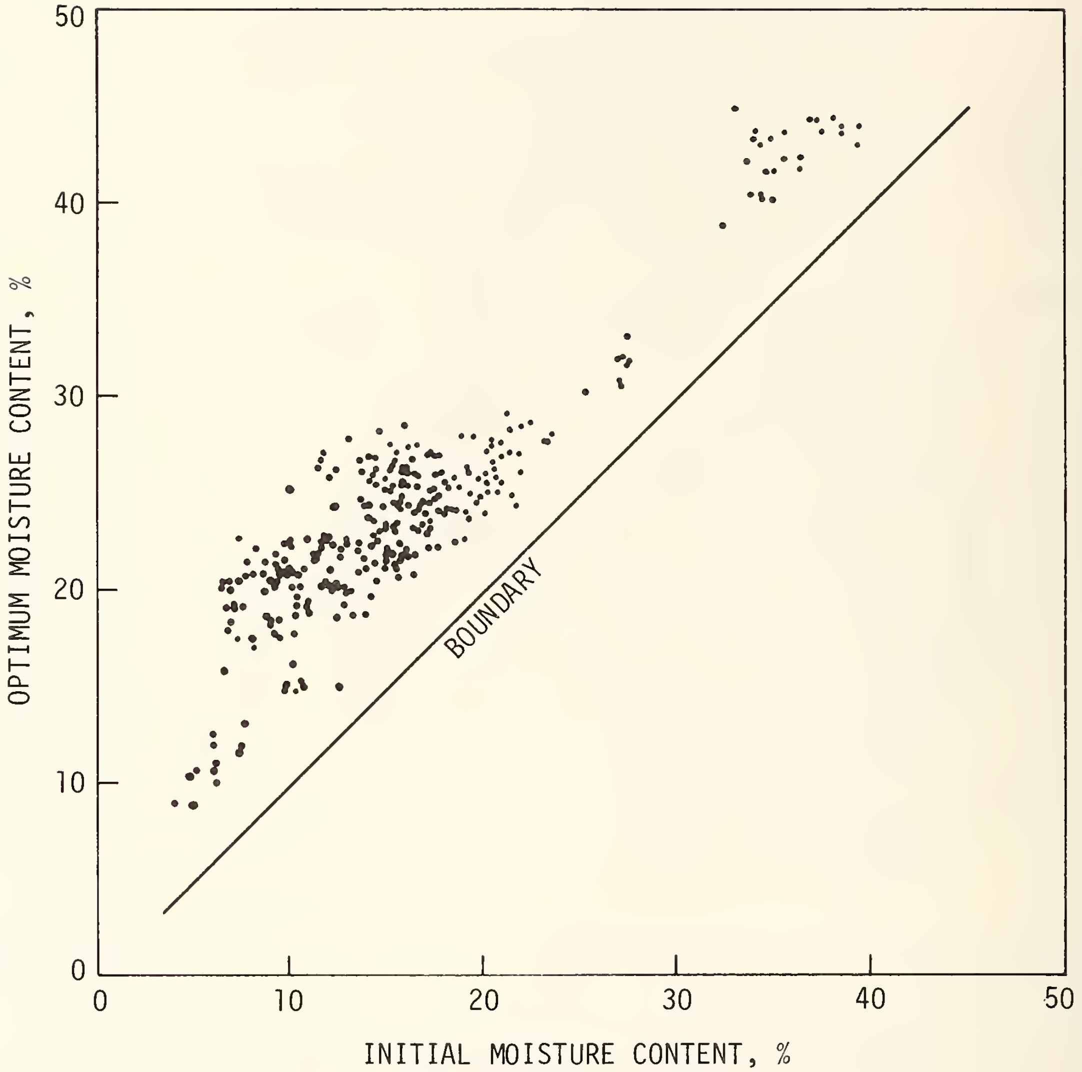

Fig. 61. Relationship of optimum and initial moisture contents, Phase II treated and untreated soils. The boundary line exists because OMC must be larger than the initial moisture content.

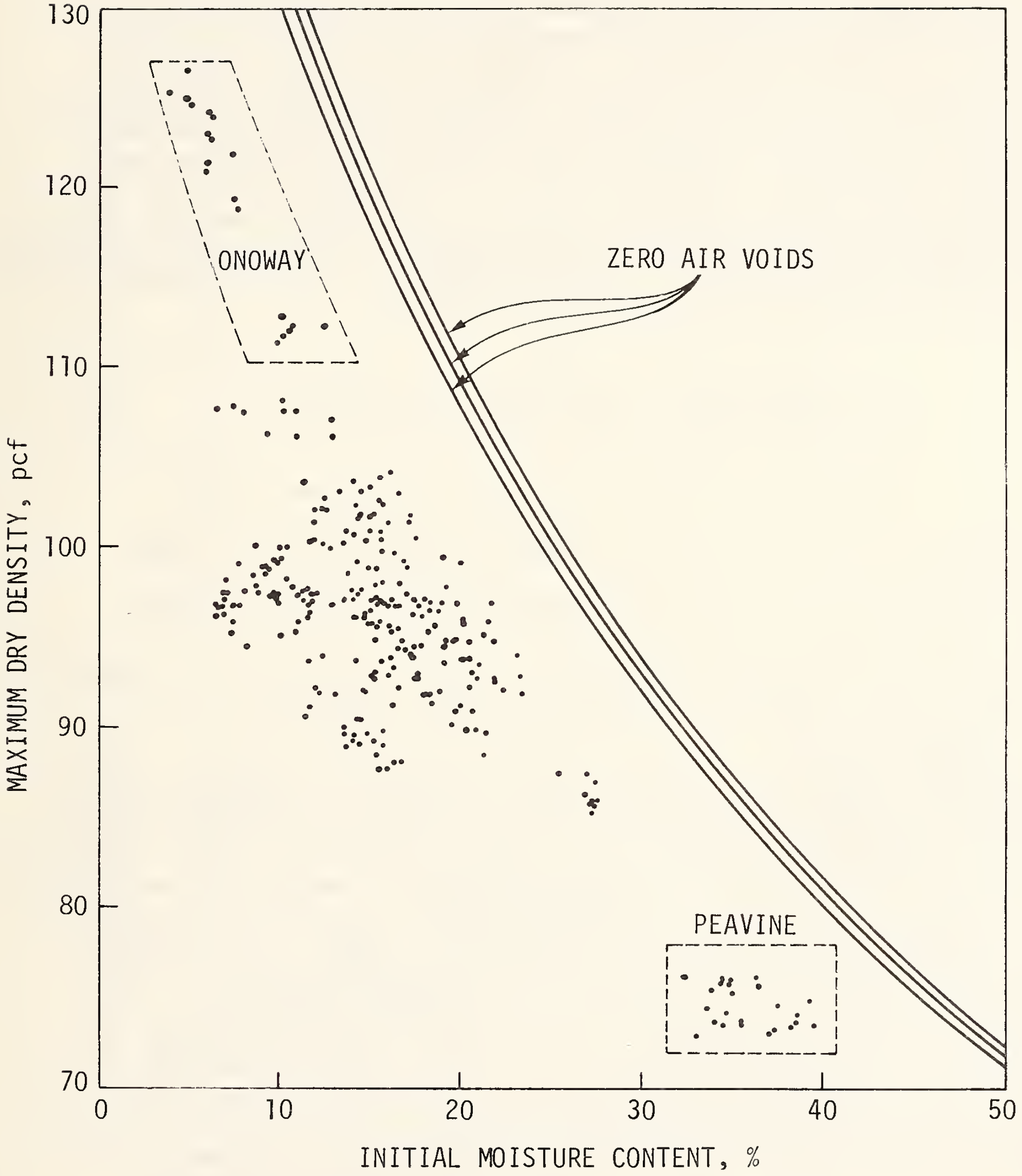

Fig. 62. Relationship of maximum dry density and initial moisture content, Phase II treated and untreated soils.

individual soil, and is shown by the outlined data of Fig. 62 for the Onoway and Peavine series.

The range of initial moisture contents at which these 18 soils were tested was seldom greater than 10%, thus representing limited portions of Figs. 61 and 62 for each soil series. It is apparent from Fig. 62 that moisture-density relationships of soils associated with relatively low values of initial moisture content would exhibit a greater response in density to minor changes in initial moisture content. Thus, the coefficient (slope) of the regression line determined between initial moisture content and maximum dry density for the Onoway soil was much greater in absolute value than that for the Peavine soil. Statistical theory states that correlation and regression coefficients are related in the following manner:

$r = b_1 \frac{s_y}{s_x}$ where r = correlation coefficient

b_1 = regression coefficient (slope)

s_y = standard deviation of Y variable

s_x = standard deviation of X variable

As a result of the above relationship, large correlation coefficients are thus less likely when the slope is small (Table 37).

Compaction Data. Figure 63 is an illustrative example of how a significant effect of a chemical might be masked by variable initial moisture contents (Data Point 2), or alternately, an apparent effect would be erroneous (Point 1). As a simple expedient, linear regression plots were made of optimum moisture content and maximum dry density vs. initial moisture content. Outliers were then computer-identified on the basis of the magnitudes of the absolute values of the residuals, i.e., observed minus predicted value. The absolute value of each regression residual was compared to the standard deviation of the residuals in such a manner that observations lying outside the 80% confidence bands were identified as to their chemical name and treatment level. Such analysis, if applied to the hypothetical data of Fig. 63, would indicate Data Point 2 as an outlier. It must be noted that use of this one-dimensional technique will identify only those products and treatment levels that are exceptionally significant.

A similar, two-dimensional analysis was made, still recognizing the effect of initial moisture content, but also allowing other variables to be simultaneously considered through multiple linear regression. This analysis was used to identify variables other than initial moisture content that might have affected the moisture-density

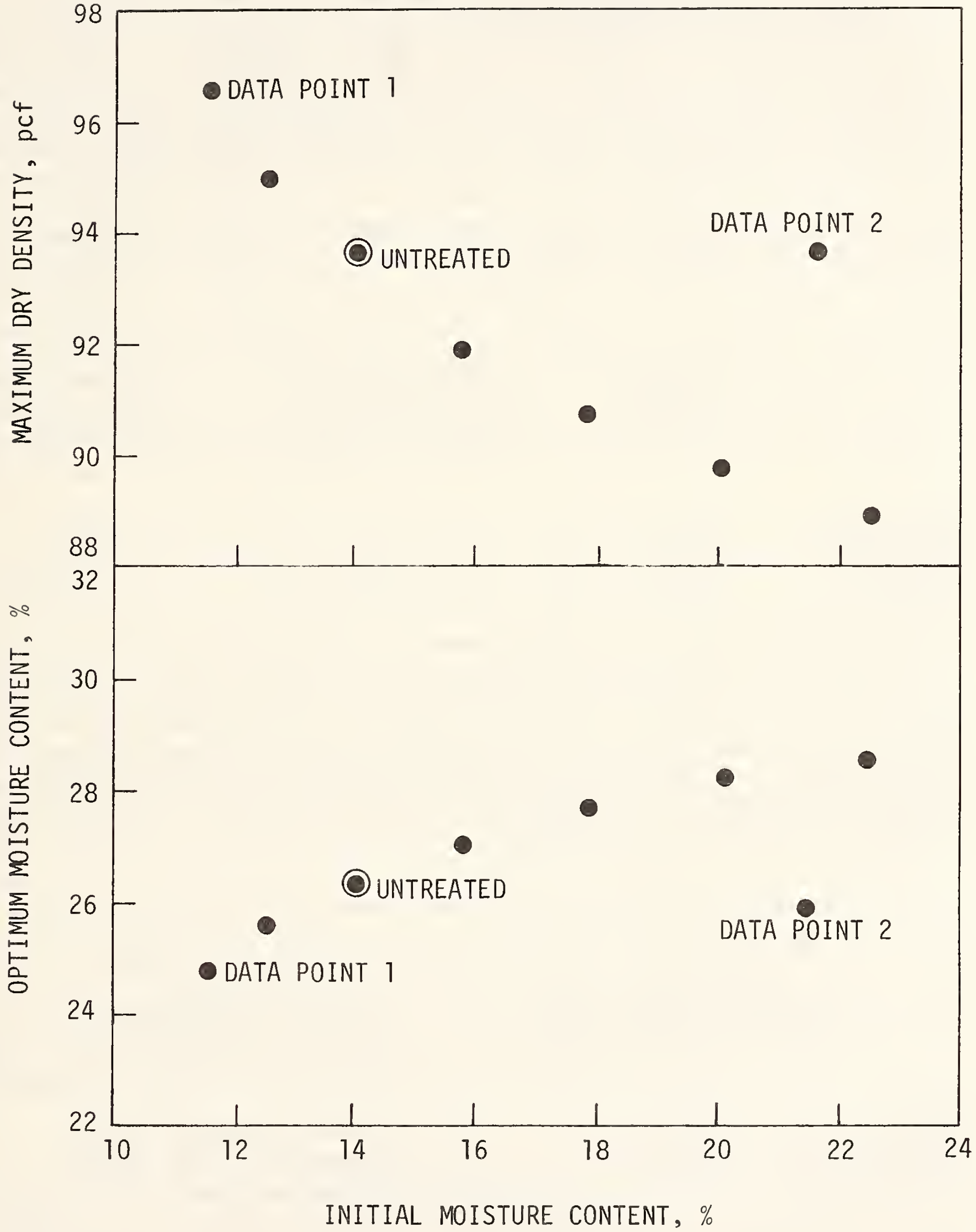

Fig. 63. Hypothetical relationship of maximum dry density, optimum moisture content vs. initial moisture content .

relationship. Again, the technique would identify only those products and causative factors which are exceptionally significant.

Soils Affected by Initial Moisture Content. As noted from Table 37, twelve soils appeared affected by initial moisture content, as indicated by linear regression correlation coefficients significant at the 5% level. For each of these soils, initial moisture content variance of the M-D data was first removed by the one-dimensional analysis. Several of the six Phase I chemicals appeared as residuals, Petro-S being the most common, and affected the maximum dry density of four of the twelve soils. However, in only two of the soils was dry density increased. The optimum moisture content was increased in one soil, decreased in another, and unaffected in the remaining two.

Soil	Level of chemical concentration	Residual change in optimum moisture content, %	Residual change in maximum dry density, pcf
Renohill	Mid	-	+1.8
Melbourne	Mid	+1.7	-1.4
Buxton	High	-1.5	+2.6
Nappannee	Low	-	-2.9

The amounts of the changes are shown in the above table. For comparison, two sets of estimates of standard deviation of optimum moisture and maximum dry density have been reported; 1.0% and 2.2 pcf,[80] and 1.4% and 1.8 pcf,[81] respectively. Standard deviations from untreated and treated M-D data of the twelve soils after correction for the initial moisture content are as follows:

Standard deviation from linear regression of optimum moisture content	Standard deviation from linear regression of maximum dry density
Maximum 1.41%, Peavine	Maximum 1.75 pcf, Onoway
Minimum 0.53%, Nappannee	Minimum 0.73 pcf, Pierre
Average 0.94%	Average 1.25 pcf

Thus, the standard deviations of the predicted optimum moisture and maximum dry density of the one-dimensional analysis are somewhat less than the generally accepted values for laboratory testing variations.

In Figs. 40 through 57, the relation of maximum dry density and optimum versus initial moisture content appears nonlinear. A linear analysis then would tend to force-predict M-D residuals. Thus, the residuals associated with Petro-S treatment could have been due to a non-representative mathematical model and not necessarily to the chemical treatment. Based on a non-linear model, Petro-S might indicate some positive and/or negative effectiveness with several of the soil series as viewed in Figs. 40-57. Similar indications of M-D effectiveness would be indicated with Clapak, Thinwater, Coherex, SC-518, Claset, and SA-1.

The most frequent outlier from the two-dimensional analysis was the amount of chemical. Actual quantities of chemicals applied to all 18 Phase II soils varied by as much as a factor of 4000. Variation of a single chemical within each soil series, however, only occasionally exceeded a factor of 10. While no clear-cut conclusions were ascertained from the two-dimensional analyses, correlation coefficients suggested that soils treated at the higher levels were compacted to higher densities at less moisture than soils treated with low rates of chemical application.

As indicated previously, surface tension of leachates appeared pertinent, and these data, therefore, were regressed against optimum moisture content, maximum dry density, surface tension of chemical in water solution, and surface tension difference between leachate of treated and untreated soil. A computer correlation matrix process,* producing correlation coefficients for every possible pair of data set variables, was used for this analysis.

Several chemicals lowered surface tension of the Phase II soil liquid pore phase, as indicated by lowering of the surface tension of the leachate. The correlation matrix procedure indicated a significant linear relationship between optimum moisture and maximum dry density vs. surface tension of leachate in several soils. However, Fig. 64 shows that the linear relationship was generated by data in two widely separated groups, such that the coefficient is indicative of slope only. Of the two other variables, i.e., surface tension of chemical in water solution and difference of surface tension of leachate of treated from untreated soils, the former appeared more promising, but again correlative relations with optimum moisture content and maximum dry density were lacking.

Though analyzed in a subsequent section of this report, measurements of pH, zeta potential, and specific conductance were obtained on minus 50 micrometer particle size fractions of the untreated and treated soils. Inclusion of these parameters in the correlation matrix indicated that they were highly correlated among themselves and with surface tension of leachates and not so strongly with moisture-density

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*Developed by SAS, Inc., Raleigh, North Carolina.

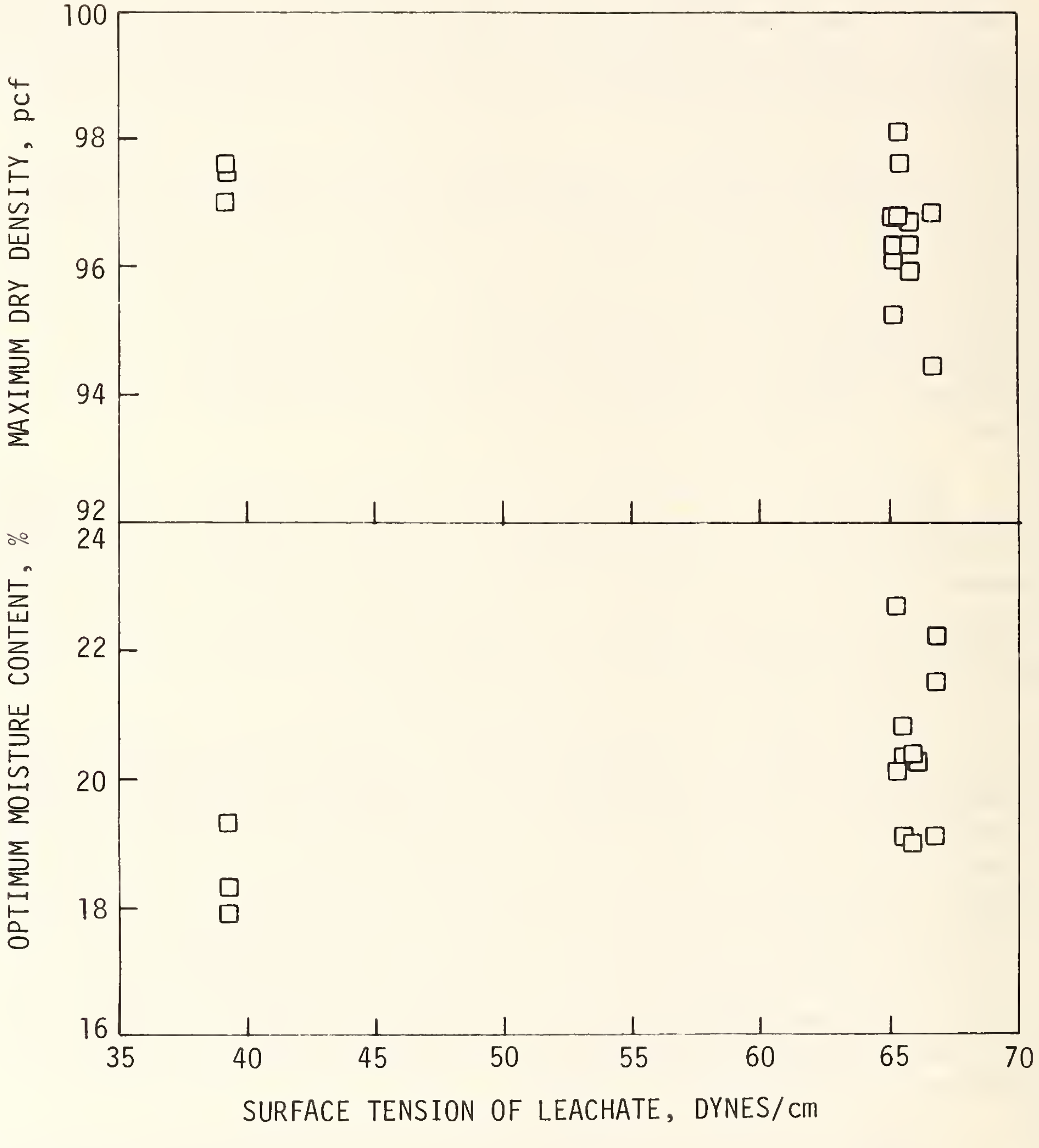


Fig. 64. Relationship of surface tension of leachate vs. maximum dry density and optimum moisture content, Rimrock series.

parameters. Figure 65 is an example of one of the stronger M-D versus zeta potential relationships. Though a semblance of a relationship exists, it would be viewed as somewhat indistinct and statistically imprecise. The initial moisture content variable was not accounted for in the M-D data of this correlation matrix.

Soils Not Affected By Initial Moisture Content. Evaluative statistical treatments also were applied to data from the six soils not affected by initial moisture content: Fannin, Persanti, Altamont, Rimrock, Vergennes, and Paulding. The correlation matrix procedure indicated that surface tension of leachate was often correlated with either optimum moisture content or maximum dry density, but these significant correlations seldom occurred simultaneously and were due largely to the data separation as previously illustrated in Fig. 64. Multiple linear regression procedures gave prediction equations for optimum moisture content and maximum dry density for most soils, but these equations seldom included the same variables, leaving little variance attributable to error. This often occurs in multiple linear regression analyses which are capable of "forcing" data into meaningless relationships when several parameters are available. The plots did not suggest any underlying nonlinear relationships and tended to discredit variables in the multiple regression models. The statistical procedures thus applied to the data failed to identify relationships warranting further examination.

Consideration was then given to the possibility that so little variation occurred in the compaction test data for these soils that all variance might be attributed to the accepted deviations from the M-D test procedure. To analyze this possibility, Table 38 presents measured standard deviation (univariate statistic) of optimum moisture content, maximum dry density, and initial moisture content for each soil, and also provides an indication of dependence upon initial moisture content. Persanti, Altamont, Rimrock, and Vergennes series were considered likely to fit in this category. The average of the four standard deviations of optimum moisture content from these soils was 0.93%, while the corresponding figure for maximum dry density was 1.03 pcf. The largest values were 1.3% for optimum moisture content and 1.2 pcf maximum dry density. These figures indicate that M-D test procedure error might be responsible for the variance in these soils, since the standard deviations are less than generally accepted values due to error alone. It was therefore concluded that a chemical effect was not measured in these four soils by use of the statistical procedures.

No variable was found which could be shown to be responsible for variations in moisture-density results of the Fannin series. The only suitable explanation lies in the highly micaceous mineralogy of Fannin. Because the density of untreated Fannin soil far exceeded that of all treatments, there was no encouragement to look for evidence of effective compaction aids in the data.

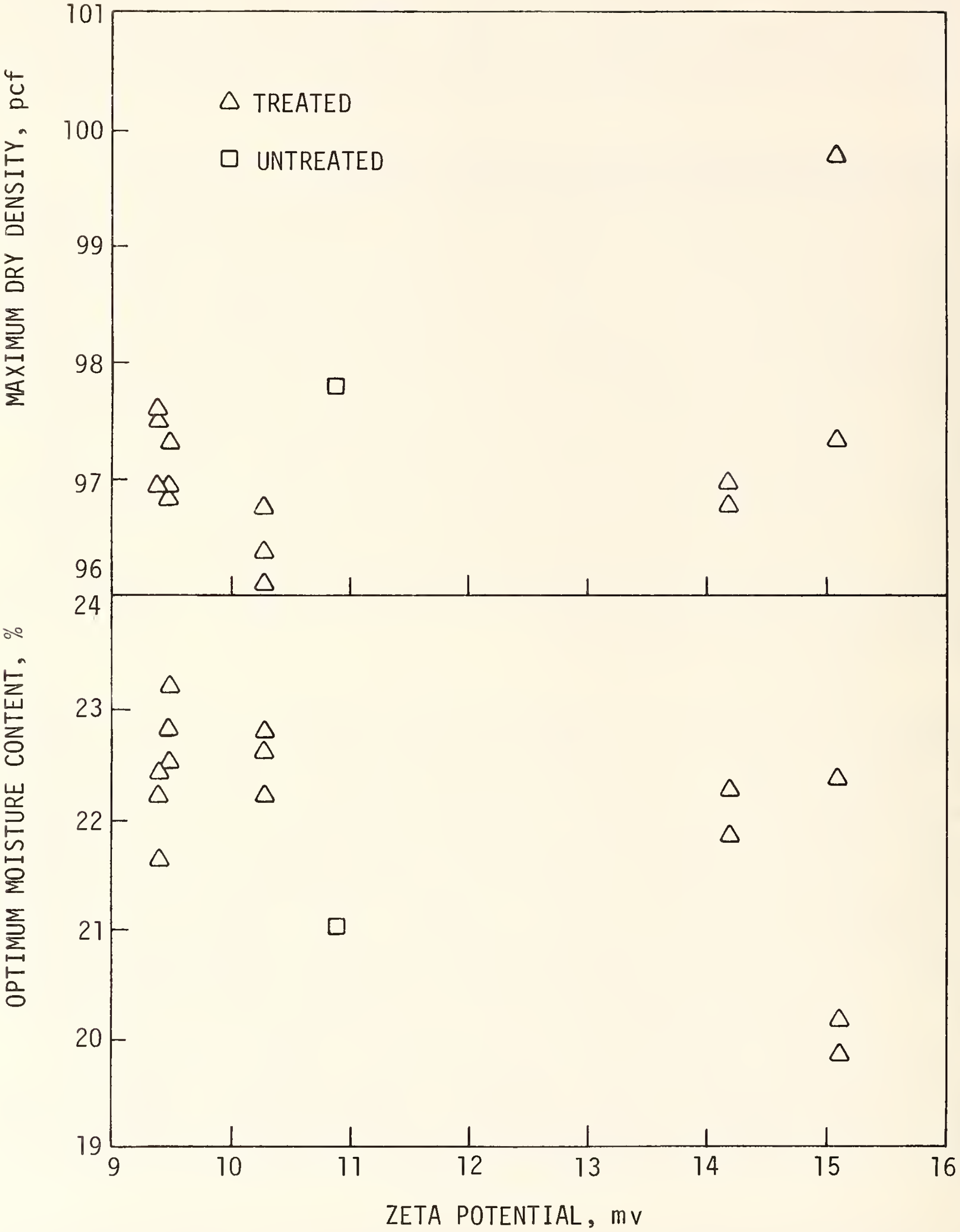


Fig. 65. Relationship of Zeta potential vs. maximum dry density and optimum moisture content, Renohill series.

Table 38. Univariate statistics from linear regression of moisture-density and initial moisture content data.

Soil	Shrinkage limit (%)	Initial moisture content (%)				Standard deviation of optimum moisture content (%)	Standard deviation of maximum dry density (pcf)
		Maximum	Minimum	Average	Standard deviation		
Frederick**	26.8	19.6	14.2	16.8	1.5	1.0	1.8
Fannin	25.5	16.0	7.7	13.5	2.6	0.5	1.7
Persanti	19.5	19.1	14.9	16.9	1.2	0.8	1.2
Bearden*	18.6	13.8	8.1	11.1	1.9	1.5	1.6
Renohill**	15.6	15.1	8.7	11.7	1.5	1.0	1.1
Pierre**	9.3	16.7	13.6	15.0	1.0	0.9	0.8
Altamont	8.1	10.4	8.6	9.5	0.5	0.8	0.9
Rimrock	3.6	8.2	6.4	7.1	0.6	1.3	0.9
Houston Black**	9.2	21.0	13.8	17.3	2.4	1.6	1.7
Peavine**	33.2	39.5	32.3	35.7	2.0	1.6	1.1
Melbourne**	29.0	27.6	17.7	23.1	4.0	3.1	2.6
Marias**	14.9	21.8	8.8	13.8	3.6	1.8	2.0
Buxton**	23.1	21.5	14.3	17.5	2.3	1.0	1.4
Vergennes	10.1	17.3	12.0	15.1	1.5	0.8	1.1
Ontonagon**	16.7	23.5	16.5	20.7	2.2	1.5	2.1
Onoway**	12.9	12.6	4.0	7.5	2.5	2.3	5.5
Nappannee**	15.6	14.5	6.6	11.1	2.3	1.3	2.2
Paulding	14.1	21.9	10.1	14.2	2.7	1.3	2.3
Averages	-	-	-	-	2.0	1.3	1.8

*Relationship between initial and optimum moisture content significant at the 5% level.
**Relationship between initial and optimum moisture content significant at the 1% level.

The Paulding series (Fig. 57) indicate significant variability of M-D results versus calculated initial moisture contents, yet linear regression of the data produced exceedingly low correlation coefficients (Table 37). As with the preceding five soils, such coefficients provided an implied supposition of lack of insufficient variation in one or more of the parameters. Assuming that the untreated Paulding initial moisture content would follow the untreated non-linear curves exhibited in Figs. 50 and 58 for the Melbourne and Peavine, respectively, it might be concluded that not only was initial moisture content significant but also that most of the chemical treatments produced positive M-D effectiveness. Critical examination of the untreated and treated Paulding M-D curves, however, illustrated all four categories of Proctor curves previously reported by Lee and Suedkamp[79] and discussed by Winterkorn and Fang.[78] With the Paulding, these categories occurred over a range of about 8% moisture content and 6 pcf density. According to these authors, such changes are brought about by drying, thus representing concurrent changes in soil structure. While interpretation of the Paulding T-99 curves appeared reasonable, difficult arbitrary interpretation decisions had to be made which may have severely reduced the value of M-D data within the regression study. It was concluded, therefore, that initial moisture content, coupled with M-D curve interpretation, may have created considerable variance within the Paulding series of tests.

Summary. Based on a linear regression method of prediction of optimum moisture content, maximum dry density, and initial moisture content, the moisture-density relationships observed in 12 of the 18 Phase II chemically-treated soils appear to be a function of initial moisture content and of low and acceptable deviatoric errors in evaluation of the initial moisture content and M-D relations. A curvilinear relation, based on the natural logarithm of the initial moisture content, indicates that the chemicals may produce a range of positive to negative moisture-density effectiveness, dependent on soil type.

The M-D relations for 4 of the 18 Phase II treated soils did not appear related to initial moisture content, nor did the effects of chemical treatments exceed those attributable to random error of measurement and interpretation of the M-D data. In particular, no variable was relatable to the M-D results obtained with the highly micaceous Fannin series; as in the qualitative analysis, no chemical appeared effective. Initial moisture content, coupled with M-D curve interpretative procedures, apparently created considerable variance within the Paulding series of M-D tests.

The evaluative analyses of M-D test data, as revealed through statistically acceptable regression techniques, thus produced only one positive conclusion: that the initial moisture content of either untreated or chemically-treated moisture-density test specimens will affect optimum moisture contents and maximum dry densities achievable under standard T-99 conditions. The study did not fully nor conclusively provide a substantive evaluation of whether or not any real chemical effects may have existed within the data.

Stability Data. Appropriate comparison of stability parameters could be made only after all values were adjusted for variations in optimum moisture induced by the levels of the initial moisture contents.

Figure 39 illustrates the moisture content-stability relationships that exist within compaction test series. This concept was examined on a broader scale through the relationship of ϕ versus moisture content of all treatments with each soil. Figure 66 illustrates such a relationship for the Marias soil, with the untreated and SA-1 treated being noted for comparative purposes and the solid symbols representing predicted ϕ values at the respective optimum moisture contents of other treatments. The relationship presented by the composite data is observed to be somewhat different from that presented by each individual compaction test, suggesting that regression lines determined for each compaction test produced similar slopes but different intercepts. Based on tests of significance of slope and intercept, statistical analysis of the regression data was performed but did not substantiate this observation. The two compaction test series were chosen at random to illustrate the need to account for change in optimum moisture induced by the level of the initial moisture content. The predicted values of ϕ_{omc} at the OMC for soil treated with SA-1 is roughly 1.5 times that for the untreated soil, with about 6% reduction in optimum moisture content. However, from Fig. 51 where SA-1 treatments are boxed by dashed lines, a 6% reduction in optimum moisture content is at least partly attributable to a 10% reduction in initial moisture content. When allowance is made for this difference in initial moisture contents, the ϕ angles are much closer.

Figure 67 presents measured values of ϕ versus moisture content of untreated and chemically-treated Peavine series specimens. Though the relationships presented are not totally dissimilar to those in Fig. 66, a more curvilinear relation may be observed, with the untreated soil presenting much the same relationship as most values of the treated soil.

Figure 68 shows the predicted ϕ_{omc} from test series with the Peavine and Marias soils. The relationship of Fig. 66 carries over into predicted values of ϕ_{omc} (Fig. 68-b). Data points lying well above or below a regression line from this data would correspond to treatments affecting soil stability. A similar relationship is not present in Fig. 68-a for the Peavine series. Since ϕ_{omc} does not increase at low moisture contents as would be expected, the improved compaction characteristics may have been achieved at the cost of a reduction in strength.

For the purpose of identifying chemical treatments that truly alter ϕ_{omc}, a "one-dimensional" analysis was again employed. A regression line of all ϕ_{omc} values for both treated and untreated soils was taken as a datum from which comparisons were made to identify chemical treatments resulting in large residuals of ϕ_{omc}. The same analysis was

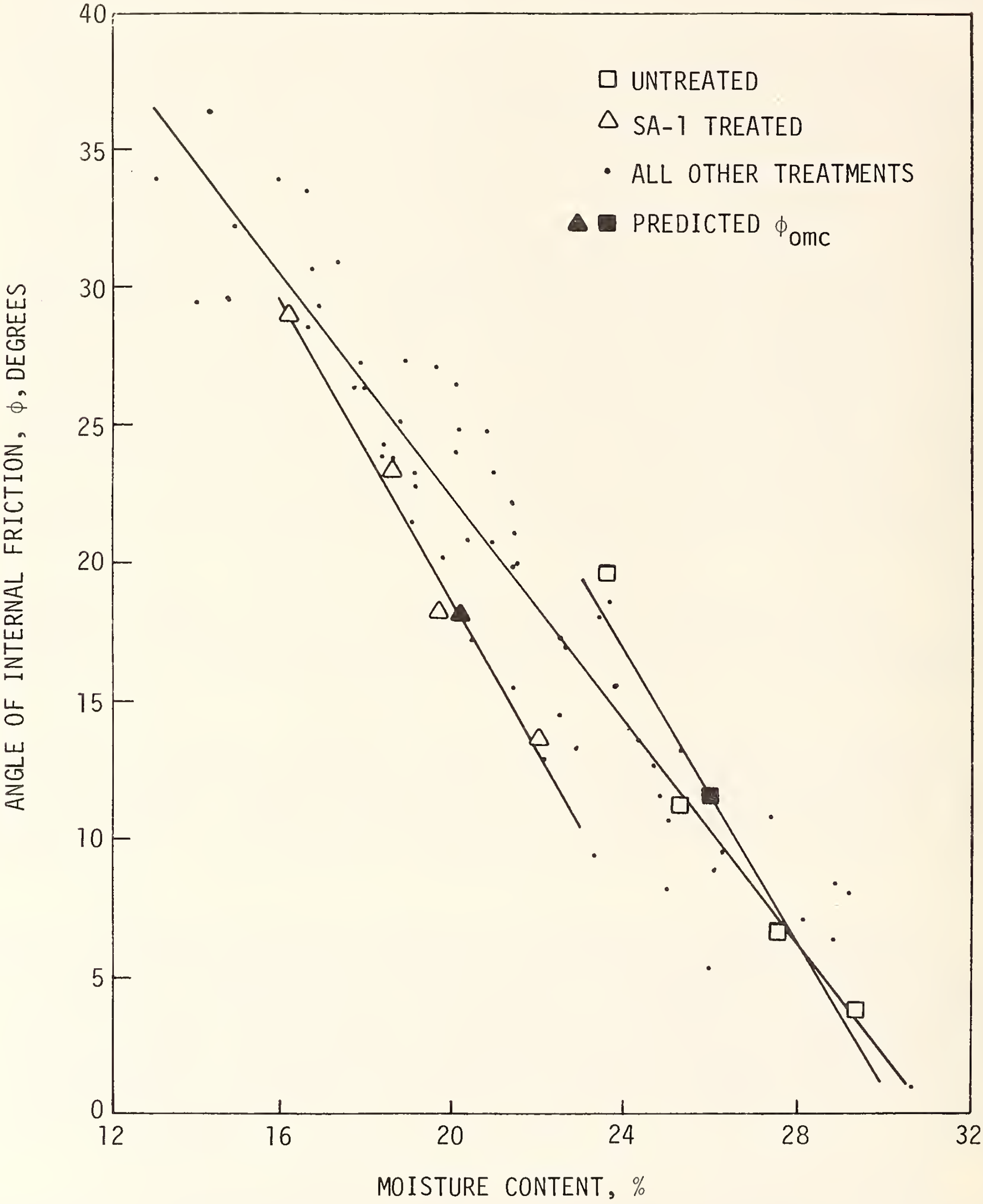


Fig. 66. Relationship between measured values of angle of internal friction and moisture content, Marias series.

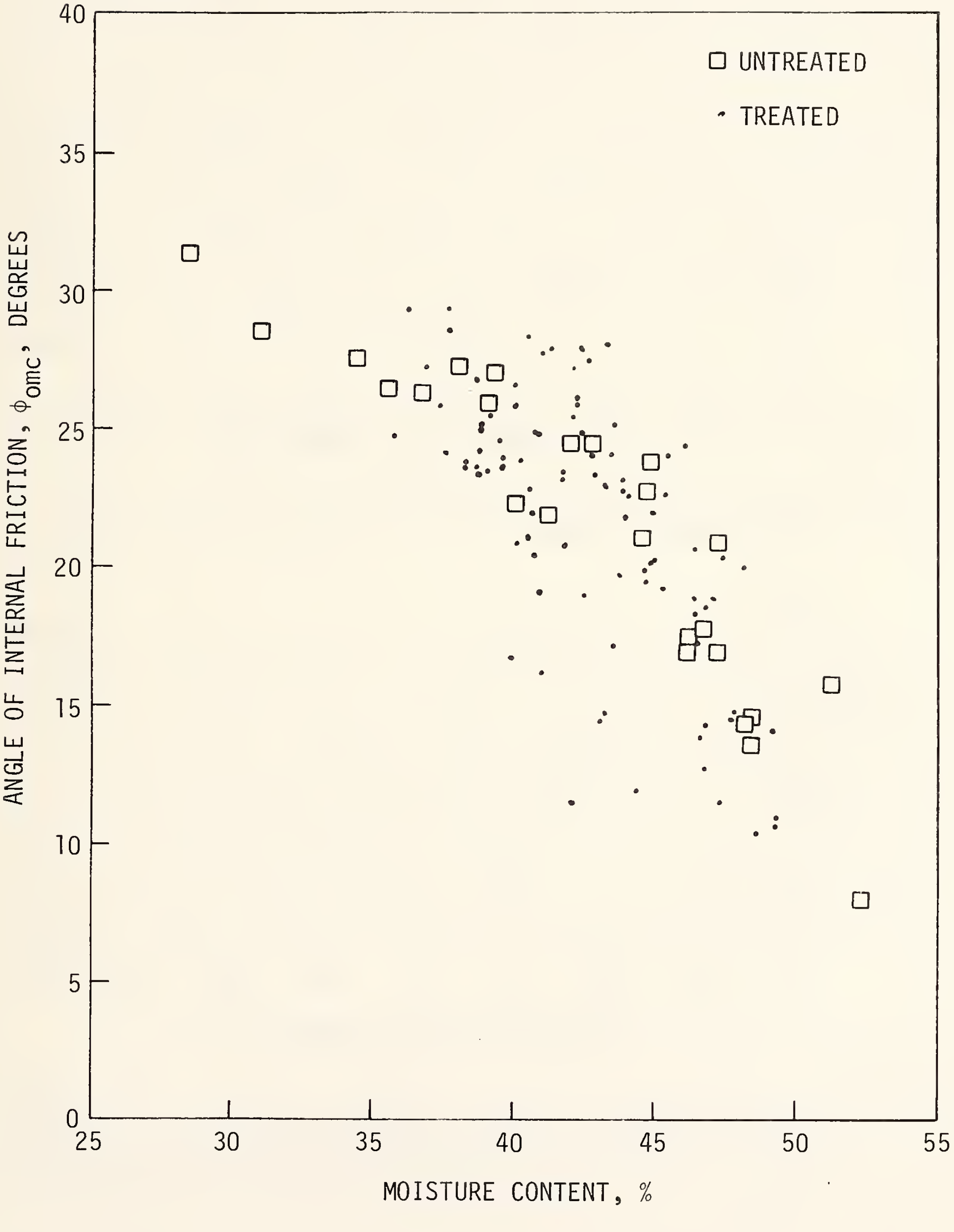
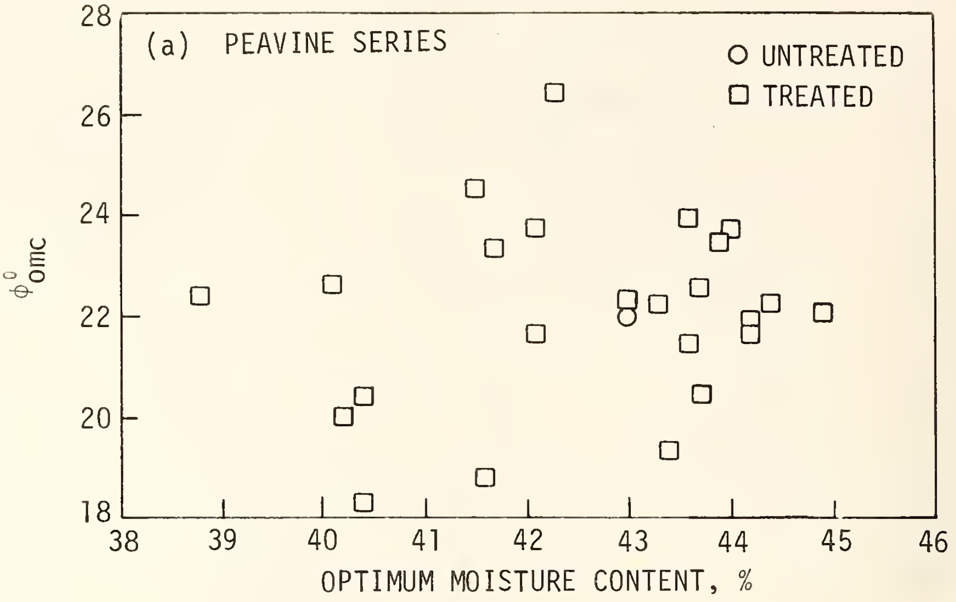


Fig. 67. Relationship between measured values of angle of internal friction and moisture content, Peavine series.



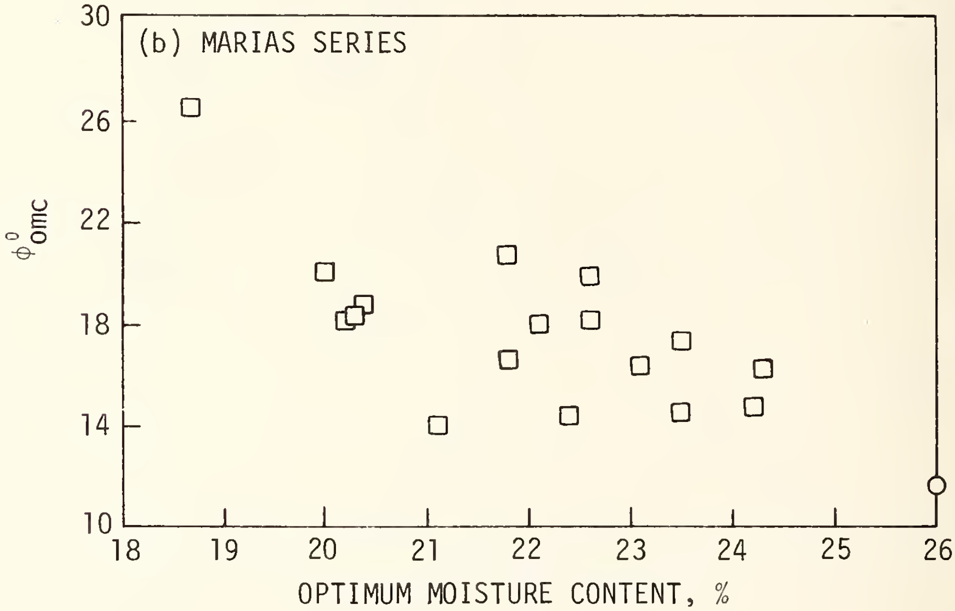


Fig. 68. Predicted values of angle of internal friction vs. optimum moisture content for (a) Peavine and (b) Marias series soils.

applied to the other three stability parameters, c_{omc}, k_{omc}, and E_{omc}. Figures 69, 70, and 71 illustrate these relationships for the Bearden series.

The parameter with the strongest relationship to optimum moisture content was K_{omc}, followed (in decreasing order) by ϕ_{omc}, c_{omc}, and E_{omc}. Table 39 is a summary of statistical data from all 18 soils concerning these relationships, as well as an indication of which soils were affected by the level of initial moisture content. It may be noted that significant relationships between initial and optimum moisture content versus maximum dry density are associated with significant relationships between optimum moisture content and some, usually two, of the stability parameters. In order for a strong statistical relation to be developed between, say, optimum moisture content and ϕ_{omc}, there must be sufficient variation in optimum moisture content to overcome errors inherent in measurement and evaluation of both parameters. Therefore, the apparent lack of a significant relationship may only indicate an abbreviated range in optimum moisture contents.

As in the compaction data, Petro-S was indicated to have affected soil stability most strongly. However, the stability parameters are indicative of less stable, rather than more stable soil. Therefore, the improved compaction characteristics with Petro-S may be at the cost of a reduction in strength. A similar observation may be noted in Fig. 6 (Vol. I) with Clapak treatment of the Cecil series, where the Spherical Bearing Value was reduced.

Summary. The stability test data posed several problems which detracted from reliability of the analyses. One problem was the necessity to analyze data composed of predicted or interpolated values rather than simply measured values. A second problem arose out of the effect that initial moisture content had on moisture-density relationships of the soils. That is, the correlation matrix procedure indicated that optimum moisture content and several stability parameters were highly correlated for many of the soils, but in most instances, the optimum moisture content also was shown to be dependent on the level of the initial moisture content (Table 37). Consequently, proper comparisons had to be preceded by an accounting for the effects of variable initial moisture contents, representing another unavoidable treatment of the data.

The treatment applied to the data consisted of (a) use of linear regressions to predict stability parameters at respective optimum moisture contents, and (b) forming a new datum from linear regression of predicted OMC stability parameters and optimum moisture content. This regression was based on measured optimum moisture content rather than initial moisture content since the effect of initial moisture content is indirectly represented by the optimum moisture content. That is, in most cases the initial moisture content was responsible for changes in optimum moisture, and the optimum moisture content in turn is responsible for changes in the values of the stability parameters.

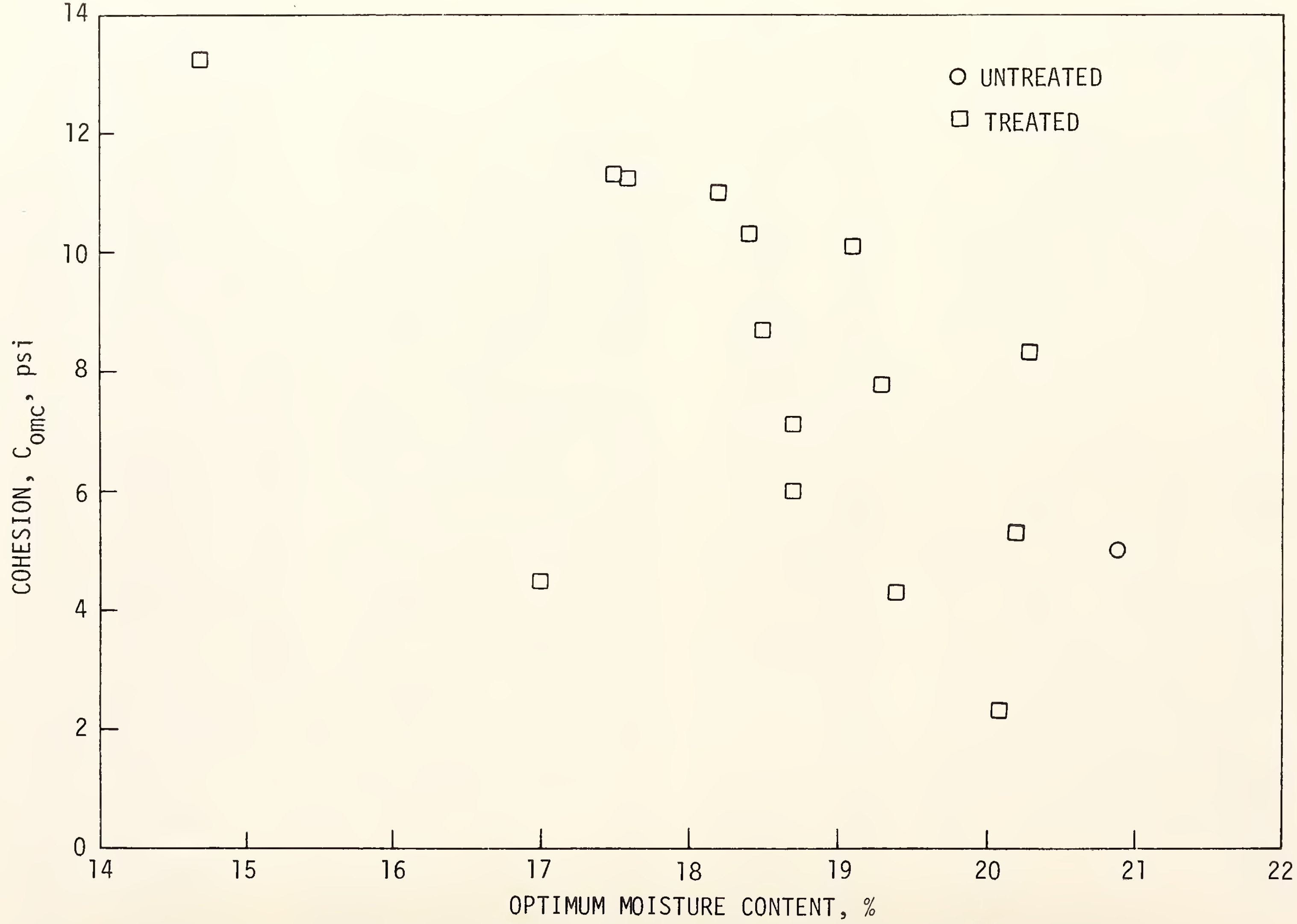


Fig. 69. Relationship between optimum moisture content and predicted values of cohesion, Bearden series soil.

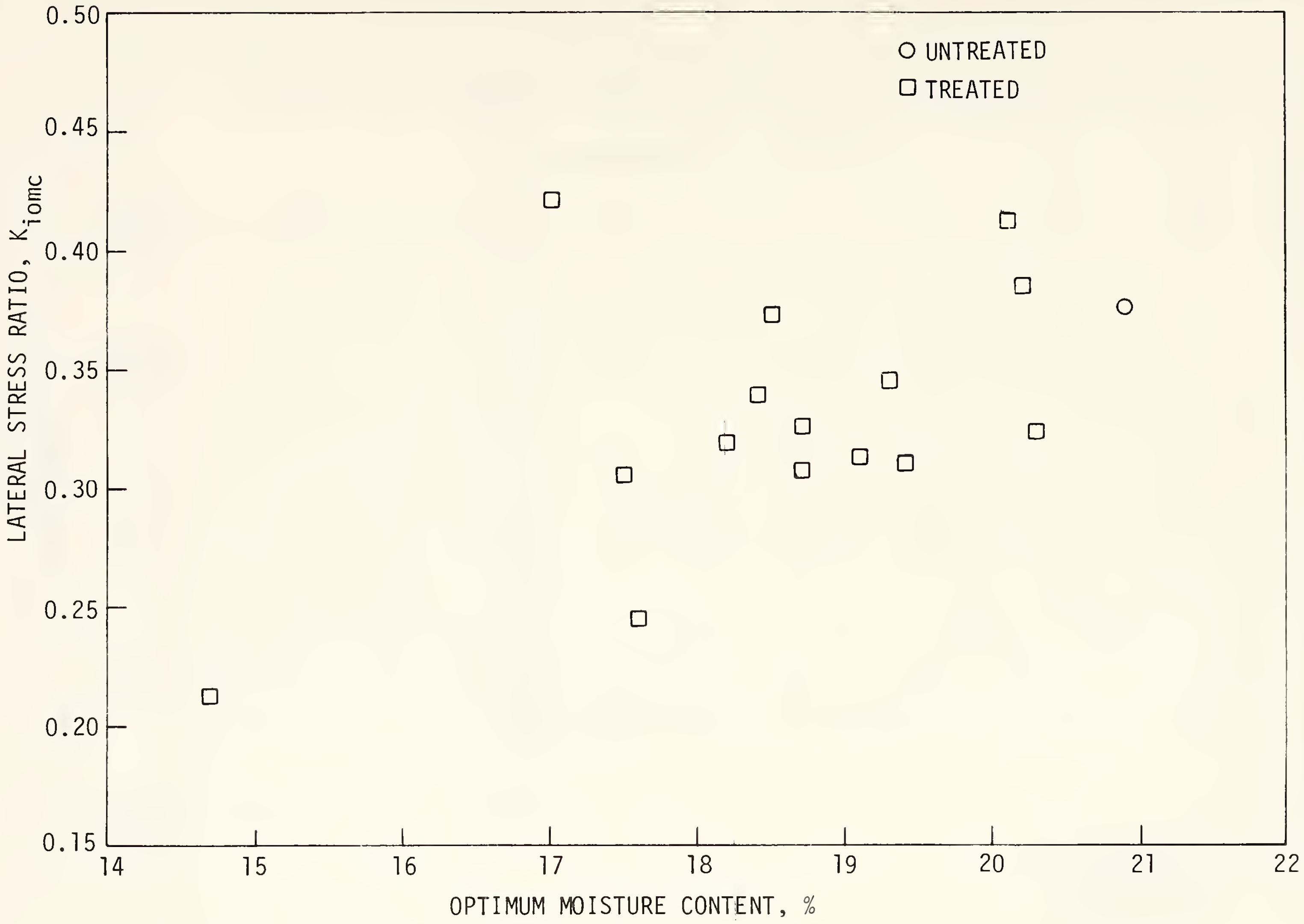


Fig. 70. Relationship between optimum moisture content and predicted values of lateral stress ratio, Bearden series soil.

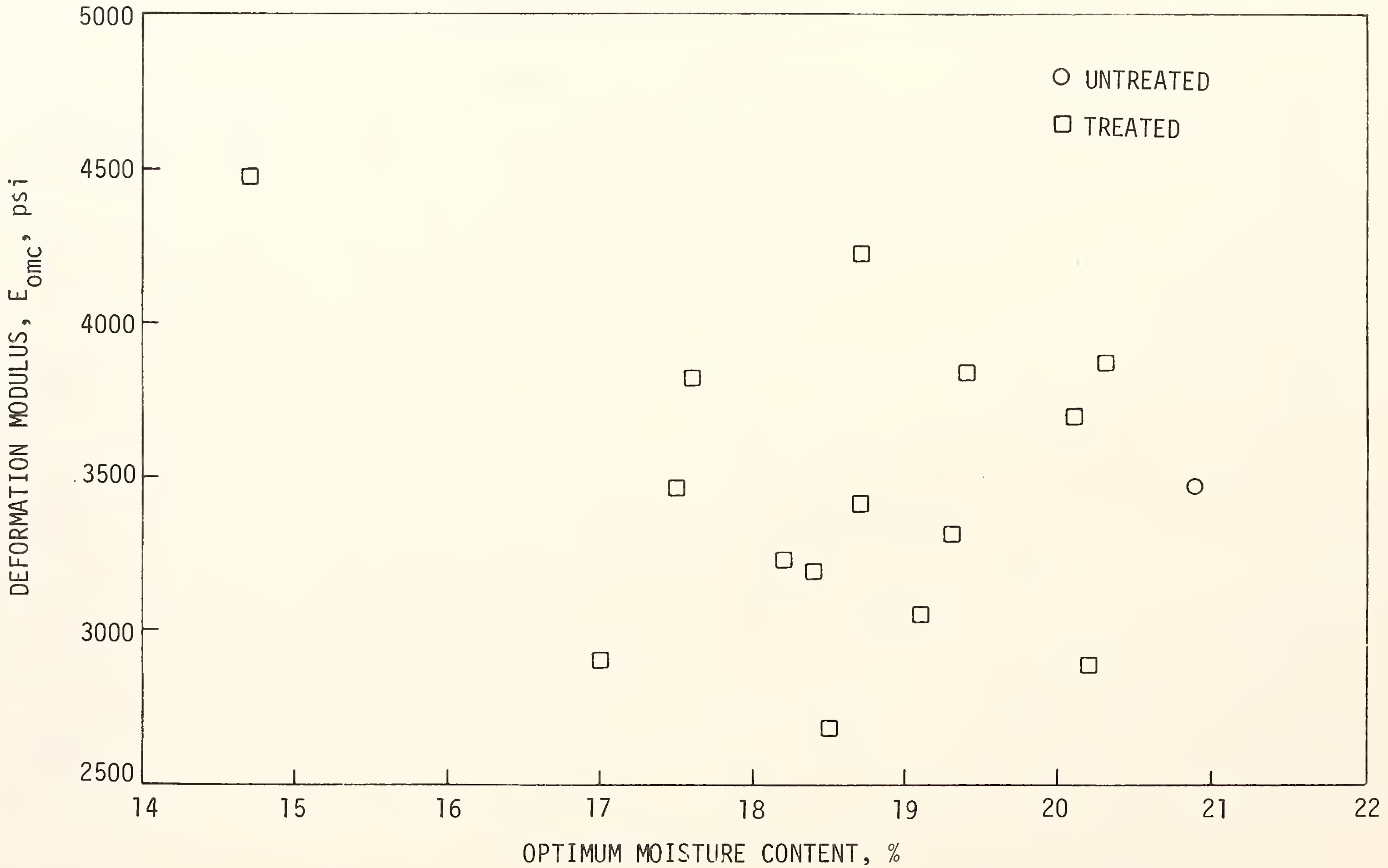


Fig. 71. Relationship between optimum moisture content and predicted values of deformation modulus, Bearden series soil.

Table 39. Correlation coefficients from linear regression between predicted stability parameters and optimum moisture content.

Soil	Correlation Coefficients			
	K_{omc}	ϕ_{omc}	C_{omc}	E_{omc}
Frederick***	-0.1	-0.2	0.6**	0.5*
Fannin	0.3	0.0	-0.4	0.2
Persanti	0.2	-0.3	-0.2	0.4*
Bearden***	0.6**	-0.4	-0.6**	-0.3
Renohill***	0.3	0.3	-0.6**	-0.2
Pierre***	0.5*	-0.7**	-0.2	0.3
Altamont	0.3	-0.4	0.3	0.2
Rimrock	0.8**	-0.9***	0.2	-0.4
Houston Black***	0.5*	-0.5*	-0.4	-0.5*
Peavine***	-0.2	0.2	-0.2	-0.1
Melbourne***	0.7**	-0.9**	0.3	0.2
Marias***	0.8**	-0.7**	-0.5*	-0.2
Buxton***	0.4*	-0.4	0.1	-0.2
Vergennes	0.8**	-0.8**	-0.2	-0.8**
Ontonagon**	-0.6*	-0.6**	0.1	-0.1
Onoway***	0.1	-0.4	-0.1	-0.8**
Nappannee***	0.7**	-0.6*	-0.7**	-0.5*
Paulding	0.6*	-0.2	-0.5*	-0.0

*Relationship between optimum moisture content and stability parameter significant at the 10% level.

**Relationship between optimum moisture content and stability parameters significant at the 5% level.

***Moisture-density relationships of these soils were affected by the level of initial moisture content.

Aside from revealing strong relationships between optimum moisture content and stability parameters, no definitive conclusions could be drawn from analyses of the stability test data. Several observations concerning the results are worthy of comment, however, in order to document impressions received from the analyses.

The first observation concerns the chemical previously deemed as most effective, Petro-S. When Petro-S significantly improved compaction characteristics of soil, the stability parameters were altered in a negative way, i.e., c, ϕ, and E were reduced and K was increased. This coincidence indicates that the changes are real. The most prominent characteristic of Petro-S is its ability to lower surface tension of the liquid pore phase of soil, as measured by surface tension of leachate obtained from chemically-treated soil. It can be theorized that reduction in surface tension of the liquid pore phase would result in an increase in the pore water pressure (a negative quantity in minisci). Soil particles would then be held together less tightly, interparticle frictional forces would be reduced, and less resistance to compaction would develop. This is a plausible mechanism for improving compaction characteristics of a soil, and it also accounts for reduction in soil stability. One may expect that, as a general case, a chemical treatment that reduces interparticle forces will tend to improve compaction and reduce stability.

In general, those soils which were indicated to have been affected by initial moisture content also had stability parameters that were highly dependent upon optimum moisture content (Table 39). Conversely, the Altamont, Persanti, and Fannin soils, apparently not affected by the level of initial moisture content, failed to show significant relationships between optimum moisture content and stability parameters. The Peavine, which was tested at initial moisture contents above and below its shrinkage limit, had a mixed response to initial moisture content and also presented stability parameters apparently not related to optimum moisture content. However, the Vergennes and Rimrock, not affected by initial moisture content, showed stability parameters highly dependent upon optimum moisture content. The tendency for an interrelationship means that stability parameters in most cases ultimately relate to the initial moisture content, but the trend is not altogether consistent.

Laboratory Compaction Growth Study

Both the qualitative and evaluative analytical procedures utilized with the Phase II studies indicated conflicting results for chemical effectiveness, as well as a strong relationship between compacted density and initial moisture content. All effectiveness evaluations were based on the constant compactive effort of AASHTO T-99 (12,375 ft-lb/cu ft of energy), leaving a question of whether compactive effort might be reduced for the treated soils, while density and shear strength could be maintained equal to or greater than, those of the untreated soil.

A laboratory compaction growth study, therefore, was conducted as a further evaluative technique. In an attempt to minimize the initial moisture content variable, the initial moisture content for specimens from each soil series was closely controlled.* Table 40 presents a listing of the soils and percentage chemical used with this study. Each percentage was selected as representative of the range of chemical used in the M-D and K-Tests of the Phase II soil/chemical combinations, and each soil was selected to represent the potential range of effectiveness within each mineralogical grouping.

Partial air-dried, fresh specimens were molded at 20, 40, 60, 80, and 100% AASHTO T-99 compactive effort (5, 10, 15, 20, and 25 blows per layer) at OMC as determined from the M-D study of each treated or untreated soil. Continuous K-Tests were performed on each specimen thus prepared. Additional untreated and treated specimens were prepared at 100% AASHTO T-99 compaction and were wrapped, sealed, and stored for 7 days in a moist-cure room at near 72 °F and 100% relative humidity.

Table 41 presents laboratory compaction growth data, K-Test parameters, and ultimate bearing capacity of the untreated and chemically treated soils (a) immediately following molding, and (b) immediately following the 7-day moist curing. Ultimate bearing capacities of the compaction growth specimens were used to illustrate changes in the shear parameters, c and ϕ, and were calculated as $q_o = cN_c$, where c is the cohesion and N_c is the Terzaghi bearing capacity factor directly based on ϕ. This version of the Terzaghi equation was selected since it was assumed that (a) the footing being supported was a truck tire having an equivalent 1 sq ft of area and thus relegating the $\gamma B/2\ N_\gamma$ portion of the equation insignificant, and (b) the tire was supported at the surface, reducing the surcharge portion of the equation, $\gamma D_f\ N_q$, to zero. Density and q_o results presented in Table 41 are also graphed in Figs. 72 through 84, with average, as-molded moisture contents given on q_o curves.

Bearden Series. As noted in Fig. 72a, the compaction growth curves of the chemically treated Bearden series generally follow those of the untreated soil. Only the Clapak showed improvement in γ_d at 80% or better of standard compactive effort. Densities of the Claset- and Thinwater-treated Bearden specimens, after a 7-day moist curing, were nearly identical to those obtained immediately after compaction, thus indicating no change of γ_d during curing.

Moisture contents within each compactive effort sequence of the untreated and treated Bearden specimens were reasonably uniform as indicated from the standard deviation calculations in Table 41.

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*Initial moisture content of all soil series specimens was about 10% less than optimum. Initial moisture content variation of all specimens within an individual series was generally less than 1.0%.

Table 40. Soils and percentage chemical used in laboratory compaction growth study.

Soil Series	Dominant Clay Mineral	Chemical, % Dry Soil Weight							
		Clapak	Claset	Coherex	Petro-S	Thinwater	SC-518	SA-1	Road Packer
Bearden	Montmorillonite	0.10	0.10	-	-	0.001	-	-	-
Renohill	Montmorillonite	0.10	0.10	1.00	-	-	0.07	-	-
Pierre	Montmorillonite	-	-	-	1.40	-	-	-	0.035
Rimrock	Montmorillonite	-	-	-	1.40	-	-	-	-
Houston Black	Montmorillonite	-	-	-	-	-	-	0.07	-
Peavine	Montmorillonite	-	-	1.00	-	0.001	0.07	0.07	0.035
Marias	Montmorillonite	-	-	-	-	-	0.035	0.07	-
Frederick	Kaolinite	0.10	-	0.70	1.82	-	0.05	0.07	0.07
Persanti	Kaolinite	-	0.01	1.00	-	0.007	-	-	-
Melbourne	Vermiculite	-	0.07	-	0.70	-	-	0.07	-
Vergennes	Vermiculite-Illite	0.07	-	1.00	-	0.007	0.035	-	0.07
Nappanee	Vermiculite-Illite	0.01	0.07	1.00	-	-	-	-	-
Paulding	Vermiculite-Illite	-	-	-	1.40	-	0.035	0.07	-

Table 41. Laboratory compaction growth data, K-Test parameters, and ultimate bearing capacity of untreated and chemically treated soils.

Soil and Dominant Clay Mineral	Treatment and % Dry Soil Weight	Compactive Effort, % AASHTO T-99	Moisture Content, %	Dry Density, pcf	K-Test Parameters				
					K_i	ϕ, degrees	c, psi	E ($\times 10^3$), psi	q_o, psi
Bearden (Montmorillonite)	Water	20	20.0	89.8	0.230	37	3.9	2.0	288
		40	20.4	98.9	0.260	33	6.6	3.4	338
		60	20.2	102.2	0.290	30	7.5	4.1	275
		80	20.1	103.7	0.350	25	7.5	3.8	181
		100	20.0	104.2	0.440	22	0.9	3.5	18
			20.1 ± 0.2						
	Clapak 0.10%	20	17.1	90.0	0.250	35	2.7	1.8	164
		40	17.0	96.8	0.250	35	6.4	2.6	362
		60	16.8	100.4	0.240	34	8.1	4.0	444
		80	17.0	104.1	0.240	34	7.7	5.5	410
		100	17.6	106.1	0.250	35	2.9	5.7	201
			17.1 ± 0.3						
	Claset 0.10%	20	18.2	83.5	0.321	29	2.4	0.8	84
		40	17.8	90.0	0.297	30	4.7	1.5	190
		60	17.0	95.4	0.324	29	3.2	2.4	118
		80	17.8	97.4	0.471	30	7.5	3.3	289
		100	16.7	99.3	0.271	32	6.3	3.8	296
		100 (7 day)	17.4	99.6	0.276	31	8.7	2.8	361
			17.5 ± 0.6						
	Thinwater 0.001%	20	17.0	87.0	0.252	33	3.8	1.0	196
		40	17.4	92.0	0.249	32	5.2	1.7	246
		60	17.6	96.4	0.241	32	7.3	2.3	323
		80	18.2	100.3	0.223	34	7.8	4.0	409
		100	17.2	101.3	0.234	34	5.7	3.8	299
		100 (7 day)	18.0	101.1	0.248	34	7.2	2.8	378
			17.6 ± 0.5						
Renohill (Montmorillonite)	Water	20	20.8	78.3	0.336	29	1.0	0.3	35
		40	21.3	87.8	0.465	18	6.1	0.7	105
		60	21.2	95.0	0.518	14	7.3	1.1	98
		80	21.8	97.6	0.526	12	9.9	1.6	118
		100	21.4	98.1	0.514	11	11.4	2.0	133
		100 (7 day)	21.5	97.9	0.328	10	19.5	1.8	206
			21.3 ± 0.3						
	Claset 0.10%	20	22.6	73.7	0.645	11	1.0	0.2	11
		40	22.3	91.3	0.558	11	7.7	0.9	88
		60	21.9	94.9	0.556	11	9.0	1.2	102
		80	19.9	99.0	0.607	9	8.1	1.7	82
		100	23.8	95.8	0.574	10	7.8	1.4	84
		100 (7 day)	23.1	96.6	0.474	9	19.1	1.7	194
			22.3 ± 1.3						
	Coherex 1.00%	20	20.3	85.3	0.372	21	5.6	0.5	116
		40	20.9	90.3	0.368	20	7.2	0.8	136
		60	20.3	93.4	0.406	17	6.5	1.0	106
		80	20.7	96.3	0.431	14	7.7	1.4	103
		100	20.9	97.4	0.408	18	6.1	2.0	101
		100 (7 day)	20.8	97.7	0.337	12	16.0	1.8	197
			20.6 ± 0.3						
	SC-518 0.07%	20	19.8	81.4	0.312	25	3.0	0.4	82
		40	23.4	87.4	0.444	17	4.5	0.6	73
		60	23.0	94.7	0.520	10	5.4	1.2	59
		80	23.8	95.3	0.490	13	5.5	1.6	69
		100	23.2	97.2	0.614	9	7.6	2.3	78
		100 (7 day)	23.6	96.0	0.434	12	18.7	2.1	228
			23.4 ± 0.3						

Table 41. Laboratory compaction growth data, K-Test parameters, and ultimate bearing capacity of untreated and chemically treated soils (continued).

Soil and Dominant Clay Mineral	Treatment and % Dry Soil Weight	Compactive Effort, % AASHTO T-99	Moisture Content, %	Dry Density pcf	K-Test Parameters				
					K_i	ϕ, degrees	c, psi	E (× 10^3) psi	q_o, psi
Renohill (Montmorillonite) (continued)	Clapak 0.10%	20	22.8	77.0	0.294	28	3.2	0.3	104
		40	22.1	90.1	0.408	17	6.6	0.8	106
		60	21.8	92.7	0.419	15	7.4	1.4	107
		80	23.1	96.2	0.447	12	8.4	2.0	100
		100	22.5	97.9	0.457	12	7.1	2.2	85
		100 (7 day)	23.1	97.5	0.471	8	19.8	2.0	198
			22.6 ± 0.5						
Pierre (Montmorillonite)	Water	20	25.8	69.4	0.231	33	3.8	0.4	196
		40	25.9	75.8	0.304	30	2.9	0.6	111
		60	26.5	79.7	0.349	24	6.9	0.8	172
		80	25.9	84.9	0.397	19	12.7	1.2	227
		100	26.5	88.5	0.337	18	10.7	1.8	188
		100 (7 day)	26.2	88.5	0.405	15	17.4	1.4	248
			26.1 ± 0.3						
	Petro-S 1.40%	20	23.9	70.4	0.266	34	1.3	0.4	69
		40	24.5	77.2	0.302	26	6.2	0.6	185
		60	24.1	82.0	0.321	25	5.8	0.8	158
		80	24.9	86.1	0.328	21	9.4	1.0	190
		100	26.1	90.5	0.469	16	9.7	1.8	145
		100 (7 day)	24.4	88.8	0.365	20	15.4	1.4	291
			24.6 ± 0.8						
	Road Packer 0.035%	20	25.2	67.7	0.284	31	1.8	0.4	77
		40	26.2	77.3	0.364	23	8.2	0.6	194
		60	26.3	78.8	0.380	22	10.0	0.9	212
		80	26.5	82.3	0.414	20	7.6	1.0	150
		100	24.9	87.4	0.390	22	8.9	1.6	194
		100 (7 day)	24.8	88.2	0.285	20	14.6	1.5	282
			25.6 ± 0.8						
Rimrock (Montmorillonite)	Water	20	24.1	77.8	0.334	24	5.9	0.6	152
		40	22.4	87.7	0.383	20	8.8	0.9	173
		60	22.8	93.6	0.428	16	12.7	1.5	197
		80	23.2	93.8	0.411	19	10.1	1.7	185
		100	22.4	95.3	0.445	15	12.3	1.8	180
		100 (7 day)	22.6	95.6	0.417	15	16.3	1.4	234
			22.9 ± 0.6						
	Petro-S 1.40%	20	17.8	78.6	0.443	17	7.2	0.6	116
		40	18.1	87.0	0.537	11	10.8	1.0	120
		60	18.1	91.4	0.501	12	12.2	1.5	143
		80	17.6	95.7	0.494	11	14.6	2.2	165
		100	17.6	97.9	0.315	25	12.9	1.9	348
		100 (7 day)	16.3	96.7	0.514	10	14.6	1.8	155
			17.6 ± 0.7						
Houston Black (Montmorillonite)	Water	20	23.1	78.0	0.328	26	4.2	0.5	120
		40	23.2	85.4	0.410	20	9.4	1.0	178
		60	22.3	88.7	0.376	23	9.0	1.6	206
		80	22.9	93.4	0.458	19	5.3	2.0	95
		100	23.2	93.4	0.400	18	13.8	1.9	232
		100 (7 day)	22.8	95.2	0.396	11	24.1	2.2	282
			22.9 ± 0.3						

Table 41. Laboratory compaction growth data, K-Test parameters, and ultimate bearing capacity of untreated and chemically treated soils (continued).

Soil and Dominant Clay Mineral	Treatment and % Dry Soil Weight	Compactive Effort, % AASHTO T-99	Moisture Content, %	Dry Density, pcf	K-Test Parameters				
					K_i	φ, degrees	c, psi	E (× 10^3) psi	q_o, psi
Houston Black (Montmorillonite) (continued)	SA-1 0.07%	20	27.5	84.0	0.585	12	5.5	1.1	67
		40	26.8	90.3	0.589	11	7.4	1.3	82
		60	27.0	91.3	0.624	10	5.9	1.6	63
		80	26.4	92.6	0.572	9	10.3	1.9	106
		100	25.8	94.0	0.619	8	8.4	2.0	82
		100 (7 day)	25.5	94.8	0.526	10	12.8	2.1	136
			26.5 ± 0.8						
Peavine (Montmorillonite)	Water	20	46.3	61.2	0.336	26	3.4	0.6	100
		40	45.9	68.4	0.381	23	7.4	1.4	172
		60	45.9	70.4	0.372	22	10.1	2.2	223
		80	46.5	71.8	0.370	22	11.3	2.4	243
		100	45.1	72.8	0.361	24	9.2	2.9	229
		100 (7 day)	46.6	72.4	0.395	19	13.1	2.8	239
			46.0 ± 0.6						
	SA-1 0.07%	20	42.5	60.3	0.311	28	4.2	0.6	140
		40	42.6	65.3	0.410	22	4.2	1.0	95
		60	43.3	69.5	0.373	22	10.0	1.5	215
		80	42.9	71.0	0.367	22	10.4	1.9	231
		100	43.3	72.9	0.345	23	12.6	2.3	292
		100 (7 day)	42.0	73.8	0.329	22	17.6	2.3	379
			42.8 ± 0.5						
	SC-518 0.07%	20	40.8	60.8	0.358	25	5.4	0.6	149
		40	41.3	65.0	0.325	26	7.1	1.1	207
		60	40.0	67.5	0.328	25	10.5	1.4	289
		80	39.8	71.1	0.300	25	16.0	2.2	443
		100	39.5	70.9	0.319	25	13.5	2.0	356
		100 (7 day)	40.1	70.6	0.312	24	15.3	2.3	384
			40.2 ± 0.7						
	Thinwater 0.001%	20	39.5	59.5	0.291	30	3.8	0.7	153
		40	39.7	64.2	0.313	27	9.1	1.2	283
		60	39.6	65.9	0.318	27	9.8	1.4	298
		80	38.7	69.5	0.298	26	14.0	1.8	411
		100	39.6	70.6	0.293	25	16.2	2.1	449
		100 (7 day)	38.6	70.2	0.245	24	16.3	1.7	396
			39.3 ± 0.5						
	Coherex 1.00%	20	37.7	58.8	0.279	32	3.9	0.7	173
		40	38.2	64.5	0.313	29	4.6	1.2	170
		60	37.7	66.2	0.319	27	9.0	1.4	274
		80	37.1	67.8	0.291	29	10.1	1.7	355
		100	37.1	70.0	0.296	27	15.0	2.0	467
		100 (7 day)	37.4	69.7	0.241	22	18.1	1.6	405
			37.5 ± 0.4						
	Road Packer 0.035%	20	43.6	62.1	0.331	28	3.1	0.7	100
		40	44.1	66.9	0.340	25	9.0	1.4	242
		60	45.5	70.1	0.333	26	9.5	2.0	265
		80	44.0	71.1	0.321	25	12.8	2.3	345
		100	43.6	72.8	0.333	23	14.3	2.8	336
		100 (7 day)	43.9	72.4	0.253	24	14.0	2.3	364
			44.7 ± 0.7						

Table 41. Laboratory compaction growth data, K-Test parameters, and ultimate bearing capacity of untreated and chemically treated soils (continued).

Soil and Dominant Clay Mineral	Treatment and % Dry Soil Weight	Compactive Effort, % AASHTO T-99	Moisture Content, %	Dry Density, pcf	K-Test Parameters				
					K_i	φ, degrees	c, psi	E (× 10^3), psi	q_o, psi
Marias (Montmorillonite)	Water	20	25.4	79.6	0.400	21	4.8	0.5	97
		40	25.6	86.7	0.532	15	5.5	0.8	79
		60	25.4	90.7	0.562	11	7.6	1.0	88
		80	24.3	95.2	0.558	10	10.5	1.6	111
		100	25.5	94.6	0.558	10	9.6	1.6	106
		100 (7 day)	26.1	95.0	0.558	9	10.8	2.2	114
			25.4 ± 0.6						
	SA-1 0.07%	20	19.7	76.1	0.249	33	5.0	0.6	256
		40	20.0	83.9	0.330	26	9.1	0.9	260
		60	20.7	88.3	0.349	25	8.3	1.1	220
		80	20.5	92.0	0.347	22	12.7	1.4	284
		100	20.7	93.7	0.353	21	14.3	1.7	294
		100 (7 day)	19.2	92.3	0.307	24	17.4	1.6	428
			20.1 ± 0.6						
	SC-518 0.035%	20	19.2	76.2	0.254	34	3.3	0.6	178
		40	19.7	82.0	0.294	29	7.4	0.8	266
		60	20.2	83.8	0.319	27	9.0	1.0	274
		80	19.6	90.7	0.346	23	11.9	1.2	281
		100	17.3	93.1	0.299	26	14.6	1.7	419
		100 (7 day)	19.4	93.4	0.335	21	17.8	1.6	364
			19.2 ± 1.0						
Frederick (Kaolinite)	Water	20	25.3	75.3	0.284	32	2.9	0.8	128
		40	23.9	80.3	0.267	34	2.4	1.3	134
		60	24.3	85.4	0.256	32	8.4	1.9	388
		80	24.1	86.5	0.270	31	8.6	2.2	281
		100	24.6	90.1	0.268	31	9.3	2.7	395
		100 (7 day)	25.2	89.5	0.303	26	12.6	2.6	373
			24.6 ± 0.6						
	Coherex 0.70%	20	21.9	72.8	0.210	38	4.3	1.0	347
		40	22.7	78.2	0.236	35	7.0	1.2	409
		60	22.6	83.0	0.252	32	10.4	1.6	472
		80	23.4	85.8	0.271	29	11.5	2.0	430
		100	21.2	88.6	0.253	30	13.4	2.5	538
		100 (7 day)	23.1	86.6	0.227	32	15.9	2.0	710
			22.5 ± 0.8						
	SC-518 0.05%	20	24.6	75.5	0.256	33	4.2	0.8	211
		40	24.8	83.1	0.274	33	4.2	1.3	211
		60	25.0	88.3	0.290	29	8.6	1.8	321
		80	25.4	92.6	0.290	29	8.6	2.8	321
		100	25.6	93.0	0.298	29	9.1	3.5	324
		100 (7 day)	25.4	94.4	0.287	26	16.8	3.1	486
			25.1 ± 0.4						
	SA-1 0.14%	20	24.5	75.5	0.282	27	7.6	0.9	240
		40	21.8	80.6	0.277	33	4.7	1.2	228
		60	23.3	87.1	0.292	30	8.7	1.6	330
		80	23.7	89.8	0.295	30	6.3	1.9	251
		100	24.9	94.5	0.395	24	4.5	1.9	115
		100 (7 day)	24.1	96.7	0.349	24	11.2	2.7	276
			23.7 ± 1.1						
	Petro-S 1.82%	20	22.0	75.5	0.232	36	2.8	0.6	176
		40	23.8	81.9	0.304	30	5.5	1.1	209
		60	23.8	89.4	0.373	24	6.9	1.4	172
		80	23.0	90.4	0.307	28	8.6	1.8	293
		100	23.2	92.9	0.313	27	9.1	2.3	292
		100 (7 day)	23.6	95.6	0.324	24	14.2	2.5	357
			23.2 ± 0.7						

Table 41. Laboratory compaction growth data, K-Test parameters, and ultimate bearing capacity of untreated and chemically treated soils (continued).

Soil and Dominant Clay Mineral	Treatment and % Dry Soil Weight	Compactive Effort, % AASHTO T-99	Moisture Content, %	Dry Density, pcf	K-Test Parameters				
					K_i	ϕ, degrees	c, psi	E ($\times 10^3$) psi	q_o, psi
Frederick (Kaolinite)	Clapak 0.10%	20	27.2	76.6	0.373	33	-1.2	0.5	-
		40	27.4	84.5	0.400	23	6.0	1.1	142
		60	26.2	89.0	0.394	22	8.3	1.5	180
		80	27.8	92.8	0.482	16	8.8	2.4	131
		100	26.1	95.0	0.359	25	7.9	2.3	207
		100 (7 day)	25.5	93.9	0.356	23	10.8	2.9	259
			26.7 ± 0.9						
	Road Packer 0.07%	20	27.2	76.4	0.297	32	1.6	0.7	74
		40	27.2	87.7	0.382	25	3.8	1.6	102
		60	26.7	87.3	0.363	24	7.3	1.9	190
		80	27.4	90.3	0.363	25	6.3	2.5	167
		100	27.0	90.9	0.362	25	6.8	2.7	179
		100 (7 day)	26.8	91.1	0.336	24	11.2	2.6	287
			27.0 ± 0.3						
Persanti (Kaolinite)	Water	20	25.0	77.8	0.271	33	2.8	0.7	107
		40	25.3	86.0	0.347	25	6.8	1.4	188
		60	24.9	87.8	0.343	26	6.6	1.3	187
		80	24.7	93.4	0.346	24	9.5	2.3	242
		100	25.8	94.0	0.320	26	11.0	2.8	307
		100 (7 day)	26.8	93.4	0.355	21	14.9	2.4	301
			25.4 ± 0.8						
	Claset 0.01%	20	26.1	77.7	0.263	33	3.8	0.7	188
		40	26.7	84.4	0.319	28	6.8	1.2	237
		60	26.4	91.0	0.346	25	9.3	1.9	247
		80	25.7	91.9	0.370	28	9.6	2.2	315
		100	26.3	94.2	0.362	24	7.6	2.8	191
		100 (7 day)	26.9	94.0	0.399	19	12.0	2.8	217
			26.4 ± 0.4						
	Thinwater 0.007%	20	23.0	77.9	0.254	34	3.7	0.8	205
		40	24.3	83.8	0.329	28	5.4	1.1	176
		60	24.1	88.1	0.324	26	8.7	1.5	261
		80	24.6	91.5	0.313	27	10.3	2.1	311
		100	24.4	93.4	0.308	25	13.9	2.9	380
		100 (7 day)	25.1	92.9	0.289	25	18.4	2.6	496
			24.2 ± 0.7						
	Coherex 1.00%	20	23.9	76.9	0.262	33	3.3	0.7	172
		40	23.5	84.3	0.310	29	6.7	1.2	235
		60	23.4	87.5	0.312	28	7.9	1.5	259
		80	23.9	90.3	0.312	28	8.4	1.9	280
		100	23.5	93.5	0.298	27	12.2	2.3	388
		100 (7 day)	23.6	92.9	0.324	22	17.1	2.2	378
			23.6 ± 0.2						
Melbourne (Vermiculite)	Water	20	30.3	75.3	0.420	28	4.9	0.7	168
		40	30.6	80.8	0.396	22	8.1	1.2	174
		60	31.0	84.8	0.419	21	7.2	1.8	147
		80	31.0	86.2	0.421	20	7.5	2.3	149
		100	31.1	86.1	0.422	19	9.3	2.6	170
		100 (7 day)	31.0	86.7	0.440	15	12.9	2.3	188
			30.8 ± 0.3						
	Claset 0.07%	20	29.5	74.1	0.293	30	3.8	0.7	147
		40	29.9	80.4	0.357	23	11.4	1.3	262
		60	28.6	84.0	0.357	22	12.1	1.4	271
		80	30.2	83.6	0.363	22	10.8	1.5	243
		100	29.5	87.1	0.382	22	8.8	1.6	196
		100 (7 day)	30.2	87.0	0.382	21	11.6	2.2	234
			29.7 ± 0.6						

Table 41. Laboratory compaction growth data, K-Test parameters, and ultimate bearing capacity of untreated and chemically treated soils (continued).

Soil and Dominant Clay Mineral	Treatment and % Dry Soil Weight	Compactive Effort, % AASHTO T-99	Moisture Content, %	Dry Density, pcf	K-Test Parameters				
					K_i	ϕ, degrees	c, psi	E ($\times 10^3$) psi	q_o, psi
Melbourne (Vermiculite) (continued)	SA-1 0.07%	20	23.2	68.9	0.252	34	2.6	0.7	149
		40	22.7	74.4	0.256	33	5.4	1.0	271
		60	22.6	77.2	0.266	31	9.5	1.3	397
		80	22.3	80.7	0.234	33	11.8	1.6	598
		100	22.5	83.2	0.234	33	12.0	2.1	603
		100 (7 day)	22.6	83.2	0.230	31	15.3	2.1	661
			22.6 ± 0.3						
	Petro-S 0.70%	20	26.1	72.1	0.258	32	5.0	0.6	227
		40	26.1	77.4	0.298	30	4.8	0.9	194
		60	26.4	82.5	0.301	28	10.0	1.4	338
		80	26.2	85.0	0.296	27	12.7	1.7	395
		100	25.9	87.1	0.290	29	10.8	1.7	382
		100 (7 day)	26.3	86.9	0.313	24	16.2	1.9	393
			26.2 ± 0.2						
Vergennes (Vermiculite-Illite)	Water	20	22.1	82.3	0.247	33	5.5	0.8	284
		40	21.3	89.2	0.252	34	5.9	1.3	318
		60	21.8	94.0	0.301	29	8.7	1.6	308
		80	21.9	96.2	0.307	28	8.0	2.0	273
		100	22.2	100.7	0.397	22	8.5	2.4	183
		100 (7 day)	22.1	99.9	0.313	25	15.2	2.6	401
			21.9 ± 0.3						
	Coherex 1.00%	20	20.9	82.3	0.257	33	4.3	0.8	220
		40	23.0	86.0	0.317	28	7.6	1.2	263
		60	22.7	92.7	0.319	27	10.4	1.7	317
		80	22.0	97.3	0.333	25	11.4	2.0	303
		100	22.0	99.1	0.347	22	15.2	2.5	331
		100 (7 day)	22.0	98.2	0.319	25	13.2	2.3	363
			22.1 ± 0.7						
	Thinwater 0.007%	20	21.8	79.3	0.335	34	6.7	0.8	358
		40	21.1	88.0	0.239	33	9.4	1.5	489
		60	21.1	92.3	0.248	33	10.5	1.7	523
		80	20.5	94.2	0.249	32	10.6	2.2	497
		100	21.0	98.0	0.248	30	14.1	2.9	561
		100 (7 day)	21.8	98.1	0.287	27	15.4	2.7	479
			21.2 ± 0.5						
	SC-518 0.035%	20	20.8	83.9	0.239	34	5.0	0.8	282
		40	22.1	88.2	0.272	31	7.4	1.3	322
		60	21.6	94.2	0.264	30	11.3	2.0	450
		80	21.5	97.8	0.269	31	10.2	2.5	419
		100	21.4	99.7	0.291	28	11.4	2.7	388
		100 (7 day)	21.0	100.5	0.286	27	15.0	3.0	467
			21.4 ± 0.5						
	Road Packer 0.07%	20	22.3	88.6	0.452	16	7.3	0.9	112
		40	22.8	95.1	0.518	13	9.6	1.2	122
		60	22.4	98.3	0.546	11	9.5	1.6	108
		80	22.9	96.8	0.322	25	13.1	2.3	350
		100	23.0	99.3	0.375	22	9.9	2.9	222
		100 (7 day)	22.6	101.4	0.614	8	8.0	2.3	80
			22.7 ± 0.3						
	Clapak 0.07%	20	21.6	83.7	0.233	33	7.2	0.8	368
		40	23.7	89.3	0.328	26	12.1	0.9	348
		60	24.2	94.7	0.374	20	13.9	1.7	275
		80	24.8	96.5	0.435	19	8.0	2.0	148
		100	23.5	99.3	0.400	17	15.6	2.7	256
		100 (7 day)	25.4	97.3	0.389	18	13.6	2.6	226
			23.9 ± 1.3						

Table 41. Laboratory compaction growth data, K-Test parameters, and ultimiate bearing capacity of untreated and chemically treated soils (continued).

Soil and Dominant Clay Mineral	Treatment and % Dry Soil Weight	Compactive Effort, % AASHTO T-99	Moisture Content, %	Dry Density, pcf	K-Test Parameters				
					K_i	ϕ, degrees	c, psi	E (× 10^3) psi	q_o, psi
Nappanee (Vermiculite-Illite)	Water	20	18.4	79.6	0.285	32	2.2	0.4	102
		40	17.7	88.3	0.308	30	4.1	0.8	156
		60	17.2	96.3	0.324	27	8.0	1.3	245
		80	18.2	97.7	0.340	24	10.9	1.6	272
		100	17.9	99.6	0.336	25	9.9	1.8	267
		100 (7 day)	17.4	99.1	0.301	24	16.6	2.0	432
			17.8 ± 0.5						
	Claset 0.07%	20	18.7	84.9	0.320	29	2.9	0.6	105
		40	20.4	91.4	0.410	23	4.0	0.9	93
		60	19.5	96.7	0.429	20	6.2	1.2	123
		80	20.2	98.3	0.420	20	7.4	1.4	144
		100	19.4	102.9	0.381	21	10.5	2.0	217
		100 (7 day)	19.1	102.2	0.436	16	10.6	1.7	164
			19.6 ± 0.6						
	Clapak 0.01%	20	19.4	85.9	0.342	25	4.7	0.6	130
		40	18.9	94.6	0.409	21	7.2	1.0	149
		60	19.1	100.9	0.439	18	9.1	1.4	154
		80	19.1	103.4	0.462	18	7.3	1.8	121
		100	18.8	104.8	0.503	14	8.1	2.1	110
		100 (7 day)	20.4	102.8	0.469	14	10.7	1.8	148
			19.3 ± 0.6						
	Coherex 1.00%	20	18.7	85.9	0.351	27	1.6	0.5	51
		40	18.8	93.0	0.387	23	6.5	0.9	153
		60	19.1	98.0	0.382	22	7.3	1.2	165
		80	18.4	99.8	0.376	23	8.5	1.4	196
		100	16.8	104.6	0.340	23	12.5	2.2	299
		100 (7 day)	17.6	105.2	0.355	18	18.8	2.4	328
			18.2 ± 0.9						
Paulding (Vermiculite-Illite)	Water	20	32.0	78.3	0.55	14	3.0	0.5	40
		40	30.0	86.1	0.70	7	4.3	1.1	41
		60	28.6	90.6	0.73	6	4.5	1.5	40
		80	30.8	90.0	0.73	7	2.9	1.7	27
		100	30.0	90.7	0.73	5	4.8	2.1	41
		100 (7 day)	30.5	90.4	0.73	3	7.4	2.2	57
			30.3 ± 1.1						
	Petro-S 1.40%	20	29.4	78.5	0.485	19	1.8	0.5	32
		40	27.8	87.5	0.672	9	3.9	0.8	40
		60	28.3	89.4	0.619	12	3.9	1.1	35
		80	27.5	91.4	0.632	8	7.6	1.4	73
		100	28.6	92.2	0.639	9	5.9	2.1	61
		100 (7 day)	28.2	92.9	0.702	5	6.2	2.0	53
			28.3 ± 0.7						
	SC-518 0.035%	20	26.3	80.4	0.457	21	1.0	0.4	21
		40	26.2	84.0	0.539	16	3.6	0.7	54
		60	27.3	82.2	0.566	12	5.9	1.0	73
		80	25.4	93.2	0.594	10	7.4	1.6	80
		100	26.9	93.5	0.574	10	8.7	1.8	93
		100 (7 day)	25.9	93.8	0.558	9	11.0	1.7	113
			26.3 ± 0.7						
	SA-1 0.07%	20	24.7	70.4	0.332	29	0.5	0.4	19
		40	23.9	81.1	0.338	26	5.7	0.7	167
		60	24.8	84.8	0.465	18	5.6	0.7	95
		80	24.5	89.3	0.471	15	9.1	1.1	132
		100	23.7	91.0	0.471	15	10.4	1.5	145
		100 (7 day)	23.4	92.1	0.399	18	14.1	1.4	233
			24.2 ± 0.6						

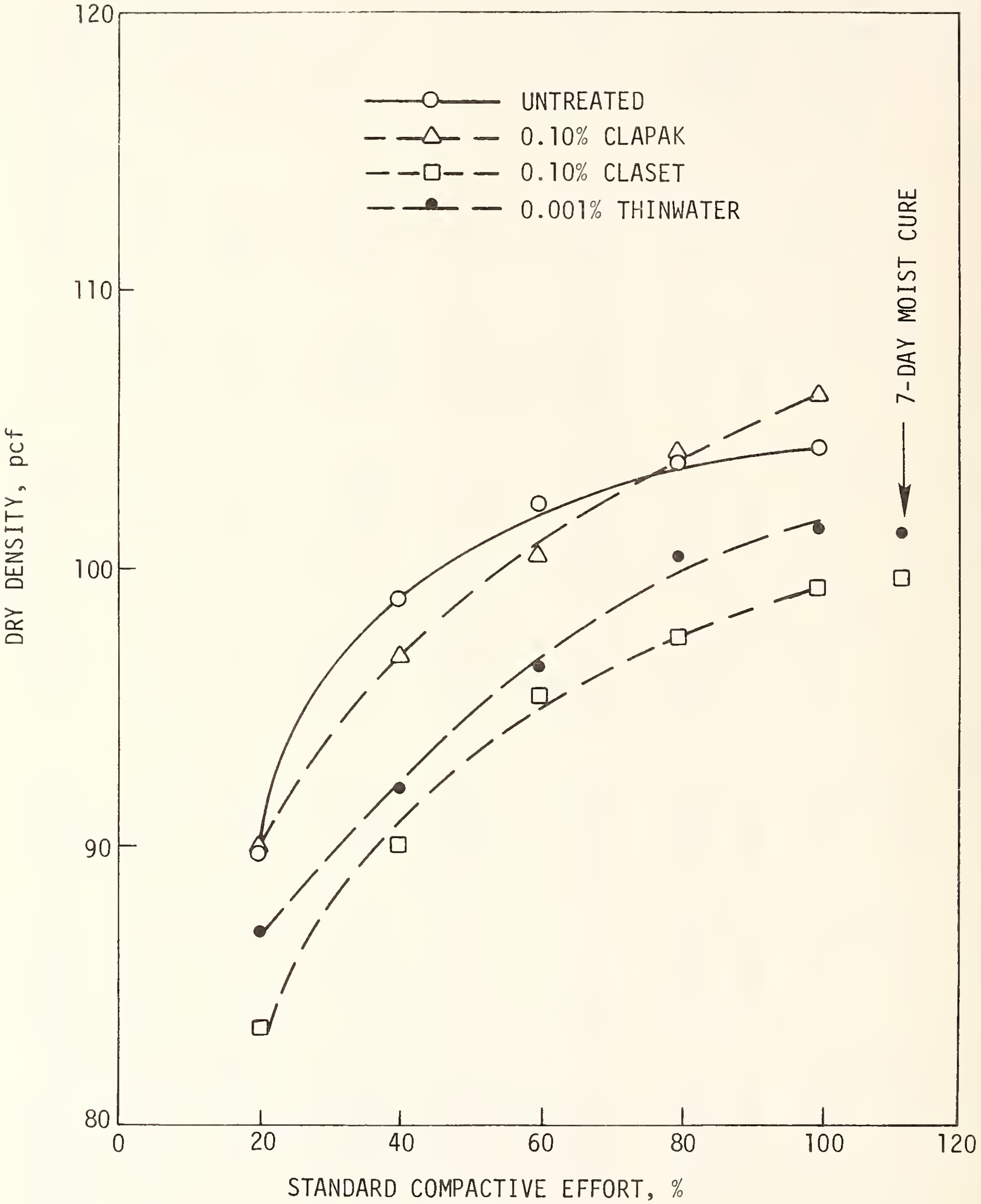

Fig. 72.(a) Compaction growth, Bearden series.

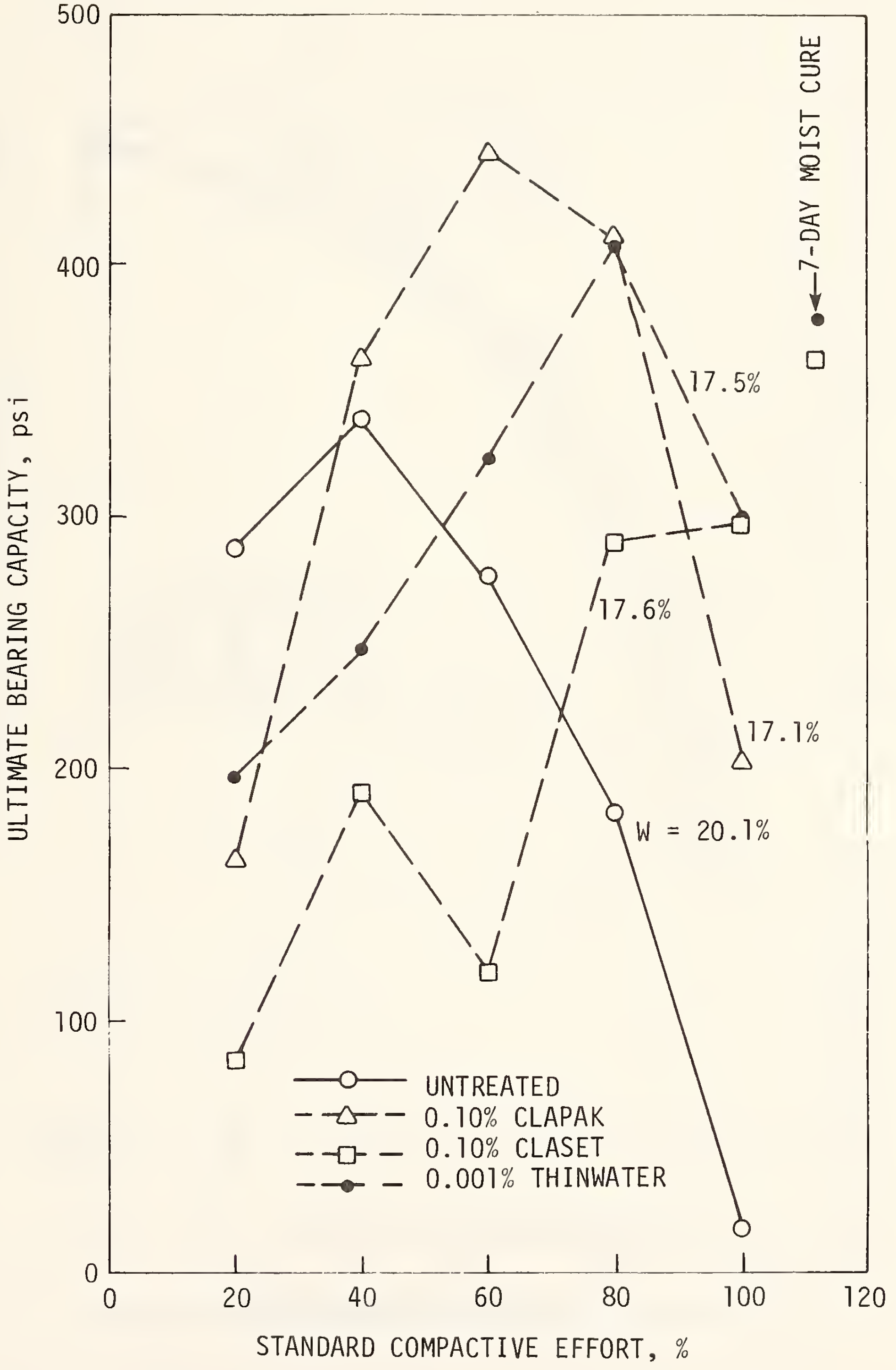

Fig. 72.(b) Ultimate bearing capacity growth, Bearden series.

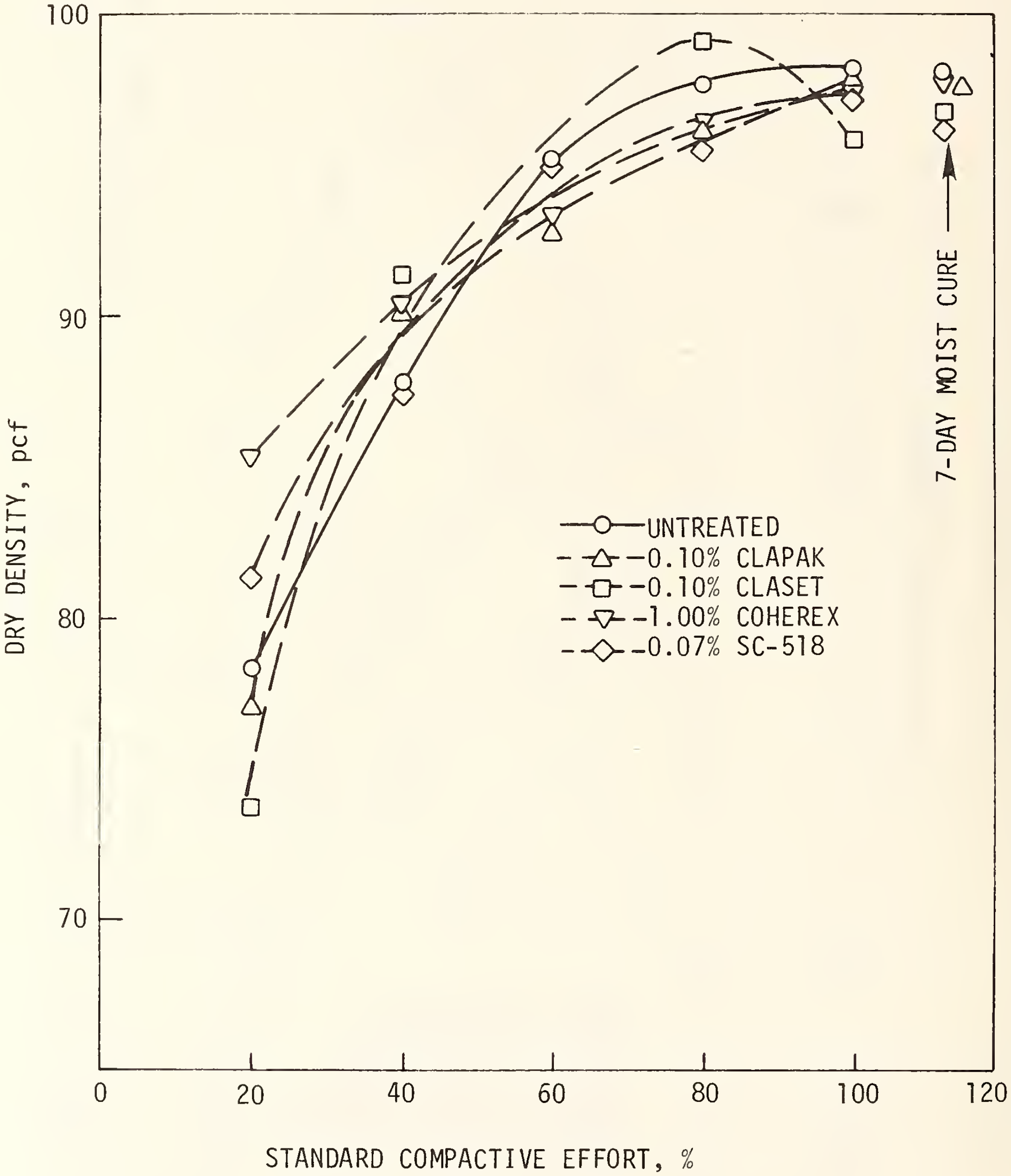

Fig. 73.(a) Compaction growth, Renohill series.

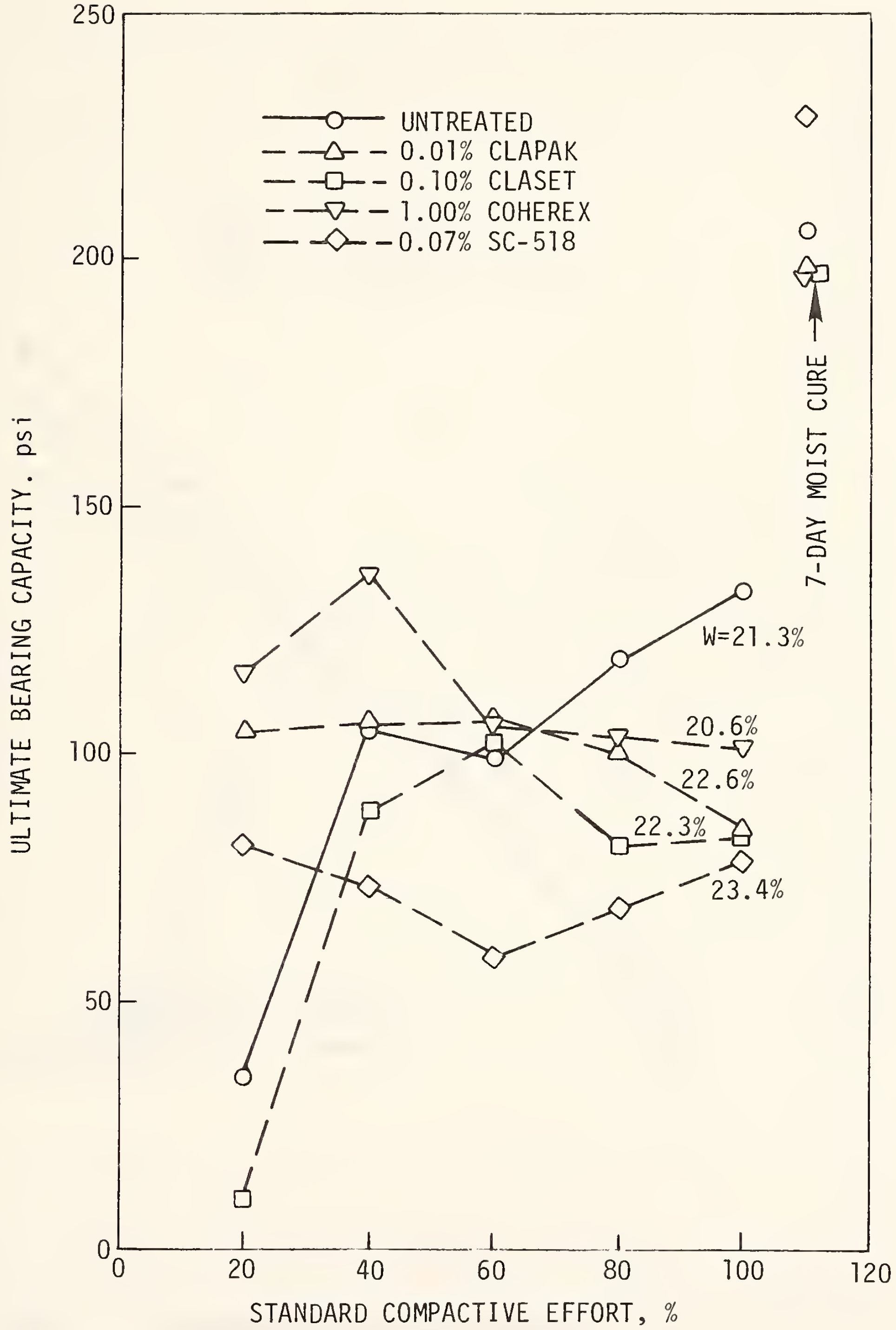

Fig. 73.(b) Ultimate bearing capacity growth, Renohill series.

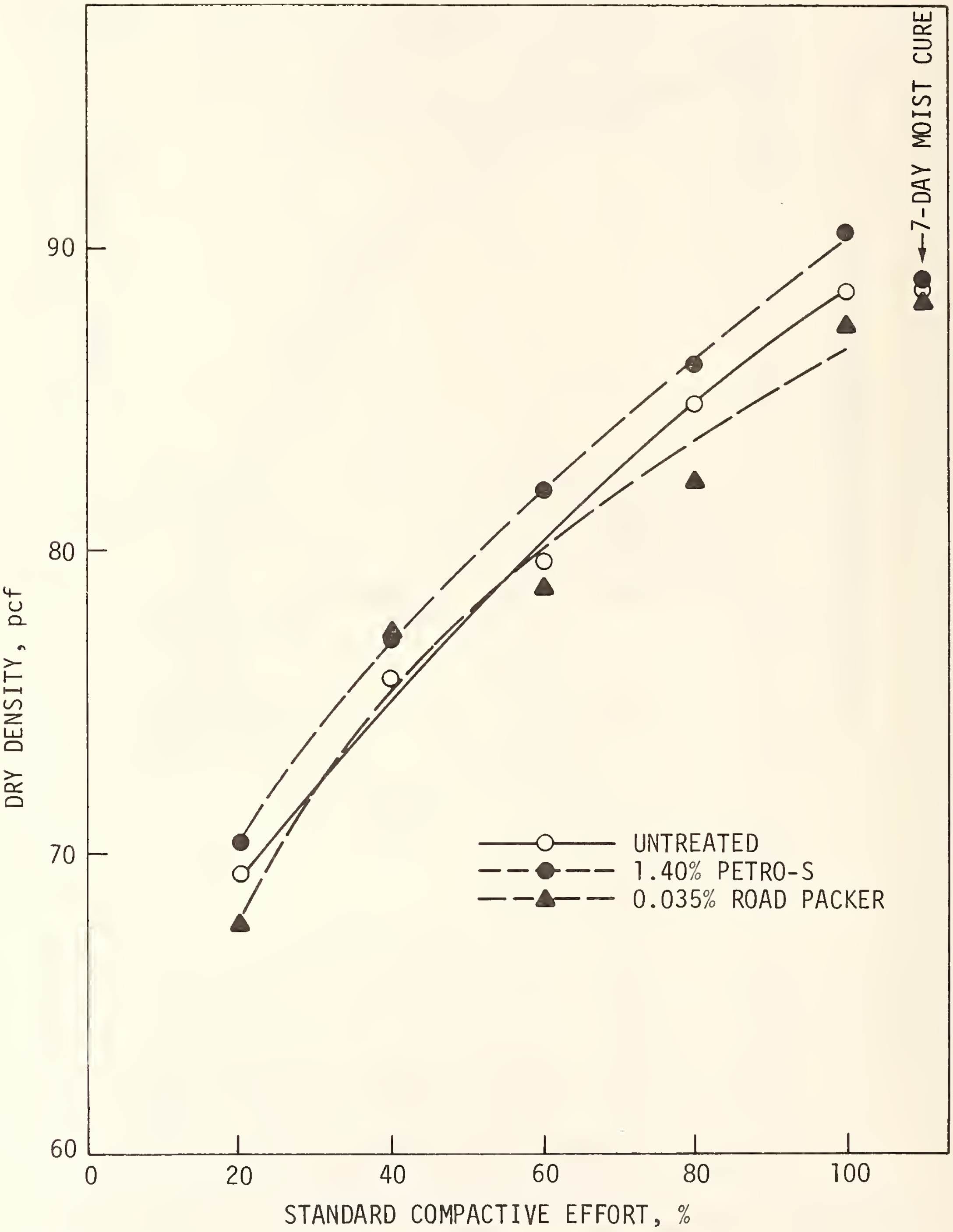

Fig. 74. (a) Compaction growth, Pierre series.

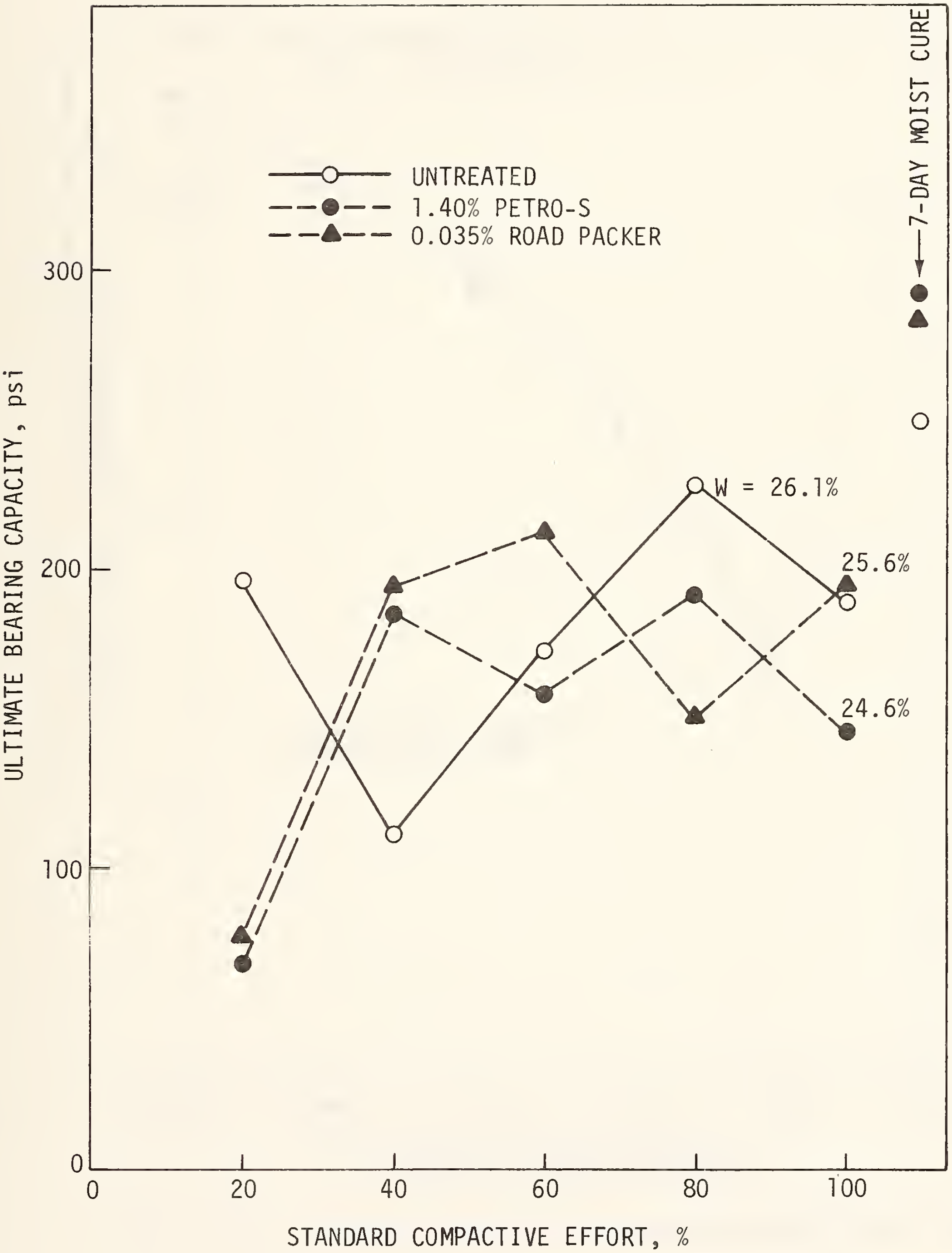

Fig. 74.(b) Ultimate bearing capacity growth, Pierre series.

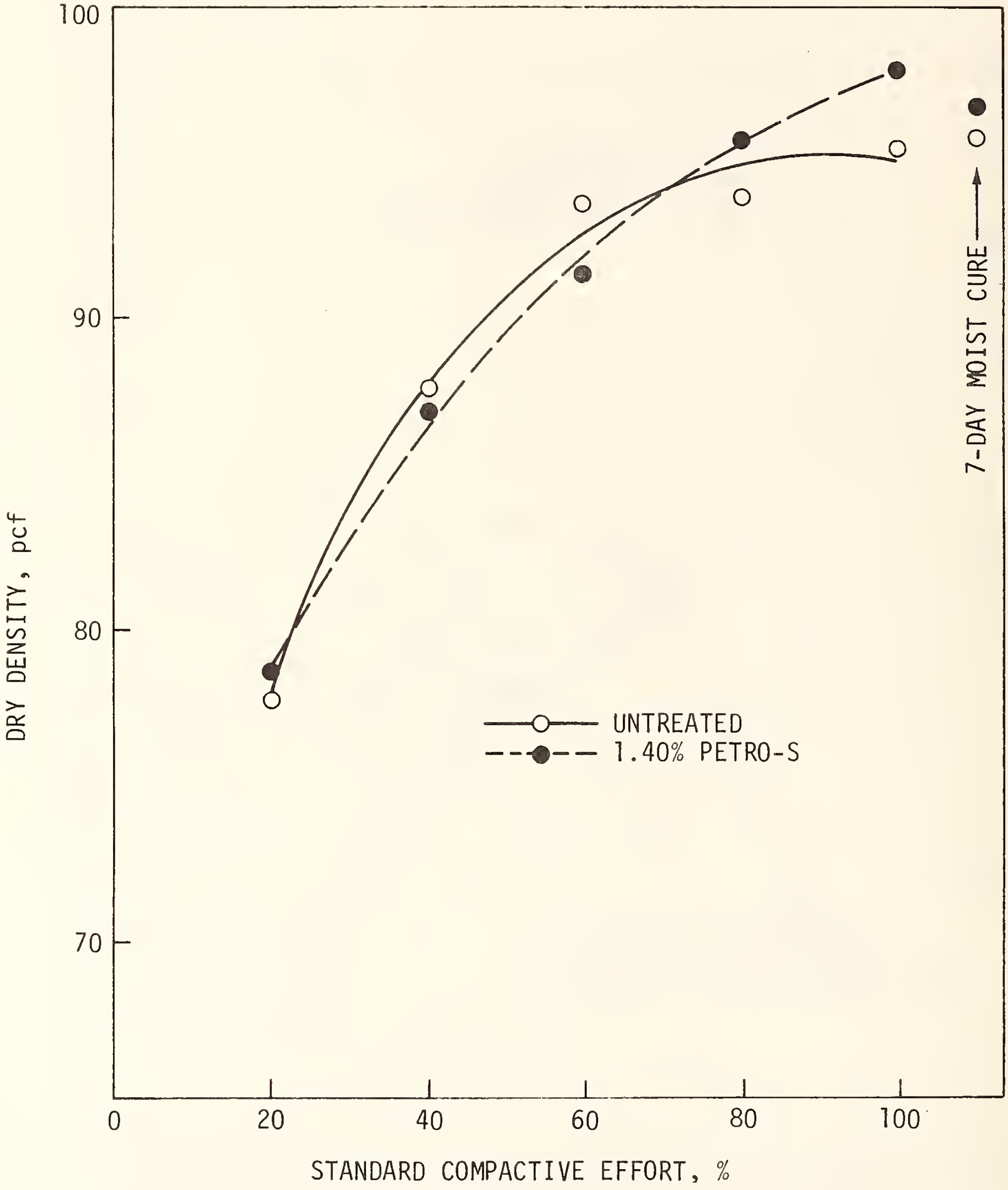

Fig. 75.(a) Compaction growth, Rimrock series.

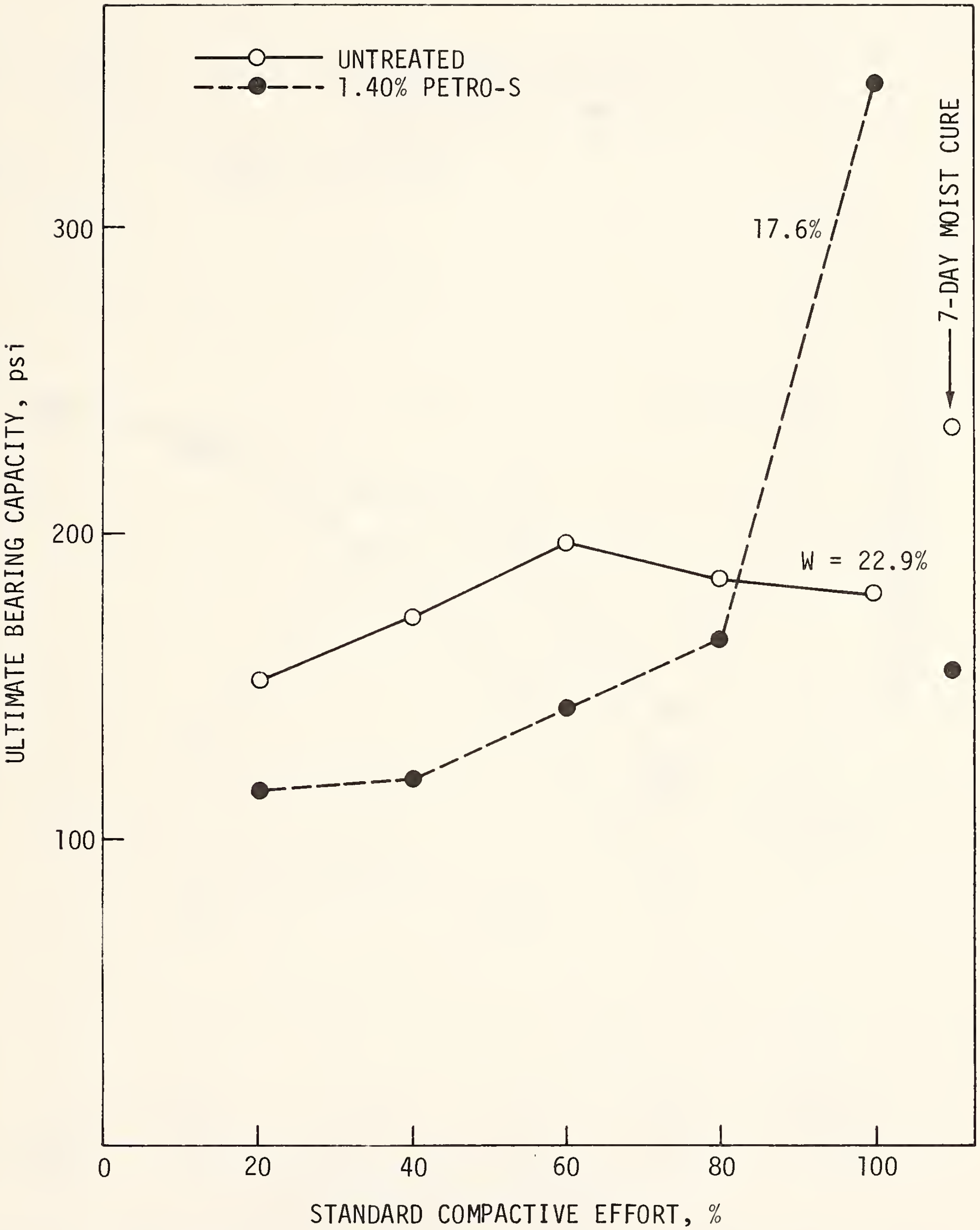

Fig. 75.(b) Ultimate bearing capacity growth, Rimrock series.

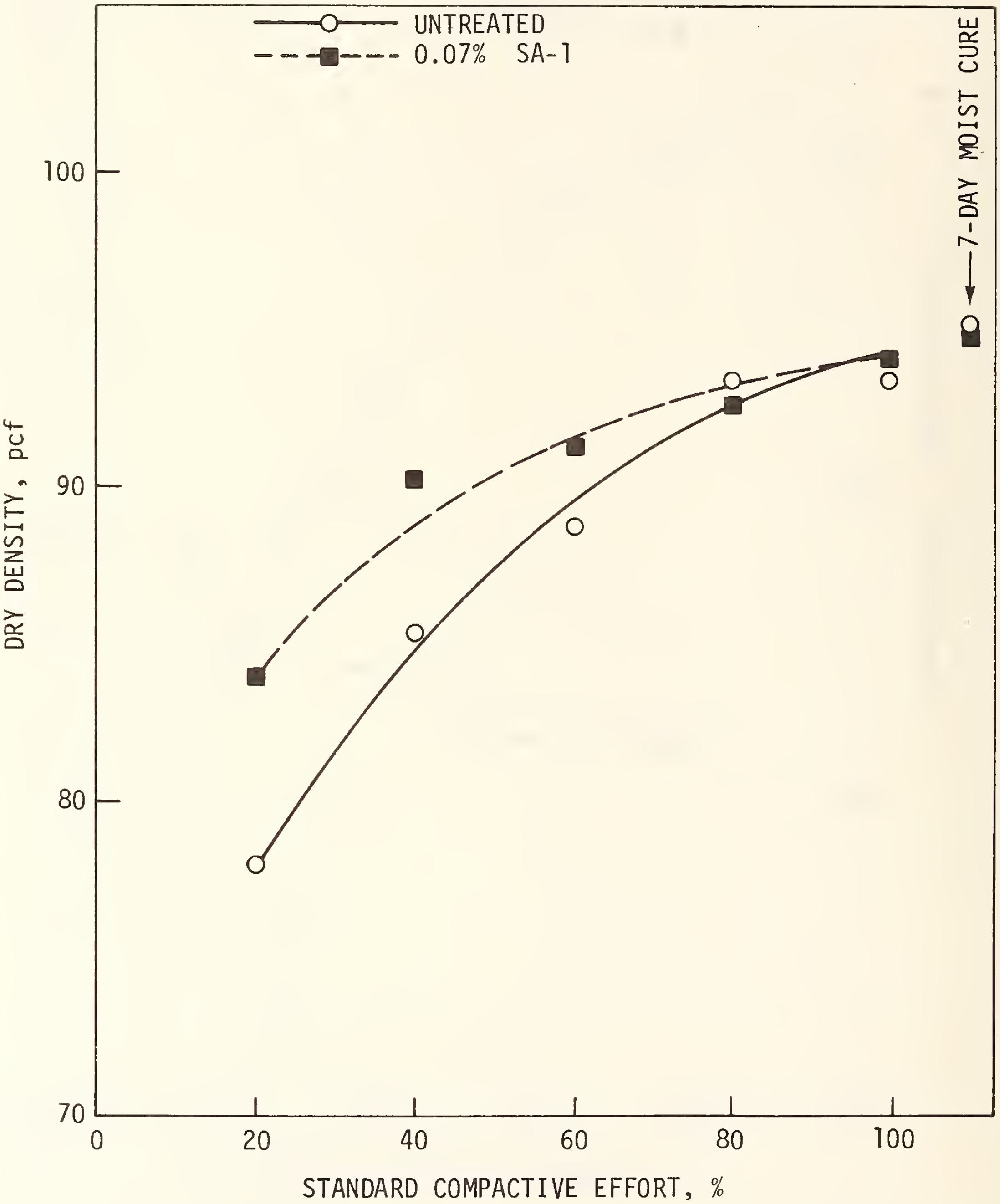

Fig. 76. (a) Compaction growth, Houston Black series.

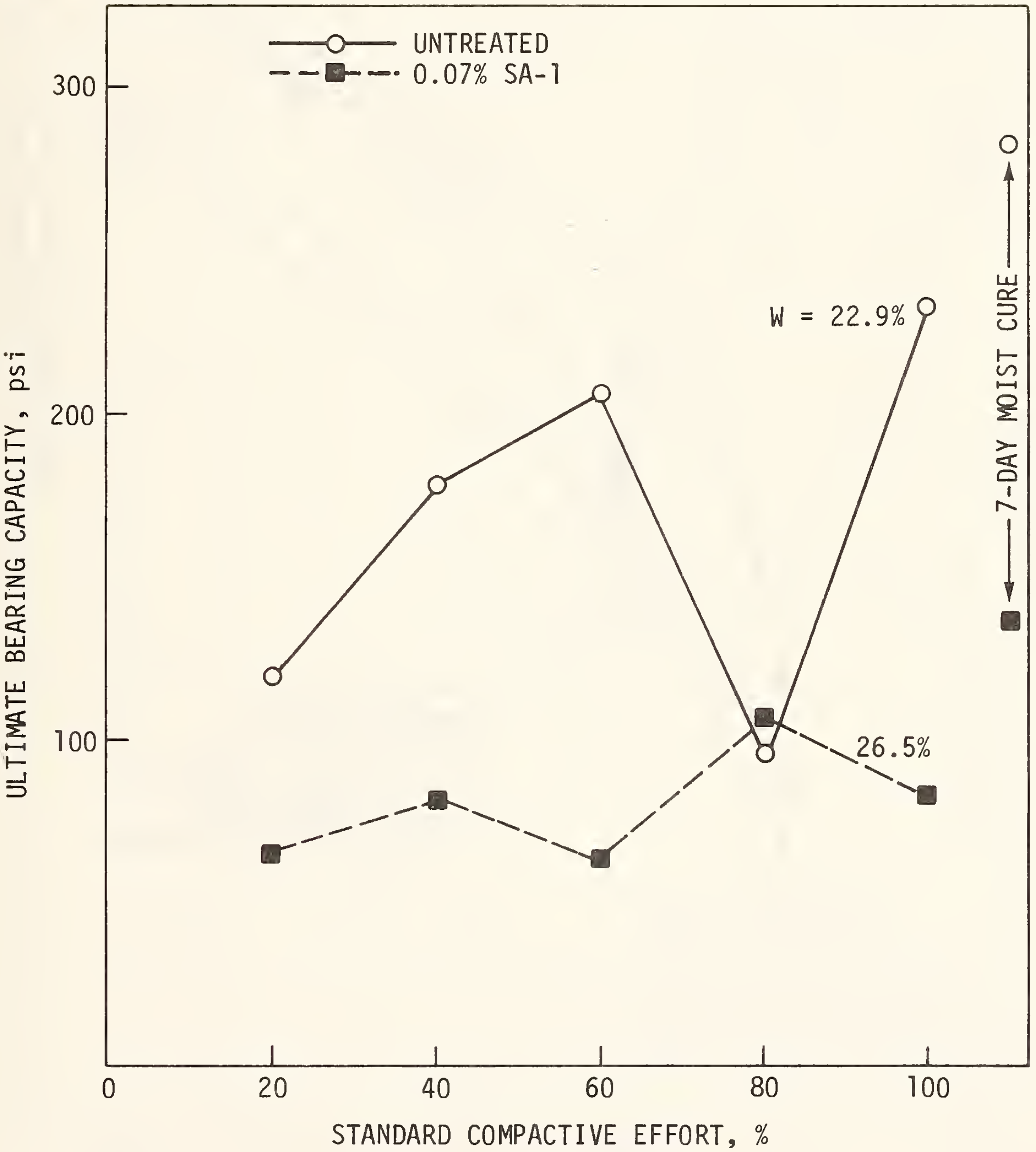

Fig. 76. (b) Ultimate bearing capacity growth, Houston Black series.

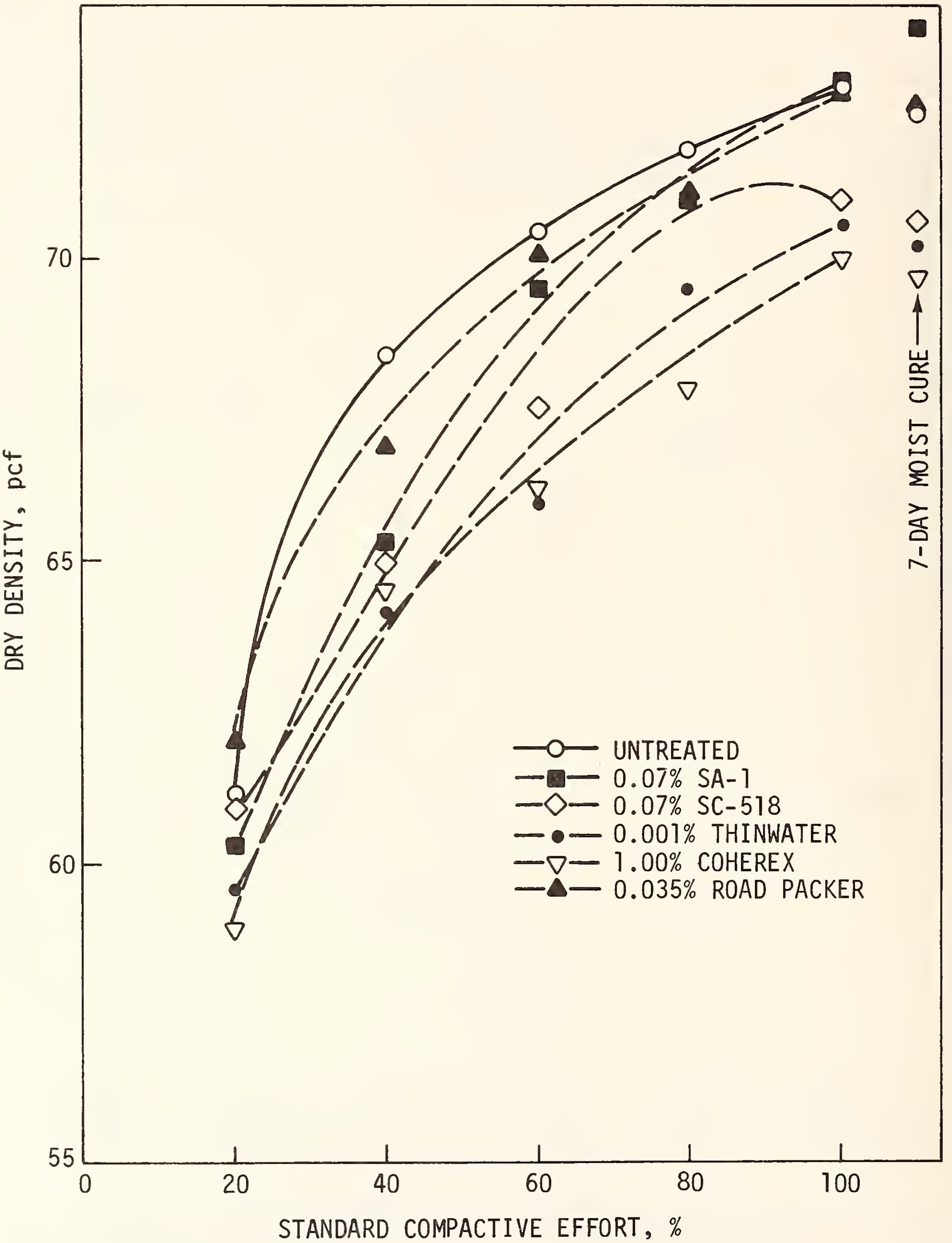

Fig. 77. (a) Compaction growth, Peavine series.

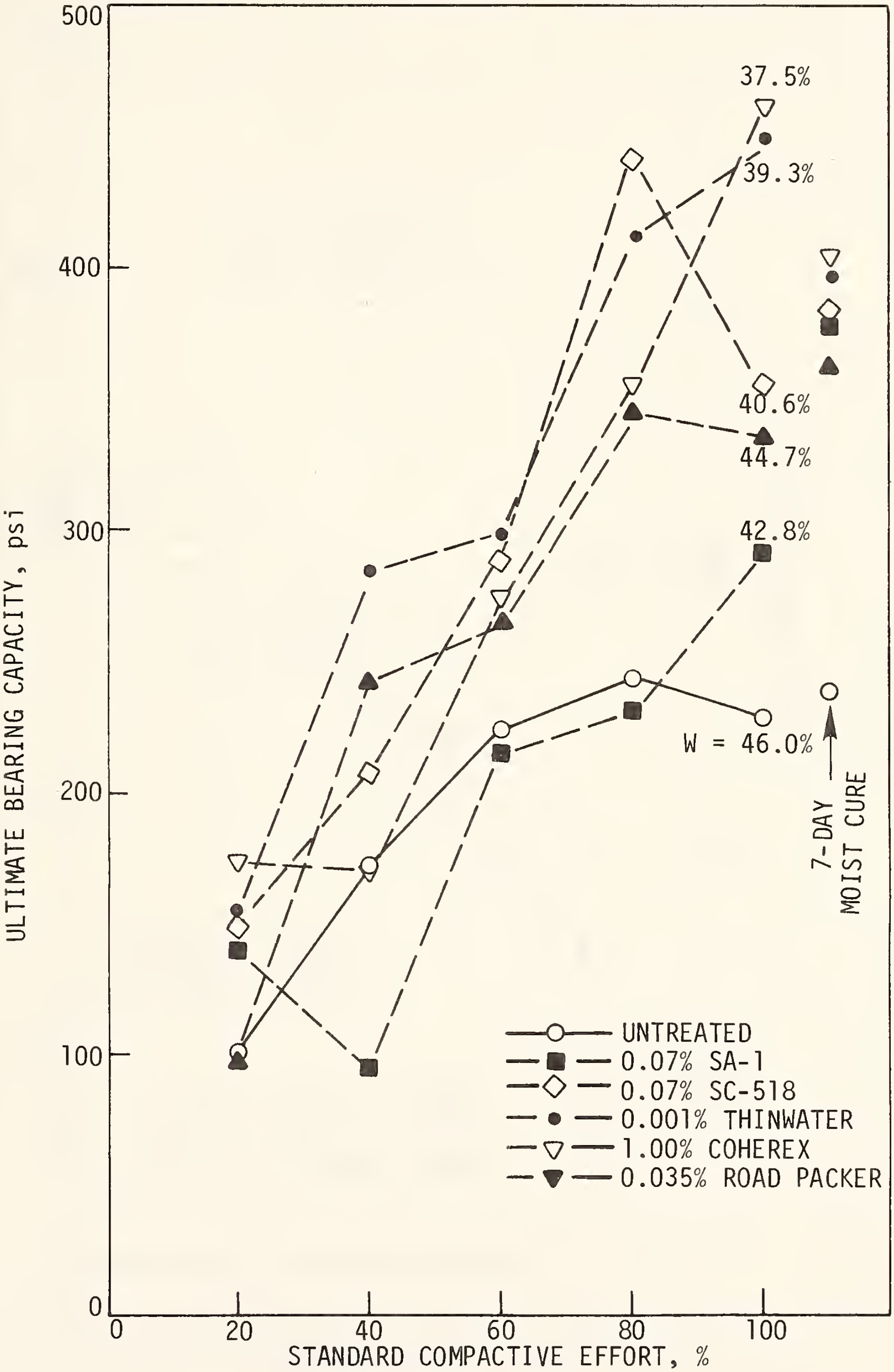

Fig. 77. (b) Ultimate bearing capacity growth, Peavine series.

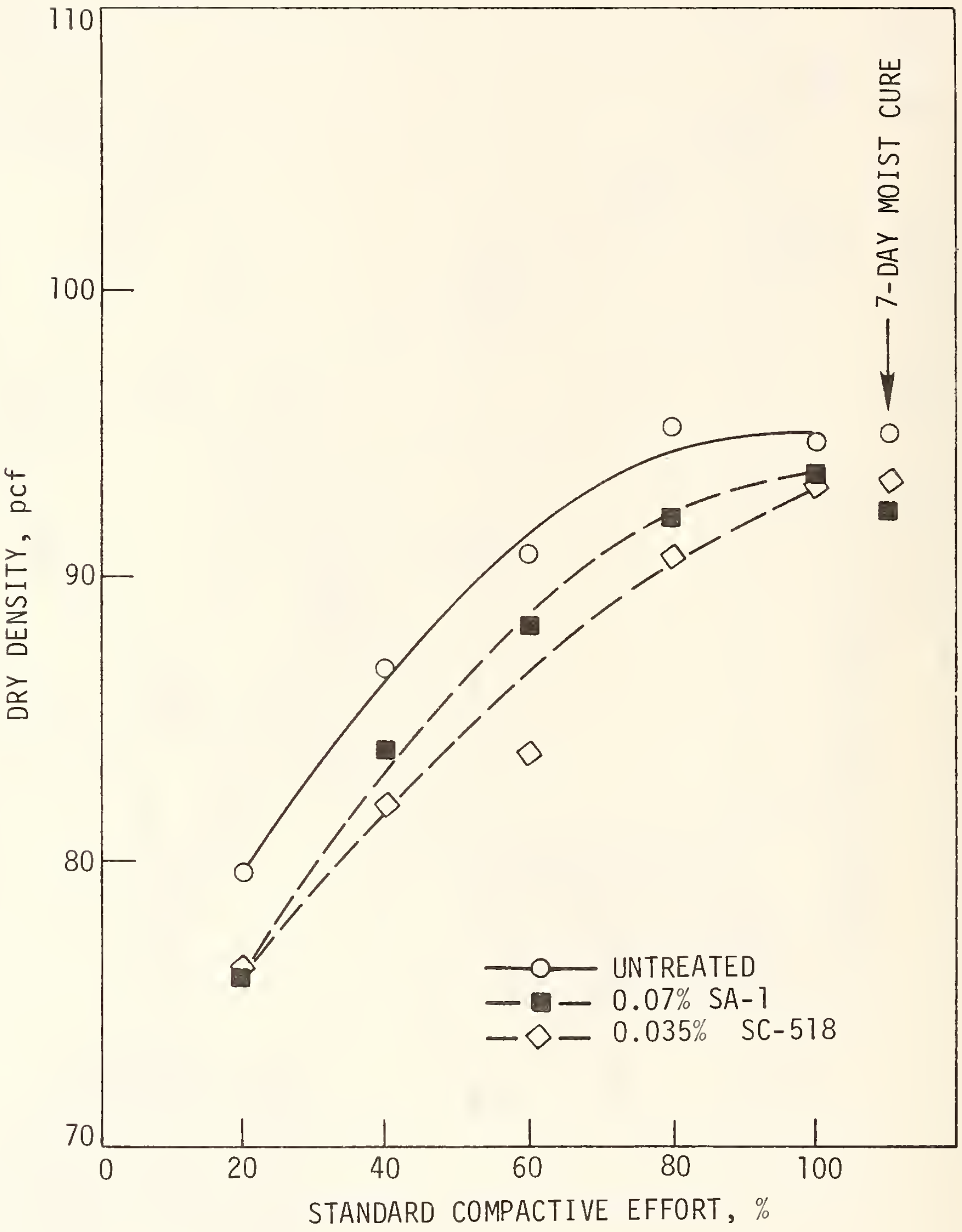

Fig. 78. (a) Compaction growth, Marias series.

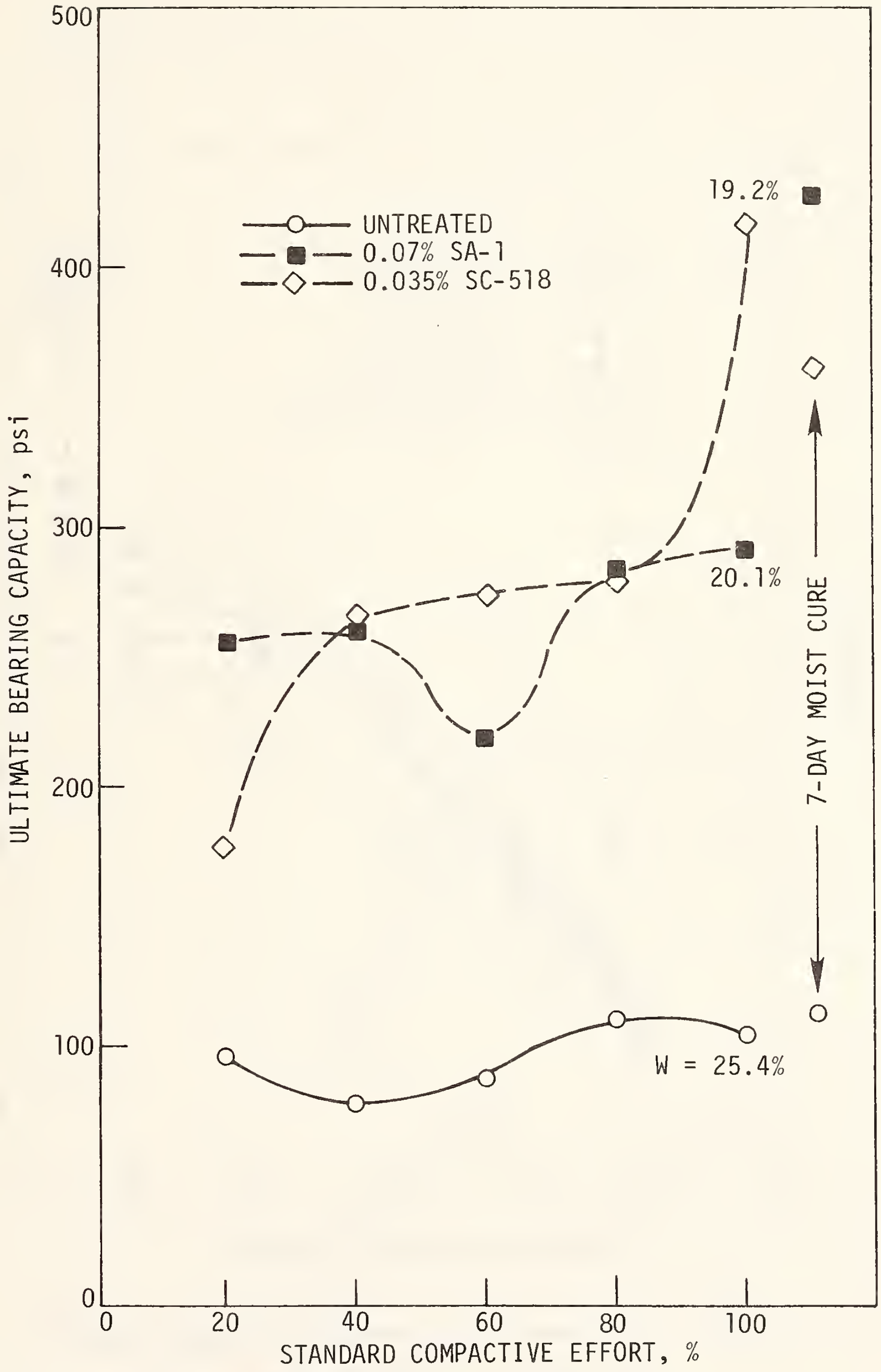

Fig. 78. (b) Ultimate bearing capacity growth, Marias series.

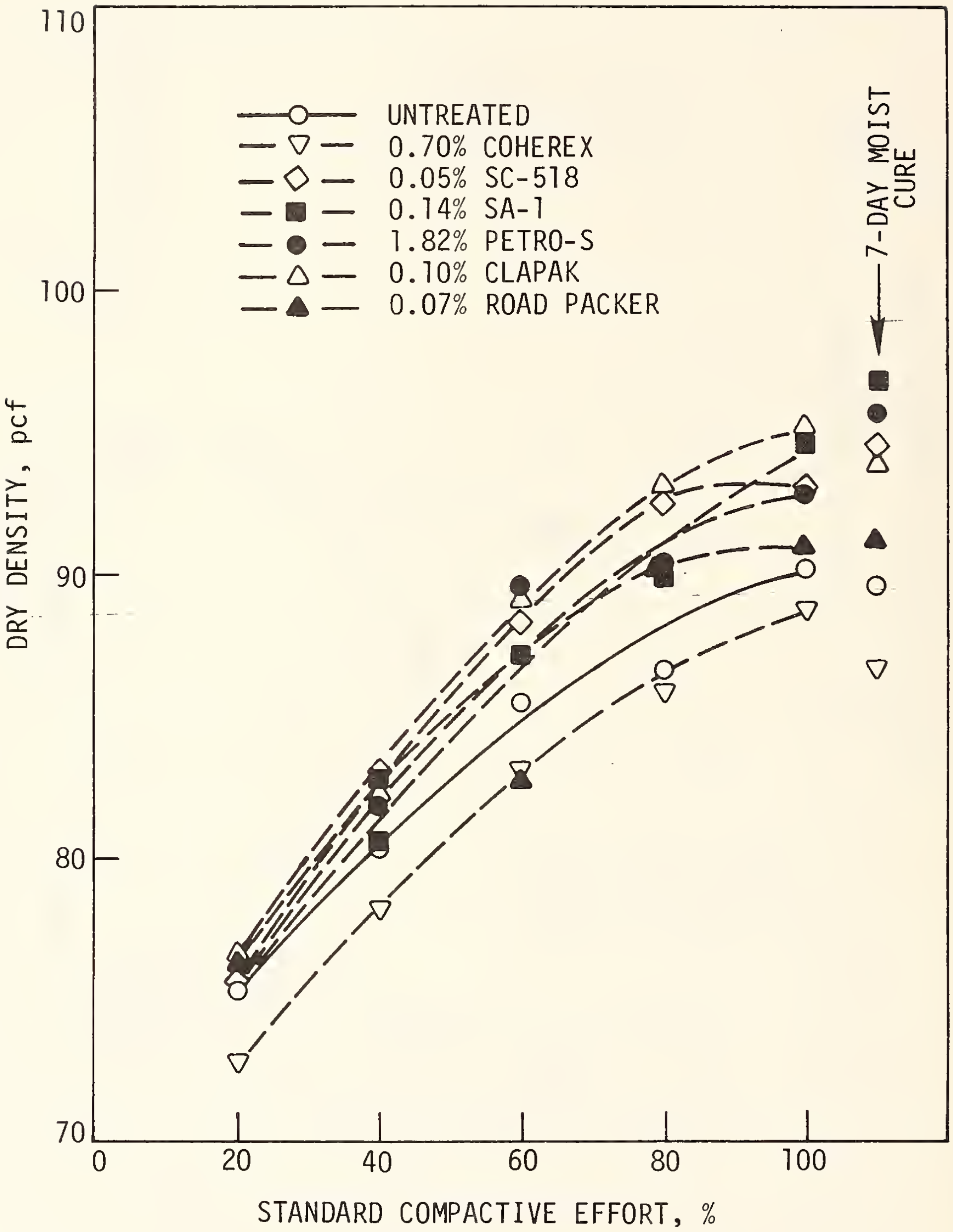

Fig. 79. (a) Compaction growth, Frederick series.

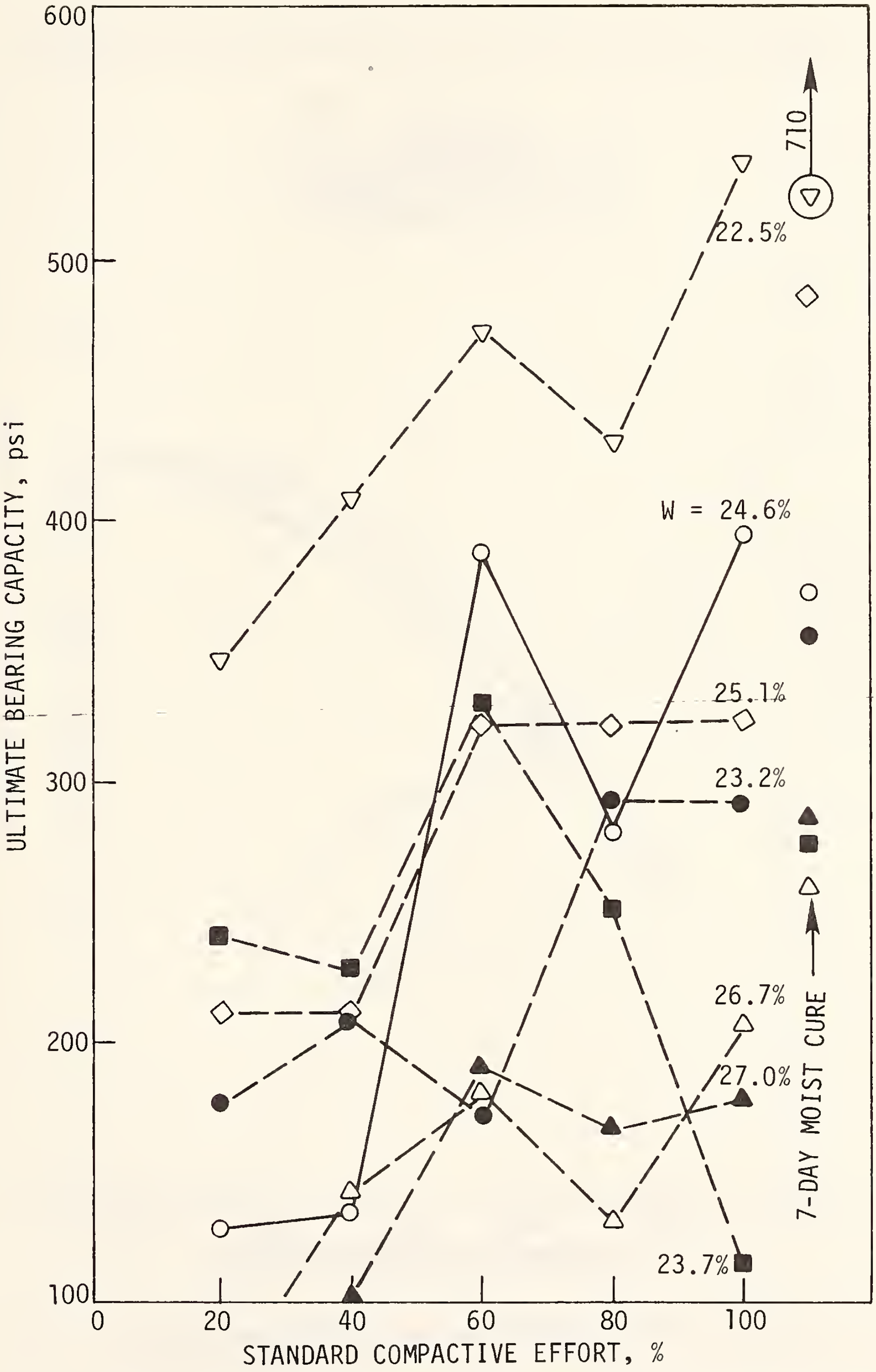

Fig. 79. (b) Ultimate bearing capacity growth, Frederick series.

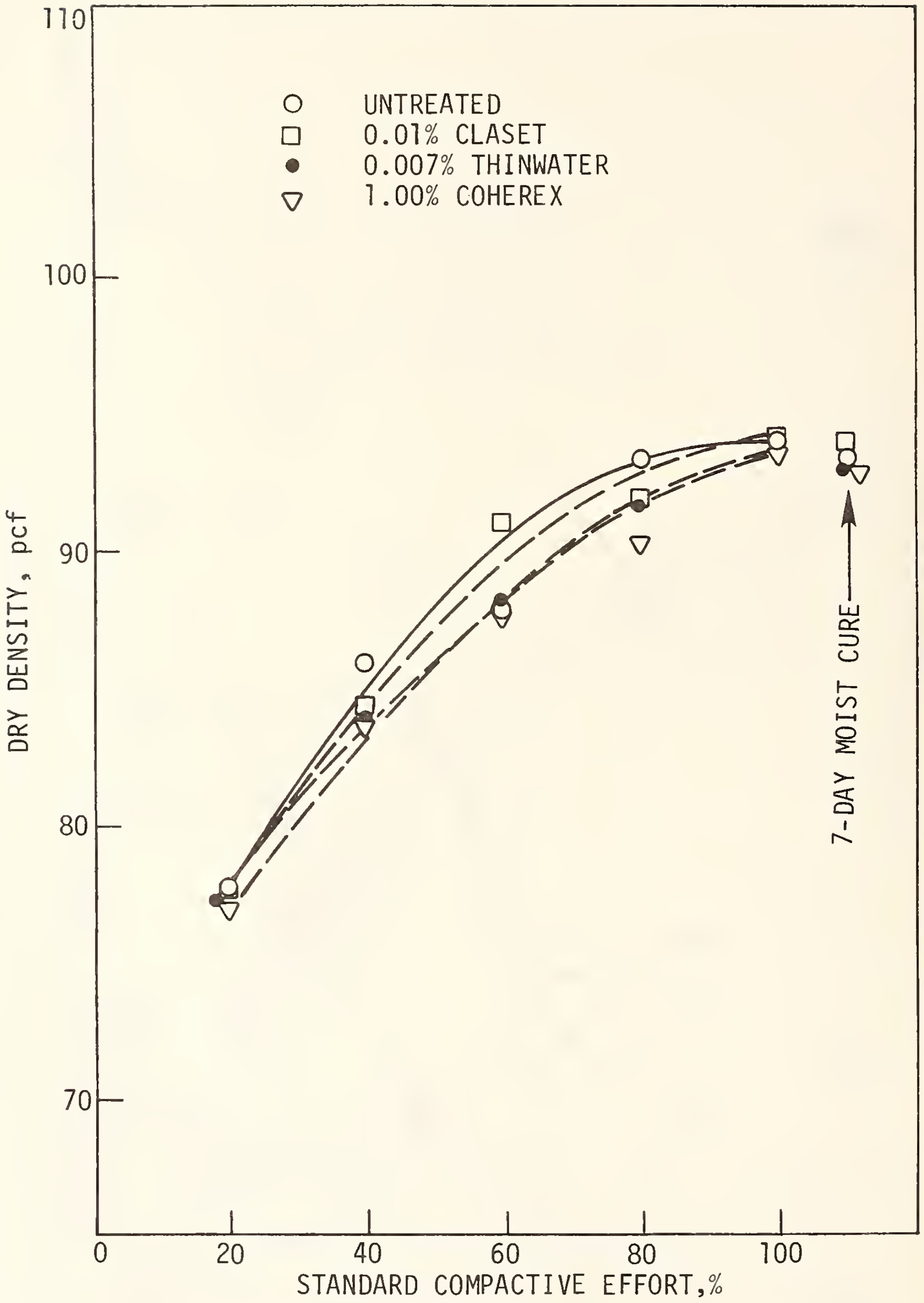

Fig. 80. (a) Compaction growth, Persanti series.

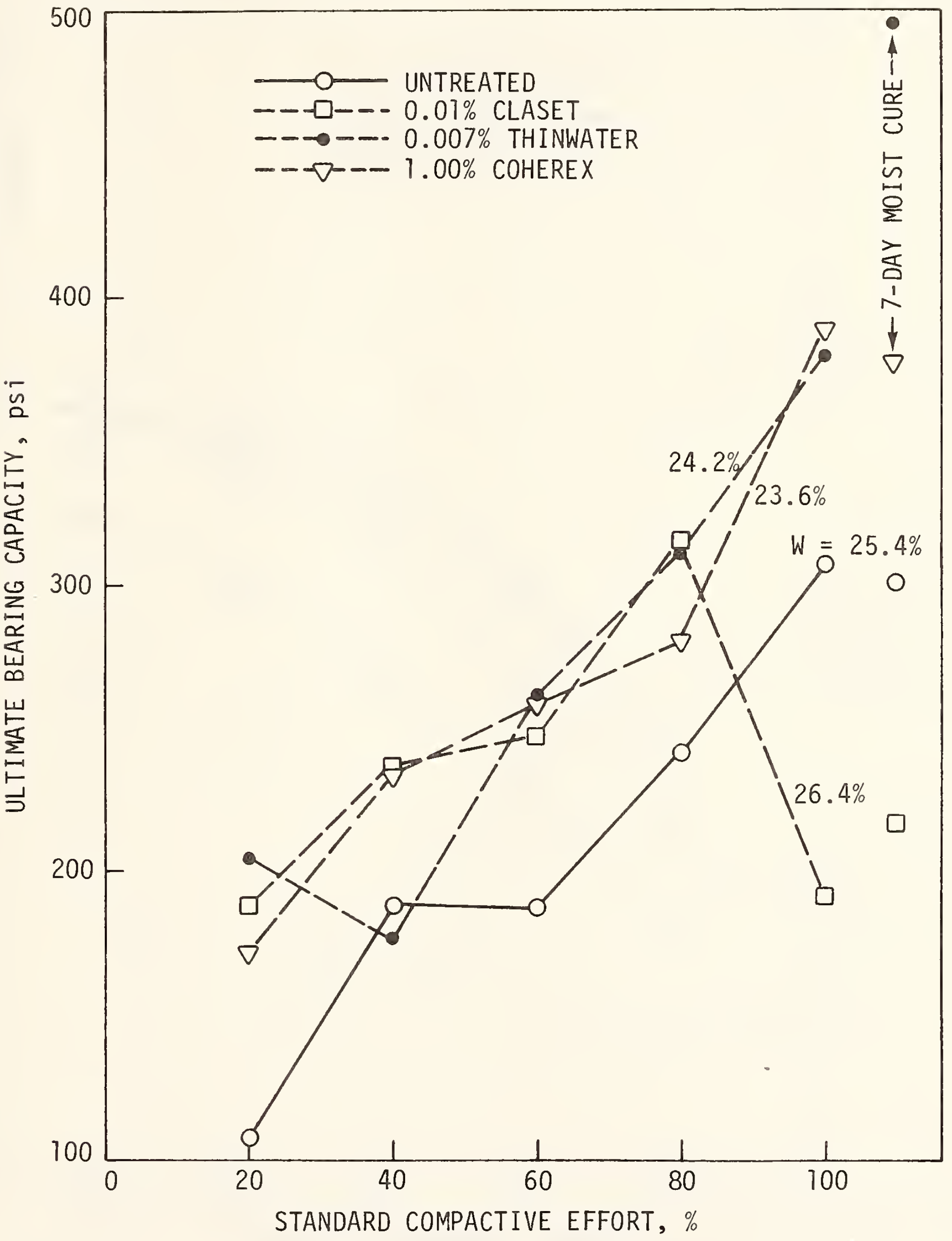

Fig. 80. (b) Ultimate bearing capacity growth, Persanti series.

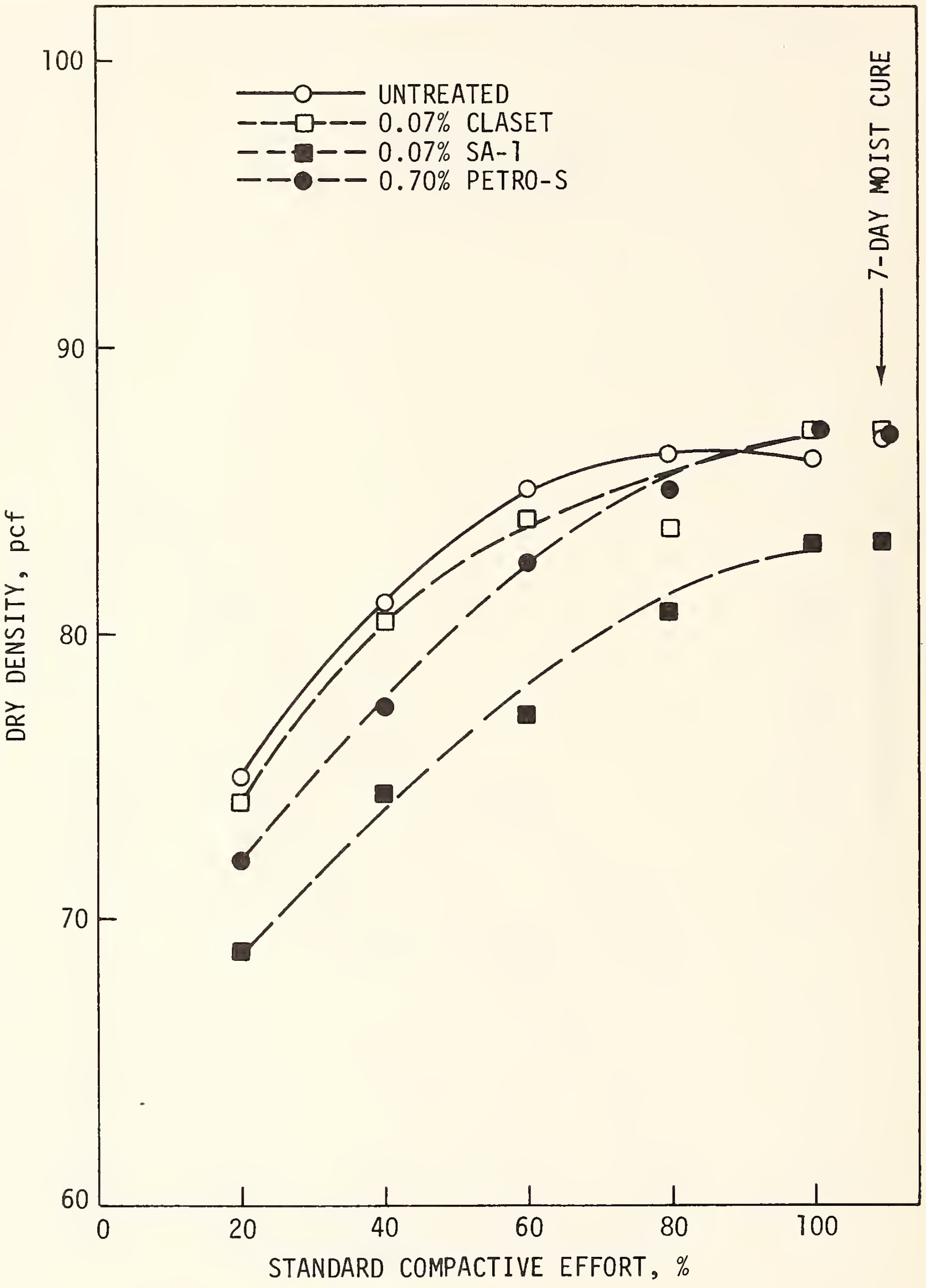

Fig. 81. (a) Compaction growth, Melbourne series.

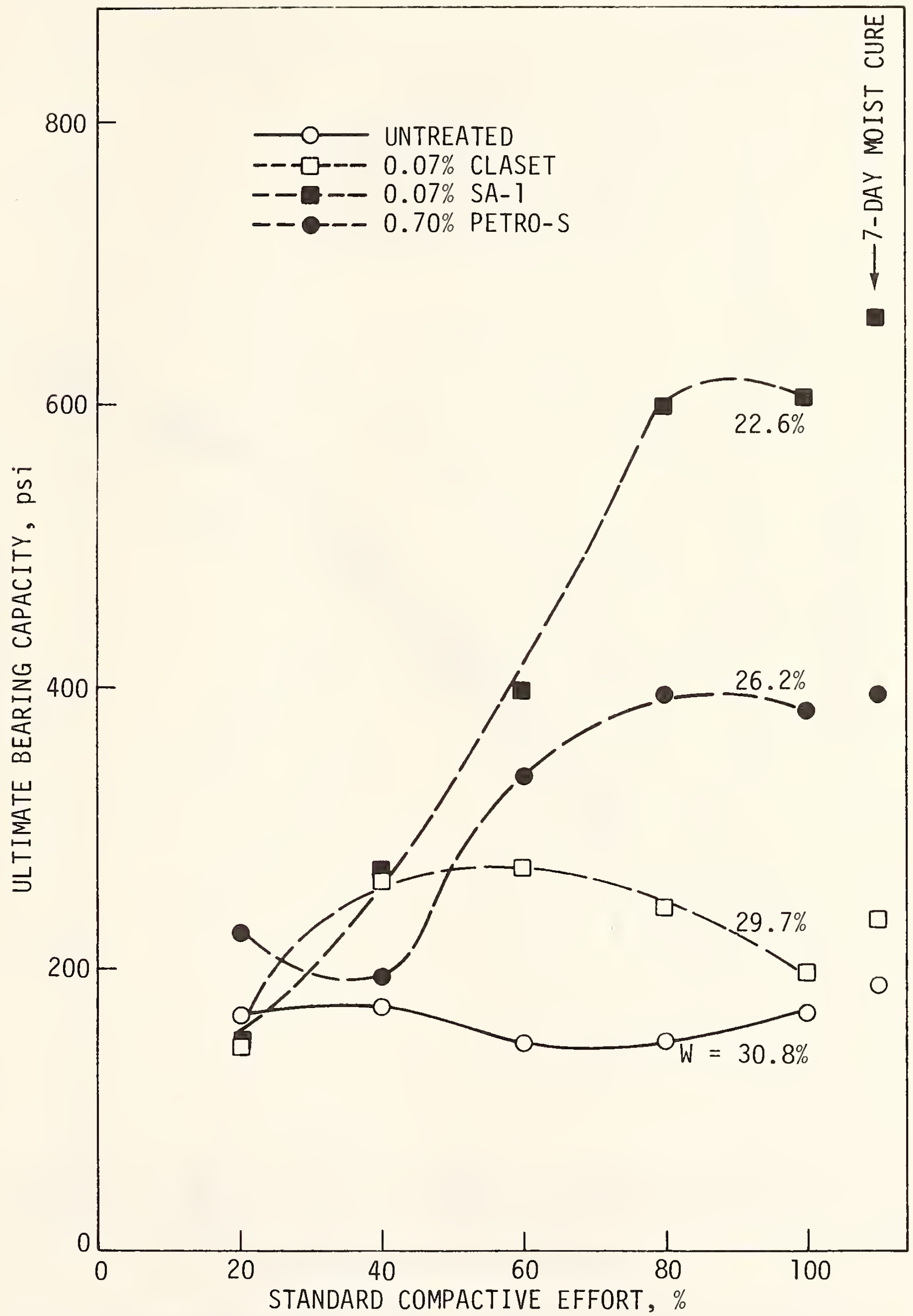

Fig. 81. (b) Ultimate bearing capacity, Melbourne series.

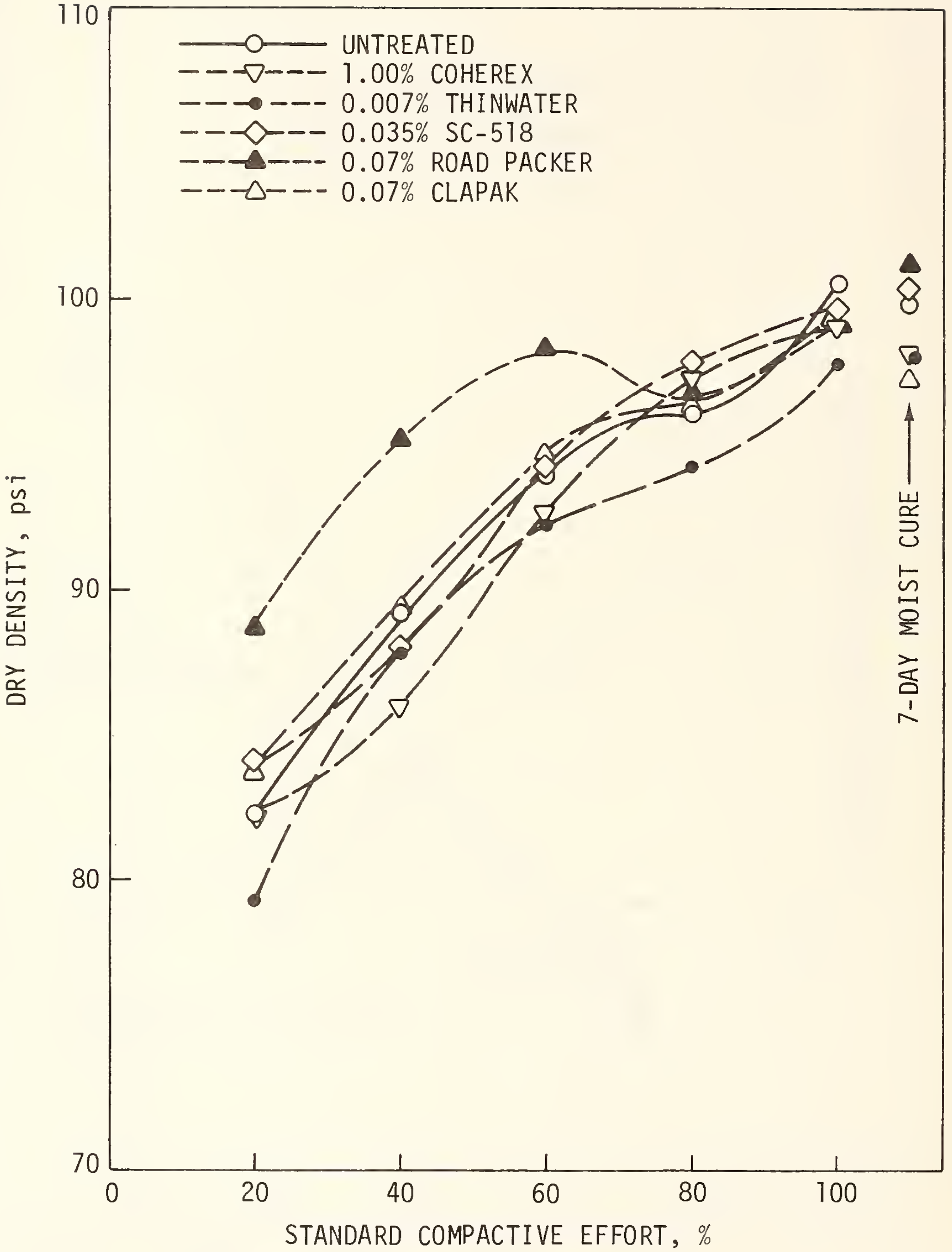

Fig. 82. (a) Compaction growth, Vergennes series

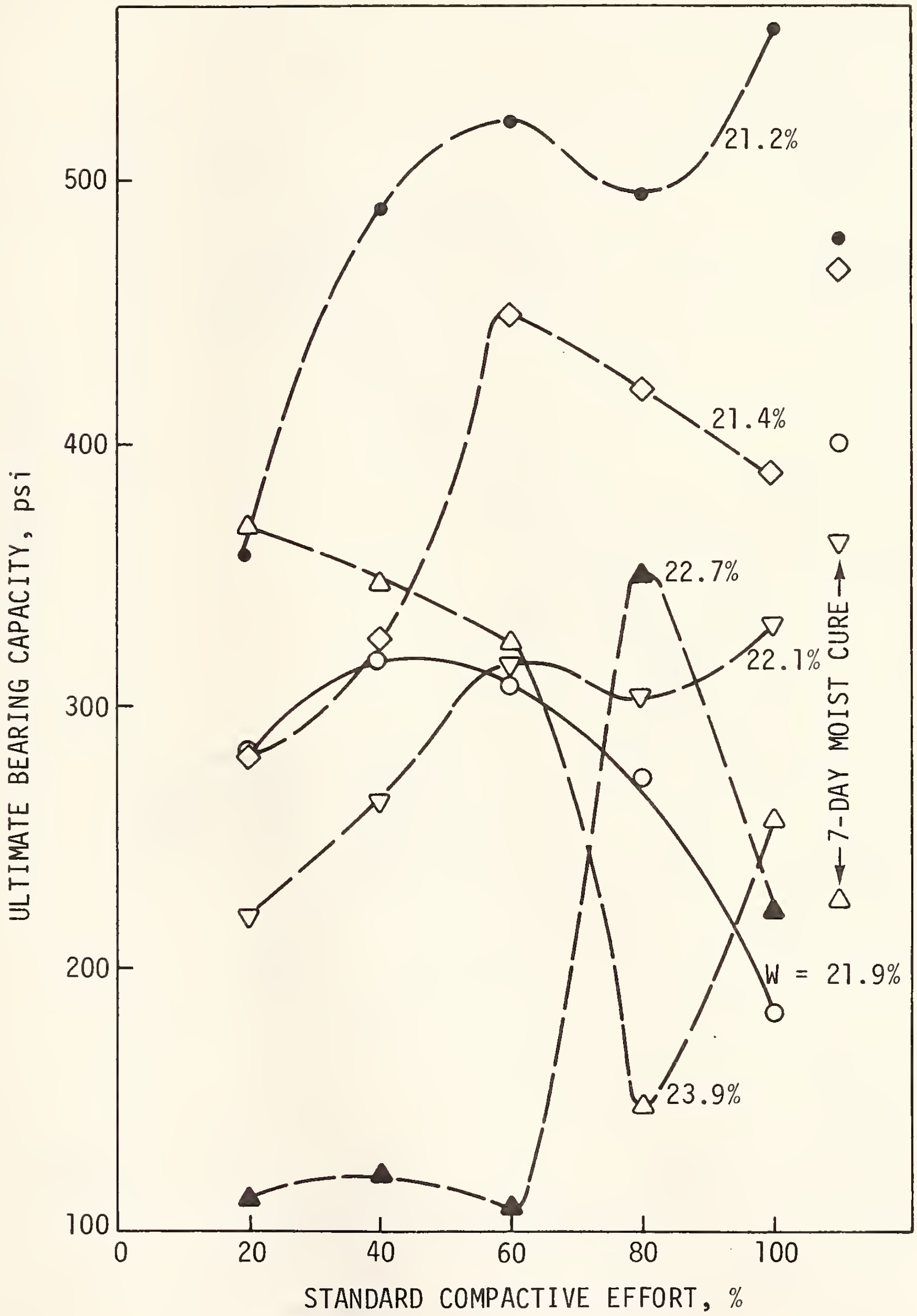

Fig. 82. (b) Ultimate bearing capacity, Vergennes series.

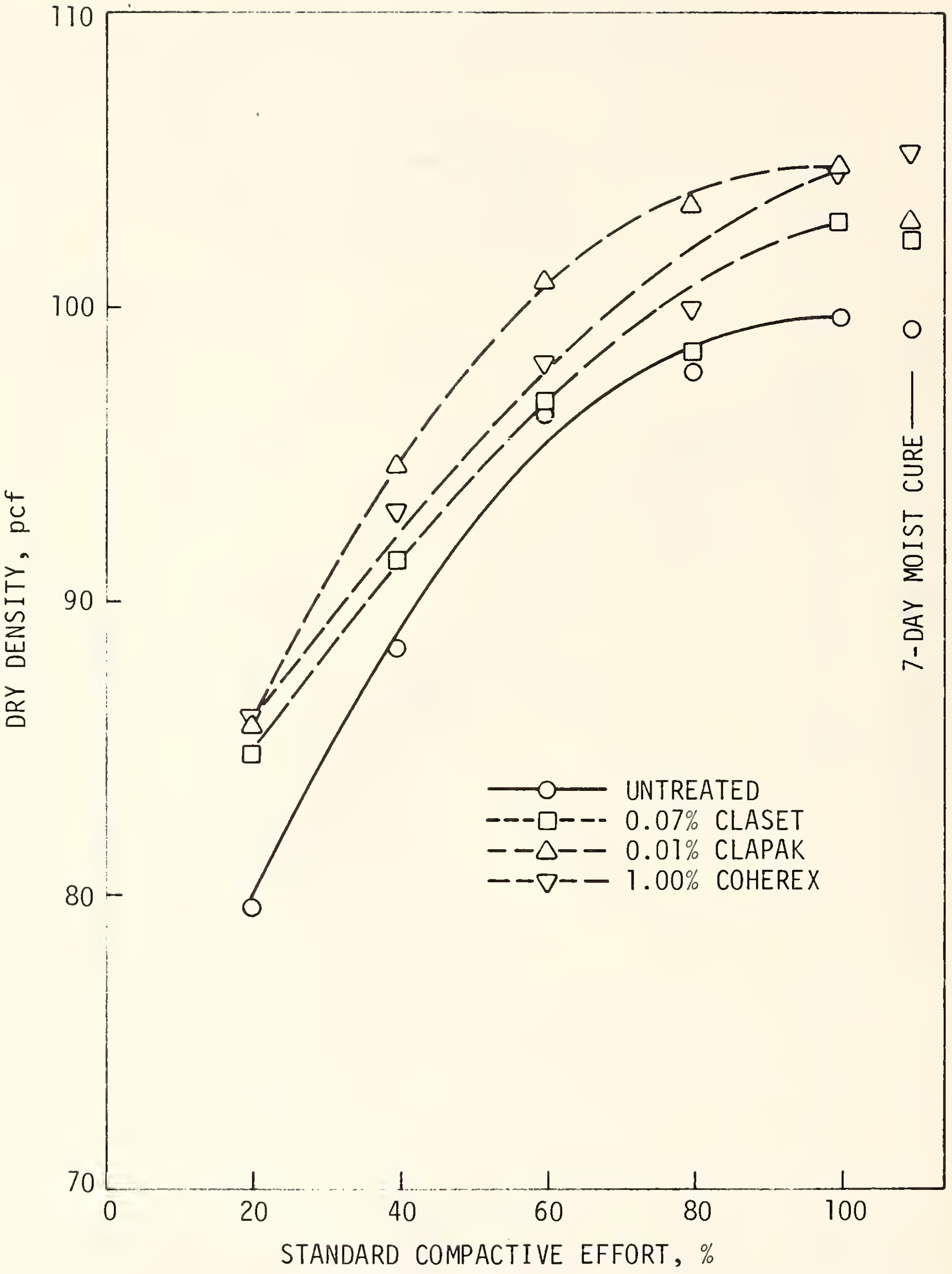

Fig. 83. (a) Compaction growth, Nappanee series.

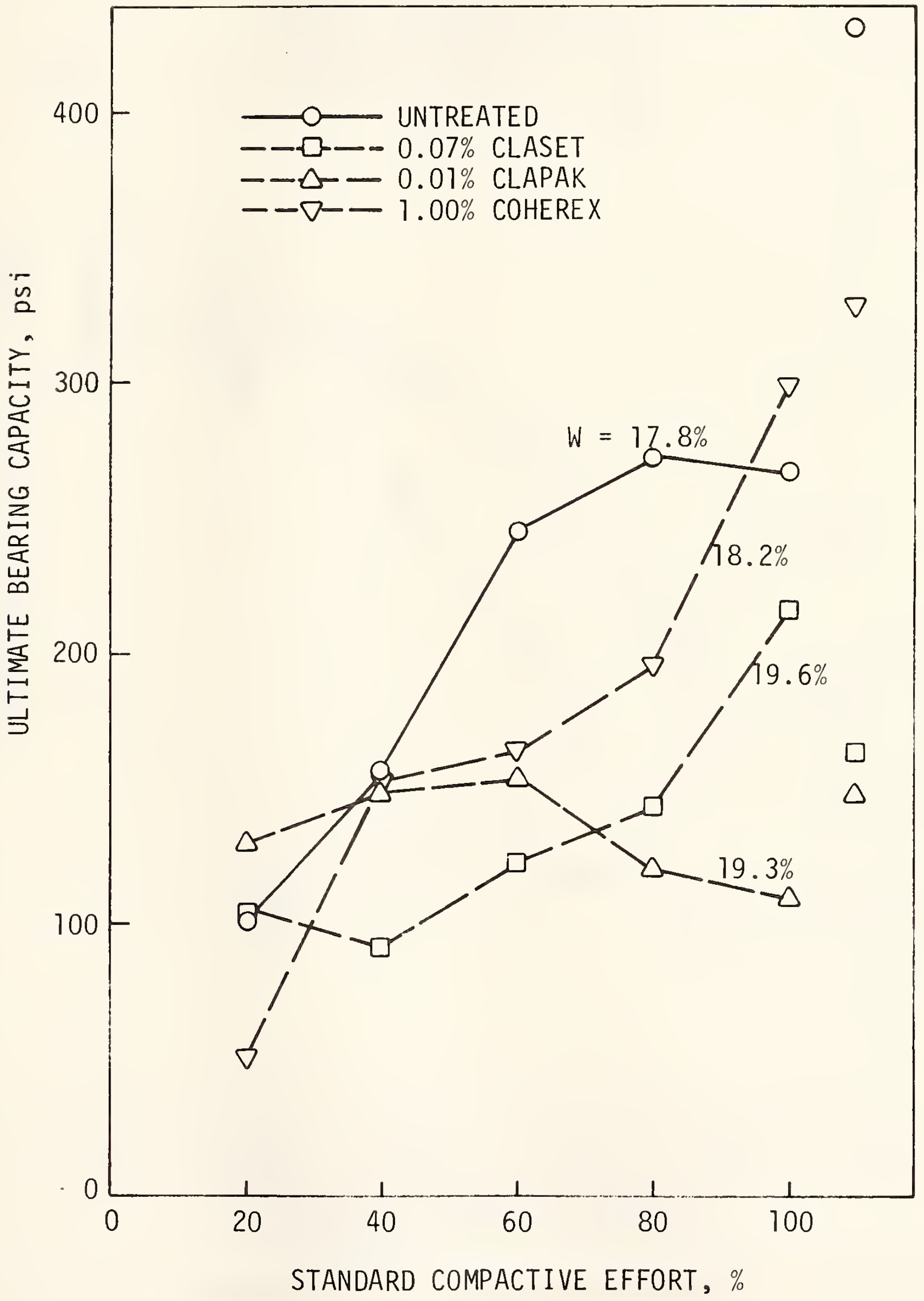

Fig. 83. (b) Ultimate bearing capacity, Nappanee series.

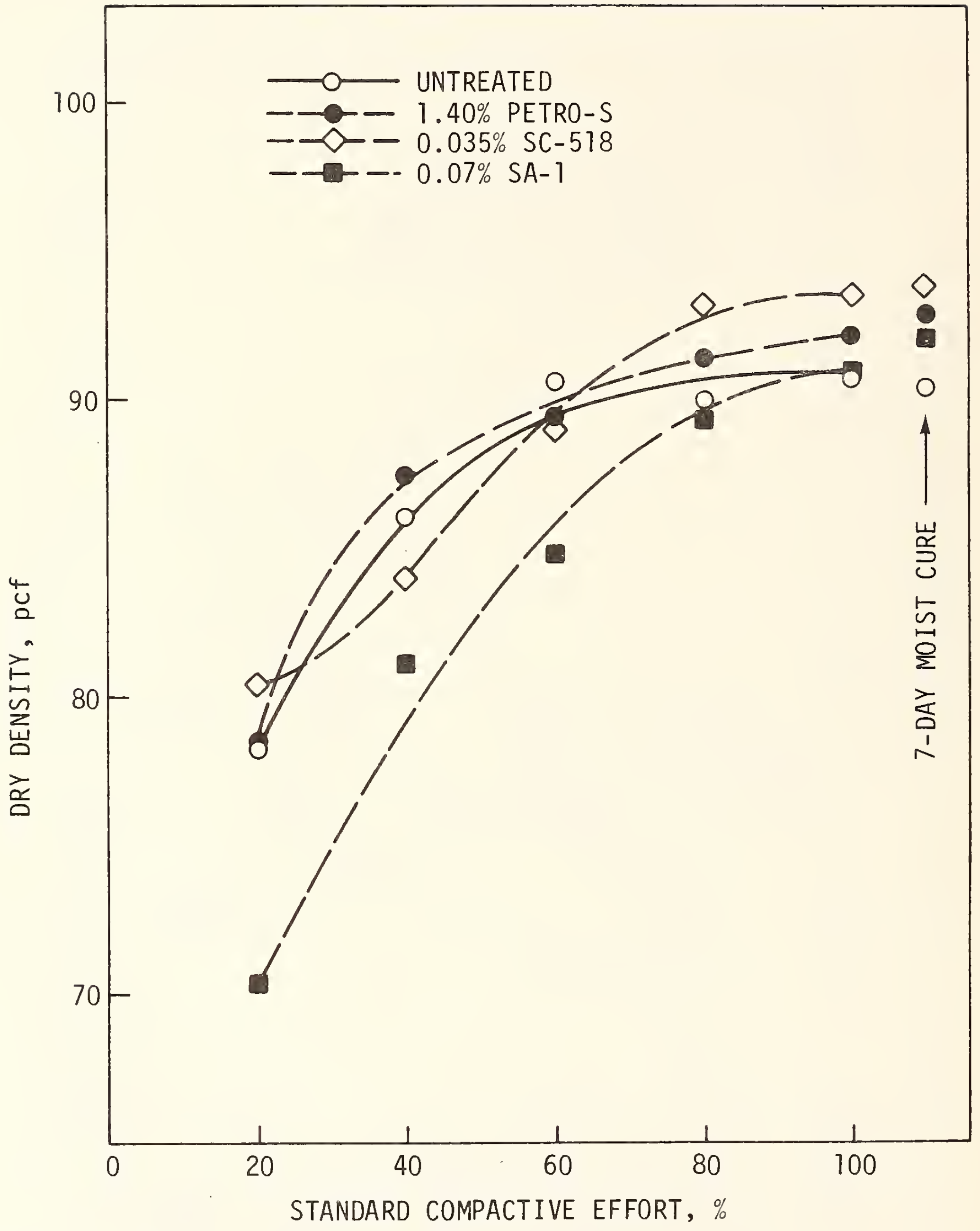

Fig. 84. (a) Compaction growth, Paulding series.

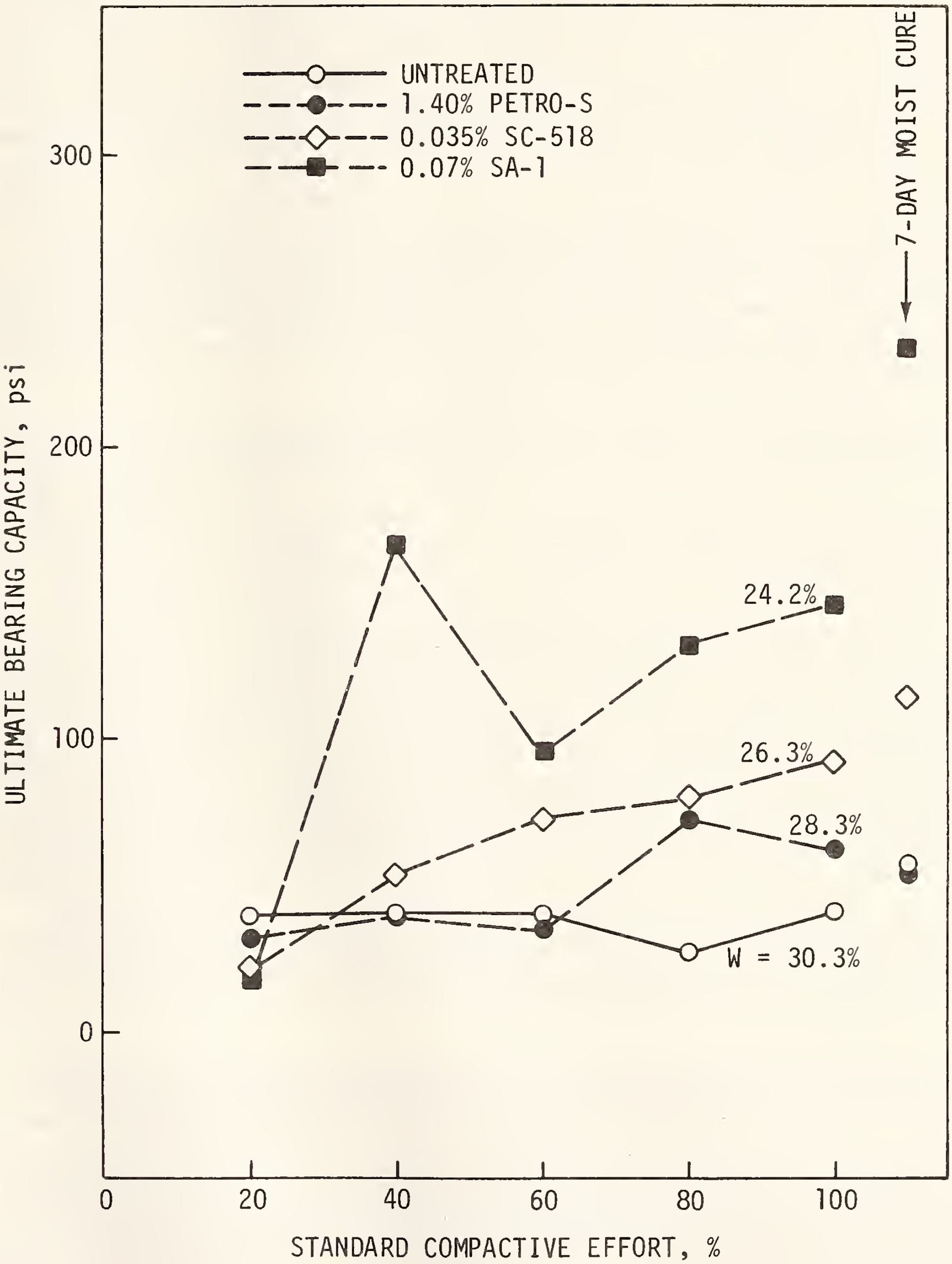

Fig. 84. (b) Ultimate bearing capacity, Paulding series.

As might be expected, shapes of the density growth curves (Fig. 72a) break to the right, indicating a decreased rate of improved density with increasing compactive effort as the air voids available for compaction diminished. This also may be a tendency to overcompact; that is, increased compaction may cause a lowering of shear parameters, resulting in decreased shear strength and bearing capacity. Overcompaction of the Bearden series is evident in the c-ϕ-q_o data of Table 41, generally tending to lower c, increase or decrease ϕ, and decrease q_o. The trend of the latter is illustrated in Fig. 72b. Maximum ultimate bearing capacity, q_o, of the untreated Bearden soil occurred around 40% standard compactive effort, severely decreased thereafter with increased compaction, and approached total shear failure at 100% T-99 energy. Maximum q_o of the Clapak, Calset, and Thinwater treated soils, which contained about 3% less water, occurred around 60, 100, and 80% standard compactive effort, respectively, with the Clapak and Thinwater q_o's decreasing thereafter.

At 100% effort, q_o of the untreated Bearden was 18 psi, of the 0.10% Clapak treatment was 201 psi (an 11× increase), of the 0.10% Claset was 296 psi (a 16.4× increase), and of the 0.001% Thinwater was 299 psi (a 16.6× increase). Seven-day moist cure testing of the untreated and Clapak-treated soil was not conducted. As a consequence, no comparisons of the untreated vs. treated q_o's are available.

Assuming 95% T-99 untreated γ_d as a possible field compaction, the data thus indicate that about 99 pcf γ_d is required. About 40% T-99 compactive effort would thus be required for the untreated soil, yet about 50% for Clapak-treated, about 75% for Thinwater-treated, and almost 100% for the Claset-treated. Thus, each treatment increased instead of decreased the needed compactive effort. At such levels of compactive effort, however, q_o of the untreated would be about 335 psi, while those of the Clapak, Thinwater, and Claset would be about 400, 380, and 300 psi, respectively. Thus, bearing capacity of the Bearden soil would increase about 15-20% if treated with Thinwater or Clapak and decrease about 10% if treated with Claset. Yet, γ_d of the treated soil would remain the same as the untreated while OMC was decreased by 2-3%.

Values of lateral stress ratio, K_i, of the Clapak- and Thinwater-treated Bearden remained fairly constant regardless of percentage compactive effort and, in addition, were considerably lower than those of the untreated. K_i values of the Claset decreased, increased, and again decreased with increased compaction, suggesting some form of structural change may be occurring between 40 and 80% compactive effort. A definite improvement in lateral stability and rutting potential occurred near 100% compaction and remained constant during the 7-day moist curing.

Values of the modulus of elasticity (E) of the Clapak improved with increasing compactive effort, equaled that of the untreated soil at about 60% compaction, and continued to increase at 80 and 100%, while the untreated E decreased. Values of E for untreated and

Thinwater-treated Bearden soil generally followed their respective q_o curves, i.e., increased to a maximum, then decreased with continued compactive effort. Moduli of both Claset and Thinwater indicated no improvement over those values obtained with the untreated soil.

Overall compaction growth of the Bearden soil showed improvements in all strength parameters when treated with 0.10% Clapak and some improvement when treated with 0.001% Thinwater; however, improvement through 0.10% Claset appears limited to strength above 80% compactive effort only.

Renohill Series. As in the M-D and K-Test product effectiveness summation (Table 36), the compaction growth study of the Renohill soil treated with Clapak, Claset, Coherex, and SC-518 generally indicated negative results. Compactive effort vs. density (Fig. 73a) indicated some nominal changes in γ_d: each curve leveled sharply, suggesting possible overcompaction. Median moisture contents of all specimens were within 1.0% of their respective OMC, and densitites of all specimens at 100% compactive effort were within about 1 pcf of their respective γ_d.

As illustrated in Fig. 73b, no improvement in q_o occurred during compaction growth, though slight improvements at 20% compaction were noted with SC-518, Clapak, and Coherex, and at 40% compactive effort only with Coherex. However, densities achieved at the above compactive efforts would be considerably less than desirable.

Densities and moisture contents of the 7-day moist cure specimens were well within the previously mentioned limits and favorably compared with those achieved immediately following compaction. Values of q_o, following 7-day cure, increased significantly for all specimens (treated and untreated) indicating no benefit from continued chemical reaction with time.

Some improvement in K_i may be noted with the 1.00% Coherex and 0.10% Clapak treatments (Table 41), as compared with that of the untreated. Values of E indicated no improvment regardless of chemical utilized.

In general, Claset, Coherex, SC-518, and Clapak were ineffective as chemical compaction aids with the Renohill series.

Pierre Series. Petro-S and Reynolds Road Packer were incorporated into the Pierre series soil. Figure 74a graphically presents γ_d vs. percent standard compactive effort. As with the previously reported M-D tests, 1.40% Petro-S consistently produced 1-2 pcf greater density than the untreated, while 0.035% Road Packer produced about 1 pcf less density at 100% compaction. Median moisture contents of all growth specimens were within 1.5% or less of their respective OMC's. Densities of the 100% compactive effort specimens were within less than 1 pcf of their respective maximum densities, with exception of the 7-day moist cure Petro-S which was about 1.5 pcf less than standard T-99 γ_d. Slope of the density-compaction growth curves did not break to the right as sharply as with the Bearden and Renohill series, thus indicating less probability of overcompaction related to shear strength.

Figure 74b illustrates q_o vs. compactive effort data. If a specification of 95-100% untreated γ_d was assumed, treatment with either Petro-S or Road Packer would be of no value for strength purposes.

Following 7-day moist curing, bearing capacity of all 100% compactive effort specimens improved; the treated spcimens showed 30-40 psi greater improvement than the untreated, indicating a limited amount of increased strength with time due to introduction of the two chemicals.

Neither K_i nor E values of the Pierre soil were improved through treatment with Petro-S or Road Packer regardless of percent compactive effort.

In general, no fundamental benefits for either M-D or strength characteristics emanate from incorporation of Road Packer or Petro-S in the Pierre series.

Rimrock Series. M-D studies of the Rimrock series treated with 1.40% Petro-S indicated an increase of 2.3 pcf γ_d and a lowering of OMC by 4.8% from that of the untreated. Continuous K-Test parameters showed a significant reduction of K_i and increase in ϕ, accompanied by a slight decrease of c. Completion of 100% compaction growth of the treated Rimrock also produced, in excess of 2 pcf, an increase in γ_d from that of the untreated, a significant reduction in K_i, and increased ϕ, but the cohesion was about the same as the untreated. Median moisture contents of the untreated and treated Rimrock specimens were within 0.3% of their respective optimums and within 0.5 pcf of their respective maximum densities.

Shape of the untreated γ_d curve (vs. the compactive effort curve) breaks sharply to the right (Fig. 75a), which is probably a reflection of its higher moisture content. Ultimate bearing capacity of the untreated soil increased to about 60% compaction then decreased slightly towards 100% effort (Fig. 75b). Ultimate q_o of the Petro-S-treated specimens improved with compactive effort but was less than the untreated until about 80% compaction was achieved, after which q_o increased to nearly double that of the untreated at 100% effort. If 100% T-99 compaction were specified, density and shear strength immediately following compaction would be in excess of that of the untreated. However, it may be noted from Fig. 75b that moist curing reversed this advantage, and q_o of the treated soil was reduced to less than that of the untreated.

While some portion of the above strength loss following-7 day curing may be attributed to slight reductions in moisture and γ_d (Table 41 and Fig. 75a), it appears likely that the chemical itself may also adversely affect strength of the treated soil over a period of time. Such effects are also illustrated with the K_i-value increasing significantly after 7-day curing, (Table 41).

Due to the deleterious effect of Petro-S after 7-day moist curing, it must be concluded that this chemical would impart no lasting benefits to the Rimrock series and should be regarded as non-effective.

Houston Black Series. Incorporation of SA-1 with the Houston Black soil was shown ineffective, regardless of treatment level, in the M-D and K-Test study. In general, the same results occurred at the end of the compaction growth study (Table 41 and Fig. 76), but during initial compaction, the treated γ_d was considerably higher than that achieved without chemical, indicating possible lubrication (probably a surface tension reduction) through use of SA-1. As compaction growth approached 100% T-99 effort, γ_d of the treated and untreated approached a near equal value, with the SA-1 treatment creating about 0.5 pcf greater density than in the M-D study.

At about 80% compactive effort, the untreated Houston Black series apparently underwent a structural change that resulted in a sharp decrease in ultimate bearing capacity (Fig. 76b). This structural change is not apparent from the density growth curve nor with the SA-1 treatment which may be due to the lubrication effect previously noted with density growth. Regardless of percent T-99 effort expended, ultimate bearing capacity of the SA-1-treated soil was generally one-half that of the untreated. Some improvement of strength occurred during curing but was quantitatively about the same for both untreated and treated, indicating no benefits from the chemical due to curing.

Values of E for the treated and untreated specimens were very similar throughout compaction growth development. During compaction, lateral pressure ratios of the SA-1 treated specimens were consistently higher than untreated, indicating a definite lack of stability due to chemical treatment.

It is apparent from the growth study that increased γ_d is achievable through SA-1 at low percentages of compactive effort. However, strength and stability factors were significantly lowered from those of the untreated, rendering SA-1 treatment of the Houston Black series ineffective. This observation substantiates previous conclusions that a product which may improve density may also be deleterious to strength and stability and, in all probability, is related to particle dispersive effects through use of the chemical.

Peavine Series. Within the M-D study, treatment of the Peavine series with SA-1, SC-518, Thinwater, Coherex, and Road Packer showed particular improvement in OMC and ϕ, with varying effectiveness in γ_d, K_i, c, and E. Reduction of OMC ranged as high as 7.7%, which is rather significant considering that optimum of the untreated was nearly 46%. Much of the variation was probably due to initial moisture content variation noted in the previous section of this report.

With its very high liquid and plastic limits but low P.I. and its nearly pure montmorillonitic clay, the Peavine series was consistently one of the most difficult soils to work with throughout Phase II and involved considerable re-run of data. Though the true specific gravity of 2.80 was one of the highest of the 18 Phase II soils, maximum γ_d was the lowest, most of which can be attributed to the high OMC. When sampled from a high near-vertical road cut, the Peavine series contained above 40% natural water content, yet barely felt damp to the touch, with little or no sticking to the sampling equipment. Densities produced within the compaction growth study exemplify difficulties encountered with this soil, particularly when compared with γ_d data produced in the M-D study. Compaction growth γ_d's of the treated soil were consistently less than the untreated, while maximum γ_d's from the M-D study were about equal to or greater than those of the untreated. Median moisture contents of the compaction growth specimens were within 1.0% of OMC's determined within the M-D study and thus indicated that little chance of the 100% T-99 γ_d growth specimens' variation from the maximum M-D γ_d was due to a wide variation of moisture content. Reruns of both M-D and compaction growth indicated little variation from the data either previously presented or indicated herein. Also, no variations in procedure or equipment were perceived.

Regardless of the above problem with γ_d, the ϕ, K_i, c, and E values of the compaction growth specimens generally followed trends noted previously within the M-D study. Thus, we can only state that the data achieved with this soil series must be assumed valid.

Compactive effort vs. γ_d curves of the untreated and SC-518-treated soil show the greatest extent of breaking to the right (Fig. 77a). These samples also have the highest moisture contents. Overcompaction of the SC-518 and of the untreated specimens is indicated in the ultimate bearing capacity reductions noted in Fig. 77b, both occurring at about 80% compactive effort, with the SC-518 treatment being the most pronounced. Seven-day moist cure densities of the untreated and all treated specimens indicate some slight variations from those produced within the 100% effort specimens measured immediately following compaction.

Ultimate bearing capacities of all SC-518, Thinwater, Coherex, and Road Packer treated growth specimens were greater in strong reflection of the water contents than that of the untreated.

Seven-day moist cure q_o of the untreated Peavine soil was but 10 psi greater than that immediately following 100% compaction. Following 7-day moist curing, q_o of the SA-1 treated soil increased about 90 psi, while q_o of the SC-518 and Road Packer treated soil both increased about 30 psi, indicating definite strength increases related to curing. After 7 days of moist curing, ultimate bearing capacity of Thinwater and Coherex treatment of the soil was lowered about 50 and 60 psi, respectively, indicating potential strength losses with time.

If 95% untreated γ_d were instituted as a compaction specification (i.e., 69 pcf), this value could be achieved at about 45% compactive effort with the untreated, 50% with Road Packer, just under 60% with SA-1, just over 60% with SC-518, about 80% with Thinwater, and nearly 90% with Coherex treatments. At such compactive efforts, q_o of the untreated would be about 185 psi, while treatment would produce about 250 psi with Road Packer, 210 psi with SA-1, 310 psi with SC-518, 410 psi with Thinwater, and 410 psi with Coherex. Though required compactive effort would be doubled, ultimate bearing could thus also be doubled through introduction of either 0.001% Thinwater or 1.00% Coherex.

Assuming a datum of 45% compactive effort for production of 95% untreated γ_d, the following variations in γ_d and q_o of the treatments would be achieved:

	γ_d, pcf	q_o, psi
Untreated	69	185
0.001% Thinwater	65	285
0.035% Road Packer	68	250
0.07% SC-518	66	230
1.00% Coherex	65	195
0.07% SA-1	67	125

As illustrated, maximum variation from the untreated 95% γ_d of 69 pcf would be only 4 pcf, while the Thinwater, Road Packer, and/or SC-518 potentially would still increase bearing capacity of the Peavine soil; however, only the Road Packer indicated some potential for strength improvement following curing, while Thinwater and SC-518 showed a possible decrease of q_o with time. Therefore, only Road Packer, indicated a potential for use at the 45% compactive effort level, attaining a density about equivalent to that of the untreated, while improving q_o by about 65 psi with some possibility of retaining and/or gaining strength vs. time.

K_i-values of SA-1 treated specimens were approximately equivalent to those of the untreated Peavine, while all other treatments produced a lower K_i, indicating increased lateral stabilities. Treatment with SC-518 produced a general decrease in K_i (i.e., strengthening) with increased compactive effort. Thinwater, Coherex, and Road Packer treatments produced rather constant K_i values regardless of compactive effort and then decreased during 7-day moist curing, indicating increased lateral stability due to curing.

Moduli E values of the treated specimens ranged from equivalent to somewhat less than those of the untreated Peavine and generally reflected the trends indicated with γ_d.

Analysis of the Peavine series compaction growth data indicated some generalized potential effectiveness through chemical treatment, at least in the areas of bearing capacity and lateral stability. This comes about mainly as a result of reduction in the optimum moisture contents determined earlier and used in this series. Since OMC was found to depend also on initial moisture content, data of Fig. 77b may be influenced by this extraneous variable. In addition, improvement of density may not be as significant as indicated with the M-D study. In general, SC-518, Thinwater, Coherex, and Road Packer show the greatest degree of effectiveness within the context of the above parameters, with SA-1 presenting the greatest potential for improved effectiveness vs. time at 100% T-99 compactive effort. Comparison of the γ_d vs. strength/stability parameters also indicates the variability of dispersion-flocculation-texturizing effects of each chemical on the Peavine series.

Marias Series. Addition of SA-1 and SC-518 to this soil series appears to have produced previously discussed flocculative effects and generated lower densities but increased strength and stability with increasing compactive effort and significant lowering of moisture contents. Both products produced a lowering of two or more pcf density as compared with the untreated, regardless of compaction effort, and retained such variation after 7 days of moist curing (Fig. 78a). Values of q_o, however, were two or more times greater than the untreated. Following 7-day moist cure, however, q_o of the untreated was nearly constant to that immediately following molding; SC-518 treatment decreased q_o, while SA-1 significantly increased q_o with time (Fig. 78b).

Lateral stability of the untreated Marias decreased with increased compactive effort and remained constant after 7 days cure (Table 41). Lateral stability of the treated soil decreased slightly with compactive effort but for both treatments was significantly improved as compared to the untreated. Cured values of K_i of the treated soil followed the same pattern as q_o, with SA-1 improving and SC-518 decreasing with time.

Both products thus imparted good strength and stability to the Marias soil, primarily as a result of reductions in OMC, but were ineffective aids to compaction other than providing the reductions in moisture.

It is interesting to note the comparative effects of SA-1 treatment within the Houston Black and Marias series, both predominantly montmorillonitic clays. During initial increasing compactive effort, SA-1 produced greater γ_d but was accompanied by a lower q_o and stability than for the untreated. Throughout each compactive effort level with the Marias, the reverse effect was shown. While it has been postulated that chemical dispersion increases γ_d and lowers strength and stability, flocculation thus lowers γ_d while improving the strength and stability characteristics. SA-1 appeared to have acted as both a dispersant (Houston Black series) and flocculant (Marias series), thus presenting an inconsistency. Table 8 shows both soils as predominantly montmorillonitic and containing feldspar as a secondary mineral. However, the Marias also contains a small amount of calcite. Table 27 shows that pH values of several water concentrations of SA-1 were less than 2.0. It may at least be assumed that the highly acidic SA-1 reacted with the small quantity of calcite in the Marias series and created new product(s) more conducive to flocculation. Thus, the effectiveness of a highly acidic or reactive chemical may be more influenced by minor than by dominant mineralogy.

Frederick Series. Figure 79 illustrates γ_d and q_o effects resulting from chemical treatment of this series. Of the six chemicals, all (except Coherex) produced at least some improvement in density, with Clapak increasing γ_d by 5 pcf at 100% compactive effort. Only SA-1 and Petro-S slightly lowered moisture contents from that of the untreated, while SC-518, Clapak and Road Packer increased moisture. Coherex produced a consistent reduction of about 1.5 to 2 pcf at a reduced moisture content.

Regardless of treatment or non-treatment, soil structural changes occurred near 60 to 80% compactive effort (Fig. 79b). While SC-518, SA-1, Petro-S, Clapak, and Road Packer improved γ_d, none were basically effective in improving q_o, with SA-1 treatment significantly reducing strength qualities of the soil from 60 to 100% compactive effort. After 7 days curing, q_o of the SA-1, Road Packer, Clapak, and Petro-S treated soil improved but still remained less than the untreated. Bearing capacity with the SC-518 also significantly improved with curing and was greater than the untreated after 7 days. During 7 days moist curing, each of these chemically treated specimens showed only little change in γ_d, yet each thus indicated a time/strength dependency, with SC-518 appearing to have the greatest potential of combined γ_d improvement coupled with time-dependent development of added bearing capacity.

While Coherex lowered both moisture and γ_d, q_o of the chemically treated soil was consistently and significantly greater than the untreated, increasing to 710 psi following 7-day moist curing, again indicating time dependency.

Lateral stability, K_i, and Modulus E values generally followed the c-ϕ-q_o parameters, with the greatest K_i benefits occurring in the Coherex-treated specimens and least K_i benefits occurring with Clapak-treated specimens.

Several of the treatments indicated possible overcompaction (Fig. 79a). However, only SA-1 produced a requisite lowering of q_o (Fig. 79b), with continued increase in compactive effort.

Only SC-518 and Coherex, therefore, produced any major benefits in the compaction growth study; the former showed benefited γ_d and improved time dependent strength, and the latter indicated improved stability and bearing capacity only.

Persanti Series. Maximum dry densities of the untreated and treated Persanti series compaction growth specimens were closely related, particularly at the low and high compactive efforts. After 7 day moist cure, γ_d's were basically the same as immediately following 100% T-99 compaction. Mid-range of the compaction growth showed a general lowering of treated γ_d as compared to the untreated. Compaction moisture contents with Thinwater and Coherex were 1 to 2% less than the untreated, while that of the Claset was 1% greater.

As might be anticipated from lowering of treated γ_d's, bearing capacity of the treated specimens was generally greater than the untreated; the exception was the Claset treatment at 100% compactive effort. In general, Coherex and Thinwater treatment produced progressive increases in q_o with increased compaction, while Claset, with its higher moisture content, appeared to have produced overcompaction between 80 and 100% effort.

Seven-day moist curing showed little or no time dependent q_o improvement with the untreated or Claset and Coherex treated. However, Thinwater treatment increased q_o after 7 days by 116 psi, indicating probable continued chemical activity over the cure period.

Lateral stability of the untreated and Claset-treated soil were similar up to 60 to 80% compactive effort, with Claset specimens losing stability thereafter. Values of K_i for Thinwater and Coherex were consistently less than those of the untreated; the Thinwater treatment continued K_i improvement after 7 days, while the Coherex treatment deteriorated. Moduli E values indicated no significant improvements due to treatment, with the Coherex showing some definite reduction therein.

Overall, none of the three chemicals provided M-D effectiveness. However, Thinwater and Coherex provided improved stability-bearing capacity, with Thinwater treatment showing additional cure-related benefits.

Melbourne Series. Incorporation of SA-1, Claset, and Petro-S in the M-D and K-Test study of the Melbourne Series (Tables 35 and 36) indicated full to partial effectiveness. Each product provided a moderate to very significant decrease in OMC and a lowering of dry density obtained with lower compactive efforts (Fig. 81a). Densities of both treated and untreated specimens were nearly identical immediately following compaction growth and at 7 days moist curing.

Bearing capacities of the treated soils markedly increased with higher compactive effort (Fig. 81b) in an inverse relation to moisture content. Thus, the decrease in OMC may have a highly significant effect on stability even if γ_d is not beneficial. Seven-day moist curing produced little q_o benefits, generally indicating no continued reactivity through chemical treatment.

Lateral stability was generally benefited through introduction of chemicals (particularly SA-1), though moduli E values of all treated specimens were slightly less than the untreated, with Petro-S showing the lowest values.

Assuming a specification of 95% untreated γ_d (about 86 pcf and 70 to 80% T-99 effort), only Petro-S and Claset would achieve the required density above 80% compactive effort, while SA-1 treatment would not achieve density, regardless of T-99 effort; each treatment, however, was at less moisture content that the untreated. On the other hand, lateral stability and bearing capacity could be significantly improved at 60% compactive effort through use of Petro-S and SA-1, even though γ_d would be reduced by several pcf. It is thus apparent that chemical effectiveness within the Melbourne series soil applies only to potential stability/strength relationships.

Vergennes Series. Compaction growth of Vergennes series, with 0.07% Road Packer treatment from 20 to 60% T-99 compaction, showed γ_d about 5 pcf greater than that of the untreated. The other chemicals were ineffective for density.

Shapes of the compaction growth curves suggest potential for both soil structural changes and overcompaction (Fig. 82a), which is verified by the q_o vs. compactive effort plots (Fig. 82b). While Road Packer improved γ_d during initial compaction growth, q_o of these specimens was only about one-third that of the untreated maximum. Treatment with 0.07% Clapak decreased q_o with increasing compactive effort. Coherex, SC-518, and Thinwater treatments produced variable bearing capacities: Thinwater significantly increased q_o above the untreated, SC-518 increased q_o beyond 40% effort, Coherex ultimately increased q_o beyond 60% effort, and each indicated fluctuating soil structure conditions.

Following 7-days of moist curing, q_o of the untreated more than doubled. With Coherex and SC-518, q_o also increased but not as dramatically as the untreated, while with Thinwater, Road Packer, and Clapak, q_o diminished with time. It therefore appears that bearing capacity effects of the chemically treated Vergennes series might be adversely affected with continued curing.

Lateral stability (K_i) effectiveness of the untreated and treated soil generally followed the c-ϕ-q_o data; Thinwater was the most effective, Road Packer the least effective. Moduli E values also tended to follow the generalized q_o pattern.

It is interesting to speculate on the possible performance of the Vergennes series soil if a 95% untreated γ_d specification were selected for field compaction, i.e., about 95 pcf. Road Packer treatment could reduce compactive effort by about one-half and bearing capacity about two-thirds, which is not exactly an advantage. At the opposite extreme, Thinwater would require considerably more compactive effort than the untreated to produce the same γ_d but would nearly double the bearing capacity and greatly improve lateral stability, at least for some period of time. Effects of the other three products fall between the two extremes.

Thus, use of the five products with this soil series is somewhat questionable and would depend on desired strength-stability development.

Nappanee Series. Within the M-D and K-Test study, Claset, Clapak, and Coherex treatments of the Nappanee series soil were noted as reducing γ_d and increasing OMC and were rated ineffective (Tables 35 and 36). Figure 56 illustrates the variation of initial moisture content observed with the Nappanee M-D tests (note that the untreated soil had a very low initial moisture while the bulk of the treated materials were at considerably higher initial contents). Initial moisture contents for the compaction growth study were closely controlled, achieving a statistical mean and one standard deviation of 11.3 ± 0.6% for all specimens, treated and untreated. Furthermore, with the Nappannee, molding moisture contents were maintained fairly constant (Fig. 83b). The primary effect was that each treatment produced a greater compaction growth γ_d than the untreated, with γ_d remaining reasonably constant after 7 days moist curing.

K-Test parameters in Table 35 also presented generally ineffective K_i, c, and ϕ values when Claset, Clapak, and Coherex were introduced into the Nappanee series. Table 41 and Fig. 83b show that compaction growth followed the same general pattern; i.e., chemical treatment of the soil did not improve strength/stability values, and at most, compaction efforts reduced such values even after 7 days moist curing.

These results definitely illustrate the need for maintenance of equal initial moisture contents when objective comparisons of chemical aids to compaction of an untreated soil are to be conducted.

Compaction growth of the Nappanee series soil followed the postulated dispersion effects of chemical soil treatment--increased density coupled with decreased strength and stability.

Paulding Series. Data from the Paulding provide a suitable contrast to the Nappanee since, as shown in Fig. 57, initial moisture content of the untreated M-D specimens was considerably higher than the bulk of the treated specimens. Median initial moisture content of all untreated and treated Paulding compaction growth specimens was held at 18.9 ± 0.9%. When observed from the standpoint of Fig. 57, the more constant initial moisture content would result in little change in OMC and in a closer alignment between untreated and treated γ_d's. Therefore, with the exception of SA-1 treatment, density growth of the untreated and of the Petro-S and SC-518 treated soil generally followed the same path. With SA-1, γ_d values were considerably less at low compactive effort but ultimately coincided with untreated γ_d at 100% effort.

K-Test c-ϕ-q_o compaction growth data (Table 41 and Fig. 84b) reflect the variable moisture contents.

In general, compaction growth analysis of the Paulding series indicates some limited benefits only in strength/stability values as a result of reduced optimum moisture contents which, in turn, were a product of initial moisture content (the troublesome extraneous variable).

Summary of Compaction Growth Study. A primary objective of this study was to provide data to allow a cost-effectiveness analysis of the use of chemical compaction aids. However, as a first step in evaluation, the success rate should be noted. Of the 41 soil-chemical combinations tested in the compaction growth study, none were found to be fully effective, but about half showed effectiveness to some degree (Table 42). The chemical found to be partially effective with the most soils was SC-518 which agreed with previous results. However, even in this case, only about half of the soils showed any benefit, and there was no relation to clay mineralogy. Thus, effectiveness of a chemical compaction aid is by no means ubiquitous, and at the present state-of-the-art, each anticipated soil-chemical combination must be individually evaluated. This in itself is a deterent to widespread use, unless the advantages are demonstrably worth the effort of testing.

As was discovered during progress of the research, moisture-density testing without attention to several very important details may provide erroneous evaluations. Also, improvement in compaction is not considered a sole criterion since the ultimate objective is improvement of soil stability under load.

The following steps therefore are suggested for determining the mix design and cost effectiveness of a chemical compaction aid:

1. Soil should be dried to a uniform moisture content about 5% below estimated optimum for compaction. Under no circumstances should the soil be air-dried and pulverized prior to testing. The partially air-dried soil should then be split into two batches, one for chemical treatment and one for control.

2. Moisture-density tests are run on the untreated and treated soil, using fresh soil for each molded specimen. The tests can be run at several chemical percentages by dry soil weight in order to obtain the most desirable level of chemical additive. If a rate of

Table 42. Summary of compaction growth - K-Test product effectiveness.*

Soil Series	Dominant Clay Mineral	Products							
		Clapak	Claset	Coherex	Petro-S	Thinwater	SC-518	SA-1	Road Packer
Bearden	Montmorillonite	+(+)	0(+)	/	/	+(0)	/	/	/
Renohill	Montmorillonite	-(-)	-(-)	-(-)	/	/	-(-)	/	/
Pierre	Montmorillonite	/	/	/	-(-)	/	/	/	-(-)
Rimrock	Montmorillonite	/	/	/	-(+)	/	/	/	/
Houston Black	Montmorillonite	/	/	/	/	/	/	-(-)	/
Peavine	Montmorillonite	/	/	0(+)	/	+(++)	0(+)	0(+)	0(+)
Marias	Montmorillonite	/	/	/	/	/	0(++)	0(++)	/
Frederick	Kaolinite	0(0)	/	+(+)	0(+)	/	+(-)	0(-)	-(-)
Persanti	Kaolinite	/	-(-)	0(-)	/	+(0)	/	/	/
Melbourne	Vermiculite	/	-(+)	/	0(+)	/	/	0(+)	/
Vergennes	Vermiculite-Illite	-(0)	/	-(+)	/	+(+)	0(0)	/	-(-)
Nappanee	Vermiculite-Illite	0(-)	0(-)	0(-)	/	/	/	/	/
Paulding	Vermiculite-Illite	/	/	/	-(-)	/	0(-)	0(0)	/

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* ++ = Fully effective, + = fully to partially effective, 0 = partially effective, - = not effective. Symbols in parentheses indicate effectiveness ratings from moisture-density and K-Test study.

application is suggested by the chemical producer/distributor, it is desirable to bracket above and below such level. Regardless of suggested rate, it must be understood that the amount of chemical added on a percentage dry soil weight basis can be exceedingly small, often in terms of a few thousandths percent.

3. K-Tests should be performed on all compacted specimens to evaluate the effects of chemical and moisture contents on strength and stability. These tests may be postponed until one week after molding during which time the specimens have been sealed and moist-cured to allow for time dependent chemical effects to be evaluated.

4. On the basis of the untreated vs. treated M-D and K-Test data, a fully effective chemical should increase the soil's γ_d, reduce OMC, and improve strength and stability parameters. Partially effective treatments may reduce γ_d, yet decrease OMC and significantly improve strength/stability parameters. If, on the other hand, neither M-D or K-Test parameters of the chemically treated soil show any improvements, the treatment must be regarded as ineffective or even deleterious.

5. Based on required field specifications of both moisture and density, select a single appropriate compaction moisture content and conduct a compaction growth study on untreated and treated specimens by varying the compactive effort for different specimens. The soil should be at the same initial moisture content as for the M-D tests, and the compaction moisture content should be somewhat on the wet side of optimum as an anticipated in-situ condition. Compaction may conveniently be conducted at 20, 40, 60, 80 and 100% of the normal laboratory compactive effort. Additional specimens, meeting minimum field specification for density, should be compacted, sealed, and cured for a minimum of 7 days moist curing at 100% relative humidity. K-Tests should be conducted on all specimens immediately following compaction or at the end of the moist cure period.

6. Finally, a comparison of the untreated and treated compaction growth data will indicate whether any benefits accrue from addition of the chemical. The primary purpose of improving density of any soil is to increase strength/stability characteristics. Such can be readily estimated from the compaction growth K-Test parameter data, plus application of a portion of that data to a simple bearing capacity analysis.

Cost effectiveness is illustrated by the following examples utilizing the data of Tables 35 and 41, and Figs. 72 through 84:

Under maximum T-99 compaction, 0.10% Clapak treatment of the Bearden series (shown as + in Table 42) improved the basic M-D and K-Test parameters; i.e., γ_d, ϕ, and c were each increased, and OMC and K_i were decreased although E was unchanged from that of the untreated soil (Table 35). Compaction growth data of the Clapak-treated Bearden indicated some variation from the untreated, particularly in γ_d at 80% or less compactive effort (Table 41 and Fig. 72). At 100% T-99 effort, compaction growth and M-D results were reasonably similar.

Assuming 95% standard T-99 untreated γ_d and optimum moisture content as the field specification, about 99 pcf is required. Anticipated compactive effort would be about 40 and 50% of T-99 for the untreated and treated soil, respectively. Thus, the advantage of the Clapak treatment would be not a reduction in compactive effort but rather a reduction in OMC by 3% water, or a 15% reduction from that of the untreated soil. At their respective compactive efforts, bearing capacity of the chemically treated Bearden is increased by about 20%, while lateral stability (K_i) and Modulus E are only negligibly improved.

Compaction costs are difficult to assess from earthwork bidding or contracts since such costs are most often included as a portion of the earthwork item. Discussion with one of the major earthmoving contractors in the State of Iowa, however, indicated compaction bid costs of \$0.005 to 0.10 per cubic yard for standard T-99 and \$0.35 to 0.50 per cubic yard for T-180 modified density specification.* Assuming \$0.10 per cubic yard as a datum for untreated soil compaction, the increased compactive effort due to introduction of 0.1% Clapak could increase (rather than decrease) compaction costs by about \$0.02 per cubic yard or by about \$0.003 per square yard of 6-in. compacted depth.

When water must be added to a subgrade soil for achievement of a specified moisture content, costs of transporting, application, and mixing remain reasonably constant regardless of addition of chemical treatment. This leaves the cost of water, which may be obtained in a variety of ways ranging from simple permits to obtain water from streams, to attaching to a community fire hydrant and paying on a metered basis. Iowa Department of Transportation specifications** require that unit bid prices for embankment compaction with moisture control include "all work of drying material, furnishing and applying water, controlling moisture content of the materials and compacting the materials, as specified." Where a contract contains no unit price for water, but such is "authorized or ordered, water will be paid for as extra work at the rate of \$6.00 per 1000 gallons."** Using the latter criterion, a 3% optimum moisture content reduction would lower the cost of water by \$0.0096 (or about \$0.01) per square yard of 6-in. compacted thickness.

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*Personal discussion with Mr. Dwayne McAninch, President, McAninch Corp., Des Moines, Iowa.

**Iowa Department of Transportation, Standard Specifications for Highway and Bridge Construction, Series of 1977, Ames, Iowa.

Clapak (as are most of the chemicals in this study) is readily dispersible in water and does not necessarily require specialized tank mixing or processing, thus eliminating such additional cost. Cost of the chemical only per square yard of 6-in. compacted thickness would be about \$0.77, based on \$14.50/gal. and a compacted γ_d of 99 pcf. Total cost of the use of 0.10% Clapak would therefore be estimated as \$0.77 + 0.003 - 0.01, or about \$0.76 per square yard of 6-in. thickness. For benefits consisting primarily of only a 20% increase in anticipated bearing capacity, such cost appears unwarranted.

The above illustration would change in the following manner by specifying 100% T-99 untreated compacted density (104.2 pcf). Compactive effort would be reduced by about 20% through inclusion of the Clapak, and compaction and water costs would be lowered by about \$0.007 and \$0.01, respectively, per square yard of 6-in. compacted thickness. Cost of 0.1% Clapak would be about \$0.81, producing a total estimate of about \$0.79 per square yard. While this cost still appears fairly high, bearing capacity would increase about 20 fold from near 20 to 400 psi, coupled with over 40% increase in lateral stability and 55% improvement in Modulus E from that of the untreated soil. From the standpoint of strength and stability, therefore, the added cost of chemical treatment could reasonably be justified.

As another example, addition of 0.007% by dry soil weight of Thinwater to the Persanti series soil did not improve maximum γ_d or OMC as ascertained from the M-D study, but K_i, ϕ, and c were benefited (Table 35). Similar effects were noted with the compaction growth data which showed an excellent potential for increased strength/stability after 7 days moist curing (Table 41 and Fig. 80). Assuming 95% untreated γ_d (89 pcf) and OMC as the field specification, Thinwater treatment of the soil would require about 10% greater compactive effort than the untreated at a cost of about \$0.003 per square yard for a 6-in. depth of lift. This cost increase would be offset by a nearly equal cost reduction in water content, leaving only the cost of chemical (less than \$0.04 per square yard at \$10.95/gal.). When coupled with benefits of over 40% increase in bearing capacity and slight improvement in lateral stability and in Modulus E, the cost appears justifiable.

Using the same criteria as in the previous illustrations, addition of 0.035% Reynolds Road Packer to the Peavine series at 95% untreated γ_d would result in the following cost effectiveness evaluative parameters:

1. Compactive effort nearly the same as the untreated.

2. Slightly over 1% reduction in OMC.

3. About 10% improvement in lateral stability.

4. Very slight improvement in Modulus E.

5. Over 35% increase in bearing capacity plus possible improvement with time.

6. Net cost of about $0.22 per square yard of 6-in. compacted thickness.

This example thus becomes a borderline situation and requires final evaluation based on the judgment of the professional engineer, since benefits of use of the product are of limited proportions in relation to cost.

Again, using the same criteria as in the previous illustrations, addition of Petro-S (Frederick Series), SA-1 (Houston Black Series), Clapak (Nappanee Series), and other products within several of the series soils, provided good to significant improvement in moisture density relations as well as compaction growth. In each instance, however, strength and stability properties ranged from no change to extremely deleterious when compared to the untreated soil. As a consequence, such properties would be totally ineffective from a cost-benefit standpoint.

As can be noted from each of the preceding illustrations, the major cost factor when adding a chemical to a soil is the chemical itself, with cost in direct proportion to chemical quantity, not unlike addition of any stabilization product to any soil and/or aggregate material. Two factors, which perplex many highway engineers deal principally with more commonly used products such as asphalt, portland cement, etc. These factors are the relatively high price per gallon (or pound) of the chemical, and the exceedingly small quantities of chemical potentially needed to produce a satisfactory highway component. Since a particular soil may require only a few hundredths to a few thousandths of a percent by dry soil weight of chemical, the price of chemical per gallon is diluted accordingly. Furthermore, the chemicals are readily added in the water.

An exceedingly important factor determining cost effectiveness has only been alluded to and this is whether the soil in the field is at, above, or below the required moisture content. Certainly, if soil already is too wet for compaction, drying back sufficiently to allow addition of a highly diluted chemical will drastically increase costs. This is particularly true if the chemical happens to lower the OMC, which it often does. The obvious conclusion is that chemical compaction aids will be most economical where the soil is dry of optimum. Furthermore, the most substantial potential saving may be by reduction of OMC in areas short of water, i.e., semi-arid areas of the west and southwest United States.

Analytical Studies

Analytical procedures used in this phase with the chemical compaction aids are in two categories: (1) Those intended to characterize or "fingerprint" the chemicals and provide a check on uniformity of different batches and of future supplies, and (2) those tests intended to reveal or characterize the soil-chemical interactions. In the first category are infrared spectra and vapor pressure osmometer data for the chemical solutions; in the second are measurements of the zeta potential (electrical charge) on clay particles before and after chemical treatment and infrared and x-ray diffraction data on treated and untreated clays.

Infrared Spectrography

Infrared adsorption spectra are peculiar to the particular molecules examined. The information obtained from studies in the "near infrared" region can be classified under six headings: (1) The thermodynamic behavior of a molecular system can be calculated if its modes of vibration and rotation are known. (2) Information on chemical bonding may be obtained, and discrimination may be made between rival structures. (3) Substances may be identified from their infrared spectra so that, by a process analogous to fingerprinting, the molecules may be identified. (4) Under certain conditions, mixtures may be analyzed. (5) Reactions may be followed. (6) Valuable information on the energy configuration of electrons in solids may be obtained.

Not all of these goals can be pursued with complete freedom since even a fairly simple molecule can give an extremely complex pattern.

Infrared spectra interpretation is mainly on an empirical basis. The interpreter takes advantage of the complexity when matching a spectrum of an unknown compound against that of a known sample. A peak-by-peak correlation is excellent evidence for identity. On the other hand, certain groups of atoms give rise to vibration bands at or near the same frequency regardless of the structure of the rest of the molecule. It is this feature which permits the chemist to obtain useful structural information by simple inspection and reference to generalized charts of characteristic group frequencies.

In this research, we attempted to use infrared spectroscopy to characterize and, if possible, identify the various chemical compaction aids. The complexity and secrecy of the chemicals limited the results obtained. However, the method was successful in revealing the main functional groups in some of the chemicals, and shall rely heavily on these characteristic group absorption frequencies.

Samples. The chemical compaction aids used in this study were all liquids. Each was diluted to 0.05 to 10% concentration, and was examined by containment between parallel plates. Between 1 and 10 mg of material was needed. A compensating cell filled with solvent was placed in the reference beam to subtract the absorption spectrum of the solvent. The spectrum thus obtained was that of the solute, except in those regions in which the solvent absorbs strongly such that no transmittance is obtained.

In this study of chemical compaction aids, the solvent was water. Sodium chloride cells were not suitable for samples containing water because of dissolution, so silver chloride cells (throwaway IR cells, No. TAC-1) and polyethelene cells were tried. Unfortunately, little or no spectrum was transmitted. Salt cells were tried and they gave reasonable results, although the water contained in the chemical compaction aids dissolved the cells to some extent. To reduce cell damage as much as possible, salt plates were used to minimize contact time between salt and chemicals by eliminating cell filling and emptying time. Circular and rectangular salt plates were used; a drop of the chemical was placed between two salt plates and squeezed to form a very thin film. Then the cell was mounted in the IR spectrophotometer to be tested.

This method was rather successful with many chemicals, but some did not show any spectrum and reacted severely with the cell material. Cell plates were polished after each test to renew their smooth surfaces.

Instrument. A Beckman Model IR4 spectrophotometer was used, employing a Nernst filament and silicon carbide globar source and a double-prism Littrow monochromator and thermocouple detector. The source intensity is automatically regulated, and the rays emitted are divided into two beams: sample beam and reference beam.

Results. It was hoped that the infrared absorption spectra recorded for chemical compaction aids might identify major components and reveal chemical identities. Composition of chemical compaction aids, in general, is too complicated to be easily identified from the IR spectra. However, at least the main functional groups of most of the chemicals could be ascertained so that any future changes can be detected, and similar compaction aids under different commercial names can be recognized. Typical IR spectra of the chemicals are shown in Fig. 85.

Following are the results of the infrared spectra interpretation:

SC-518. A transparent blue, viscous liquid, soluble in water, insoluble in benzene, carbon tetrachloride, or chloroform. Strong broad IR peaks at 2.9 and 6.1μ, weak peak at 4.7μ, and strong background at 8 to 15μ. Presence of water is indicated. A rather strong triplet occurs at 3.45μ, medium sharp peak at 6.95μ, medium triplet at 7.3μ, strong peak at 9.1μ, and additional weak peaks at 7.8, 8.1, and 10.7. The IR spectrum suggests an organic aliphatic alcohol.

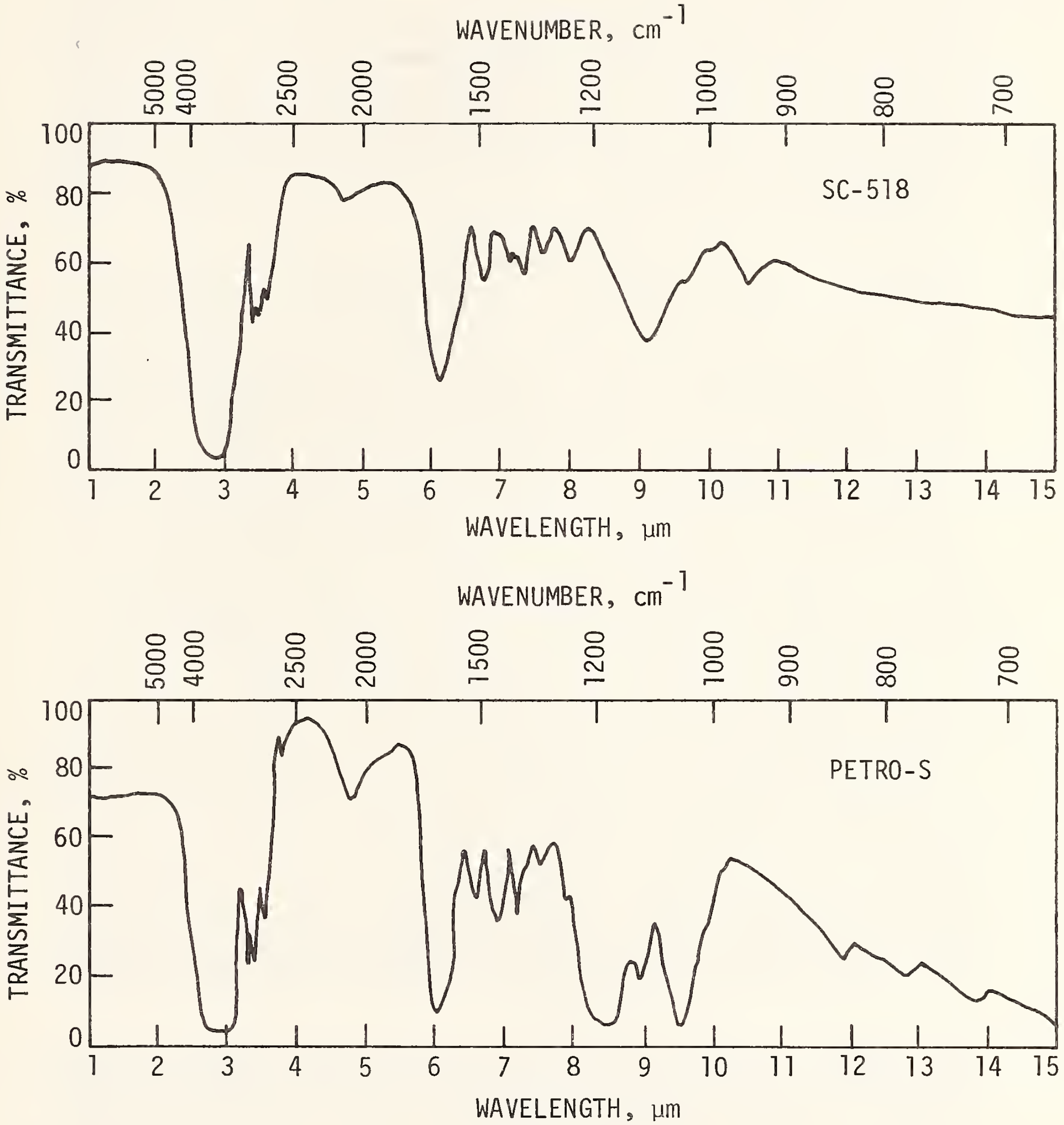

Fig. 85. Typical infrared spectra of chemical compaction aids.

Petro-S. A transparent reddish-brown, viscous liquid, soluble in water, insoluble in benzene, carbon tetrachloride, or chloroform. Strong, broad peaks at 2.9 and 6.1μ and a weak peak at 7.4μ indicate the presence of water. A strong triplet occurs at 3.4μ, and weak but sharp peaks occur at 6.6, 6.9, and 7.3μ, with a strong broad peak at 9.5μ. The strong triplet at 3.4μ suggests the presence of an aliphatic compound. However, the spectrum also indicates a high percentage of water which may obscure adsorption of other compounds. The producer, Petro-Chemical Co., Inc., refers to Petro-S as a sodium alkyl ethylene sulfonate in liquid form.

Coherex. A yellowish-grey, viscous liquid, soluble in water, insoluble in benzene, carbon tetrachloride, or chloroform. The producer, Golden Bear Division, Witco Chemical, refers to Coherex as a concentrated, highly stable emulsion of petroleum oils and resins consisting of about 60% resins and 40% wetting solution. The IR spectrum showed medium broad peaks at 2.9 and 6.1μ and a high background at 8 to 15μ indicating the presence of water. A medium sharp peak at 6.9μ may be due to a C-H stretch, while a similar peak at 7.3μ may indicate CH_3. The spectrum indicates the possibility of an unsaturated aliphatic compound.

SA-1. A black viscous liquid, soluble in water, insoluble in benzene, carbon tetrachloride, or chloroform. Highly acidic, the SA-1 appeared to react with the sodium chloride IR cell plates and did not produce any significant peaks.

Clapak. A black viscous liquid, soluble in water, insoluble in benzene, carbon tetrachloride, or chloroform. Highly acidic, the Clapak appeared to react with the sodium chloride cell plates, producing a meaningless smooth line spectrum.

Claset. A transparent orange liquid, soluble in water, insoluble in benzene, carbon tetrachloride, or chloroform. Very strong broad peaks at 2.9 and 6.1μ and a strong background at 8 to 15μ indicate an abundance of water which may have obscured adsorptions of other compounds.

PVO X-2100. A white viscous liquid, soluble in water, insoluble in benzene, carbon tetrachloride, or chloroform. Strong broad peaks at 2.8 and 6.0μ and a weak peak at 4.7μ indicate presence of water. Medium sharp peaks occur at 5.65, 6.5, 6.7, and 8.35μ, with a medium broad peak at 7.9μ, a doublet at 3.85μ, and weak broad peaks at 7.6, 8.9, 9.4, and 11.9. The spectrum suggests either an ester or an acetate.

PVO X-1000. A yellowish-white, viscous liquid, soluble in water, insoluble in benzene, carbon tetrachloride or chloroform. Medium broad peaks at 2.8 and 6.0μ, a weak peak at 4.7μ, and background at 8 to 15μ, indicate water. Strong peaks occur at 3.3 and 5.65μ, with weak broad peaks at 6.8, 7.2 and 9.95μ. The spectrum suggests the possibility of an ester.

PVO International, Inc., the producer of both X-2100 and X-1000, describe the products as liquid concentrates of polymers dispersed in water with non-ionic surfactants, emulsifiers, and plasticizers.

Thinwater. A transparent, medium viscous liquid, soluble in water, insoluble in chloroform or carbon tetrachloride. This product reacts with benzene, producing a white solution. The spectrum indicates a strong sharp triplet at 3.4μ, a strong broad peak at 8.8μ (probably due to C-O stretch), a medium peak at 2.9μ (possibly due to OH in an alcohol), medium sharp peaks at 6.55, 6.8, 7.65, and 10.5μ, a medium broad doublet at 12.0μ, and weak sharp peaks at 6.7 and 8.9μ. Thinwater may be an aliphatic alcohol but it may also contain some ether.

Tergitol 15-S-9. A transparent viscous liquid, soluble in water, chloroform, and carbon tetrachloride. Reaction with benzene produces a white solution. This product shows a strong broad peak at 8.8μ, a strong sharp doublet at 3.4μ, and medium peaks at 2.9, 6.8, 7.35, 7.7, 8.0, and 10.5μ. The spectrum suggests the presence of an aliphatic alcohol and possibly some ether. Both Tergitol and Thinwater appear to contain the same major compounds, although Thinwater appears in addition, to contain a small quantity of an unknown, unsaturated material.

A nuclear magnetic resonance spectrometer test was conducted on a 50% solution of Tergitol, using carbon tetrachloride as the solvent. The NMR spectrum showed the product as nonaromatic, nonolefinic, but containing ether and alcohol. The 1967 North American edition of McCutcheon's Detergents and Emulsifiers lists other Tergitol products as nonylphenyl polyethylene glycol ethers.

Aerosol OT-75%. A transparent viscous liquid, soluble in water, benzene, carbon tetrachloride, and chloroform. Strong sharp IR peaks at 2.8, 5.8, and 9.5μ, medium peaks at 6.0 and 6.8μ, weak peaks at 7.15, 9.15, and 11.3μ, and a strong sharp triplet at 3.4μ. The spectrum suggests that it might contain some ester and alcohol. The manufacturer, American Cyanamid Co., lists this product as a sodium dioctyl sulfosuccinate.

Poly-Tergent B-300. A transparent viscous liquid, soluble in water and chloroform, but reacts with carbon tetrachloride and benzene to form a white solution. Strong sharp peaks at 2.8, 3.4, 6.1, 6.5, 6.7, 7.6, 7.7, 7.9, and 8.3μ, strong broad peaks at 9, 10.5, and 11.9μ, and weak peaks at 5, 5.7, 6.2, 11.2, and 13.6μ. The IR spectrum suggests partially unsaturated alcohol and ester. McCutcheon's Detergents and Emulsifiers shows this product to be a nonylphenoxy polyethoxyethanol.

Vapor Pressure Osmometer

Membrane osmometry is a good means for determining the number-average molecular weight ($\overline{M}_n$) for polymers which cannot diffuse through the semipermeable membrane. Because of this diffusion restriction, polymers usually must have molecular weights in excess of 20,000 in order to be considered as appropriate candidates for membrane osmometry. Light scattering and viscometry also have minimum molecular-weight restrictions. The ebullimometric and cryoscopic techniques usually employed for micromolecular substances have been used to determine $\overline{M}_n$ for polymers whose molecular weight was below 30,000; however, these methods are both time-consuming and imprecise. The determination of molecular weight by end-group analysis using either physical or chemical means is applicable to polymers with a low degree of polymerization. The best method for determining molecular weights as low as 200 and in excess of 10^6 and for providing the molecular-weight distribution for the system appears to be gel permeation chromatography. The vapor pressure osmometer (VPO) is a low cost, solvent-independent instrument for determination of the molecular weight of small macromolecules.

Theory. The name "vapor-pressure osmometer" is perhaps an unfortunate choice since the device is designed to record a temperature difference between solvent and solution. The temperature difference is created by condensation of solvent on a sensitive thermistor containing a solution of the solute whose molecular weight is to be determined. For ideal solvents with low heat of vaporization, the differential thermistors of the VPO are capable of detecting differences in temperature of the order of 0.0001°; this sensitivity should permit determination of $\overline{M}_n$ for samples up to 20,000. Since the solute-solvent interaction will vary with concentration, any molecular-weight measurements by VPO, as with other solution methods, must be conducted over controlled changes in concentration. If the concentration is too high, significant condensation will occur on the solution droplet thereby reducing the difference in vapor pressure between the solution and the solvent. Sensitivity of the measurement is reduced at low concentrations.

The equation used for interpretation is

$$\frac{\Delta R}{c} = \frac{K}{M_n} (1 + T^2 c)$$

where ΔR is the change in thermister resistance, c is the solution concentration, K is a calibration constant, T is another coefficient, and $\overline{M}_n$ is the molecular weight. A plot of R/c vs. c should be linear and extrapolated to c = 0 gives

$$\overline{M}_n = \frac{K}{(\Delta R/c)_{c \to o}}$$

Since ΔR is a relative quantity dependent on both the solvent and the probe, the VPO must be calibrated with a known molecular weight solute for each solvent and probe used. Known concentrations of sucrose (M.W. = 342.30) dissolved in distilled water were used in this case to determine the molar constant (K). The calibration curve is shown in Fig. 86. The calibration curve extrapolated to infinite dilution is used to determine K which was found to be 34.937. Once K is established, it does not vary for the particular probe and solvent used, and only a single calibration is needed. Similar curves are made with the unknown solutes (in this case, the chemical compaction aids) by using specific weight concentrations and distilled water as the solvent. The weight concentrations used, which varied from one chemical to another, were chosen after many trials to best suit each chemical's physical properties and to give the best possible results. The resulting curves are shown in Figs. 87, 88, and 89. Each curve is extrapolated to infinite dilution to determine $(\Delta R/c)_{c\to 0}$.

Results. Sensitivity of the vapor pressure osmometer with water as a solvent is lower than its sensitivity when an organic solvent is used. The reason is the high heat of vaporization of water. ΔR for water is about 55 ohms per mole. A 3% weight concentration would give 1% precision for molecular weights up to 700 and 4.3% precision up to 3500. The final accuracy of a measurement is dependent on several factors (unrelated to instrument precision) such as the extrapolation, interactions, purity, and concentration effects.

There were two main problems which resulted in errors in the VPO molecular weight determinations of the chemical compaction aids. These were (1) impurity of the chemicals, and (2) some chemicals contained undetermined amounts of water. Manufacturers, literature, patents, etc., have indicated that many of the products which were studied in this project may contain either water or other volatiles. The infrared spectra indicated presence of water in many of the chemical compaction aids and also the presence of alcohol and/or ether in some of them. Some of the products may contain combinations of water, alcohol, etc. For example, Aerosol OT-75% is described by the manufacturer, American Cyanamid Company, as containing "75% active ingredient, the remainder being water and approximately 5% of a lower alcohol to provide fluidity."

The weight loss of each product after being subjected to 105 °C temperature for 24 hours was measured. Weight losses due to volatilization of portions of the various products ranged from 0 (Poly-Tergent B-300 and Tergitol 15-S-9) to 95.0% (Paczyme). The percent weight loss of Aerosol OT-75% was 21.5% (within reasonable proximity of the manufacturer's statement of volatiles content). One exception to a weight loss at 105 °C was the 4.1% weight gain with SA-1. Several re-runs produced identical results. Either the SA-1 undergoes some form of chemical change or tends to absorb moisture after being at 105 °C.

Table 43 presents results of the vapor pressure osmometer tests. Molecular weights reported under column A represent the entire product,

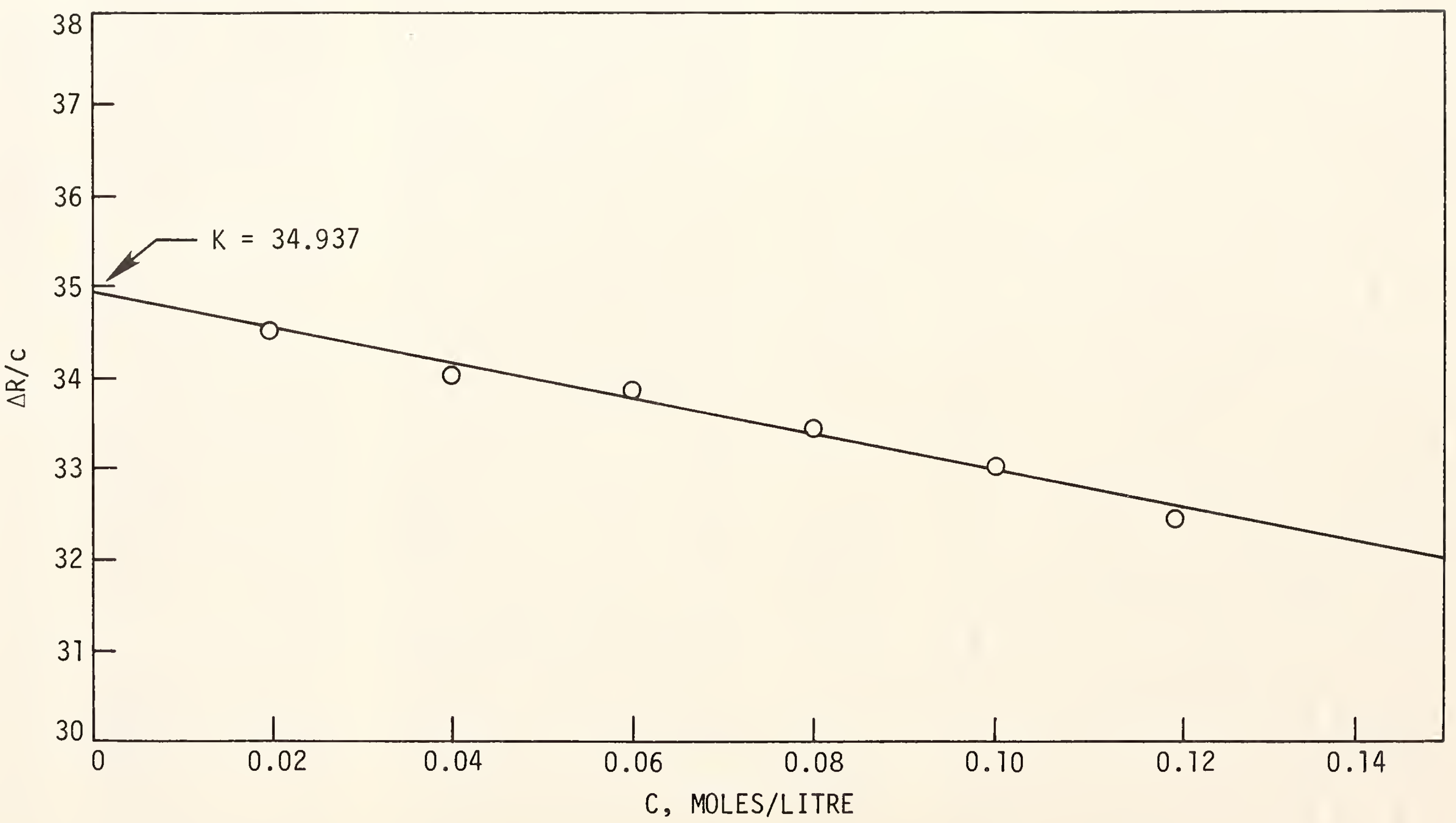

Fig. 86. Calibration curve (sucrose in H_2O).

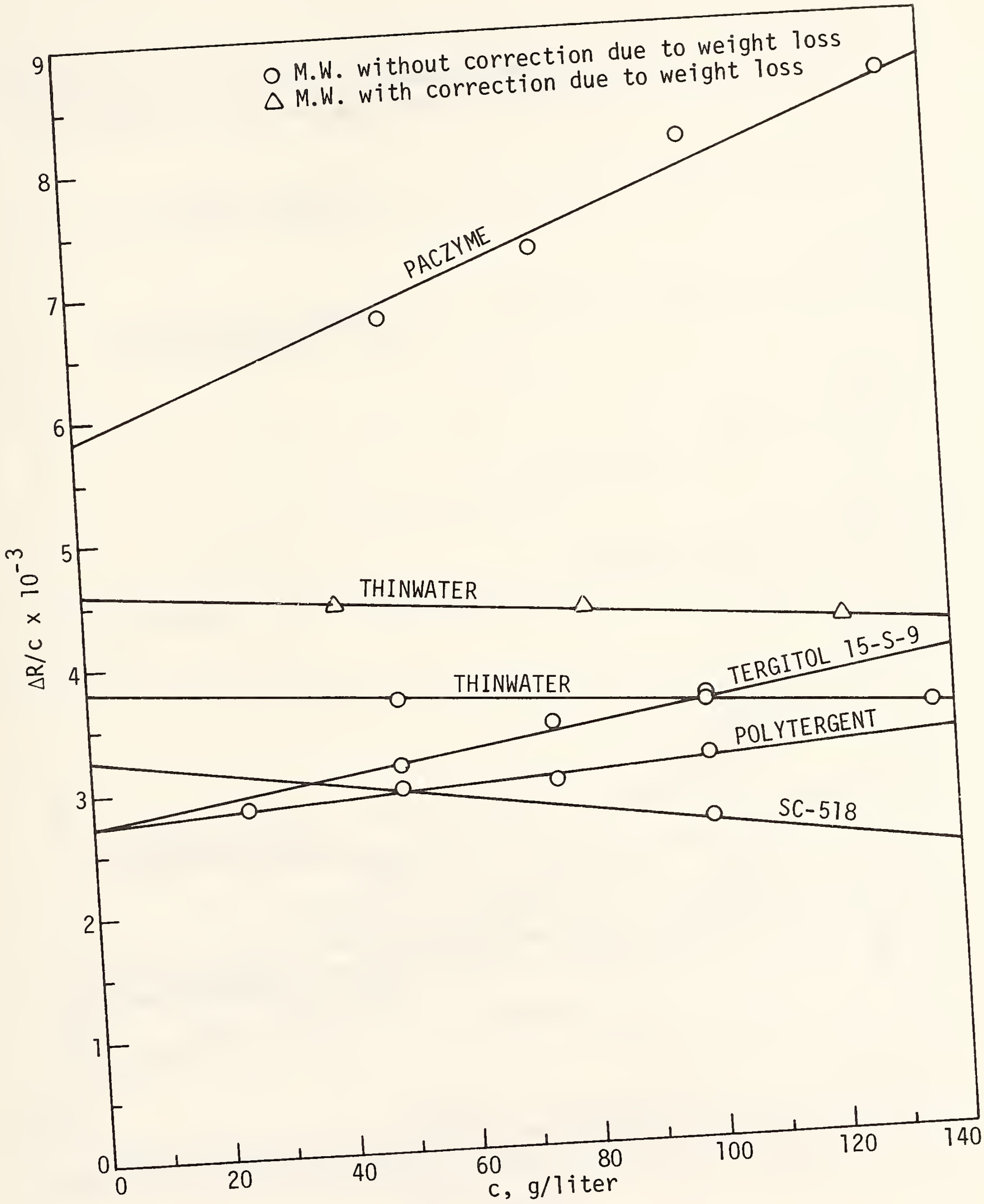

Fig. 87. ΔR/c vs. c of chemical compaction aids.

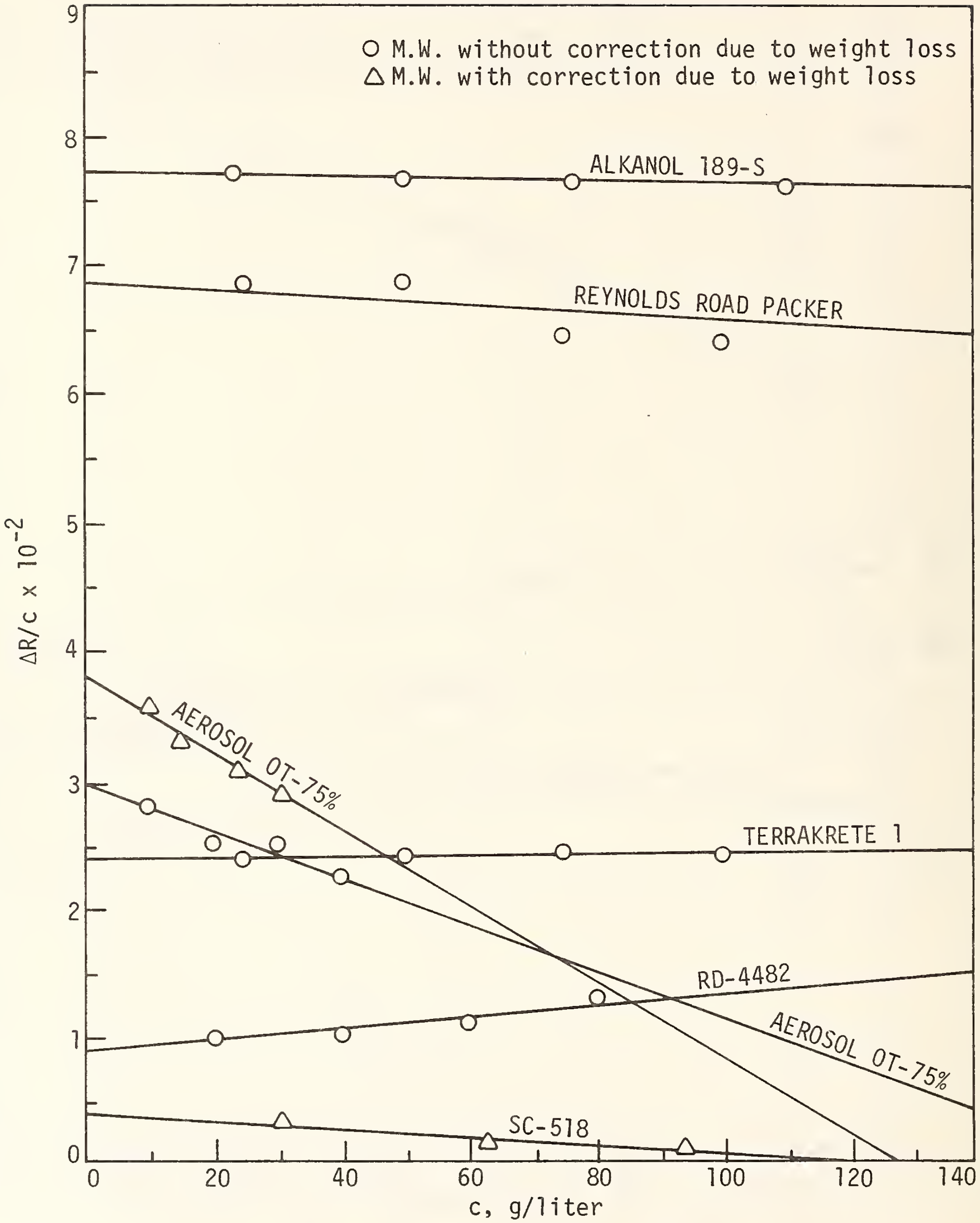

Fig. 88. ΔR/c vs. c of chemical compaction aids.

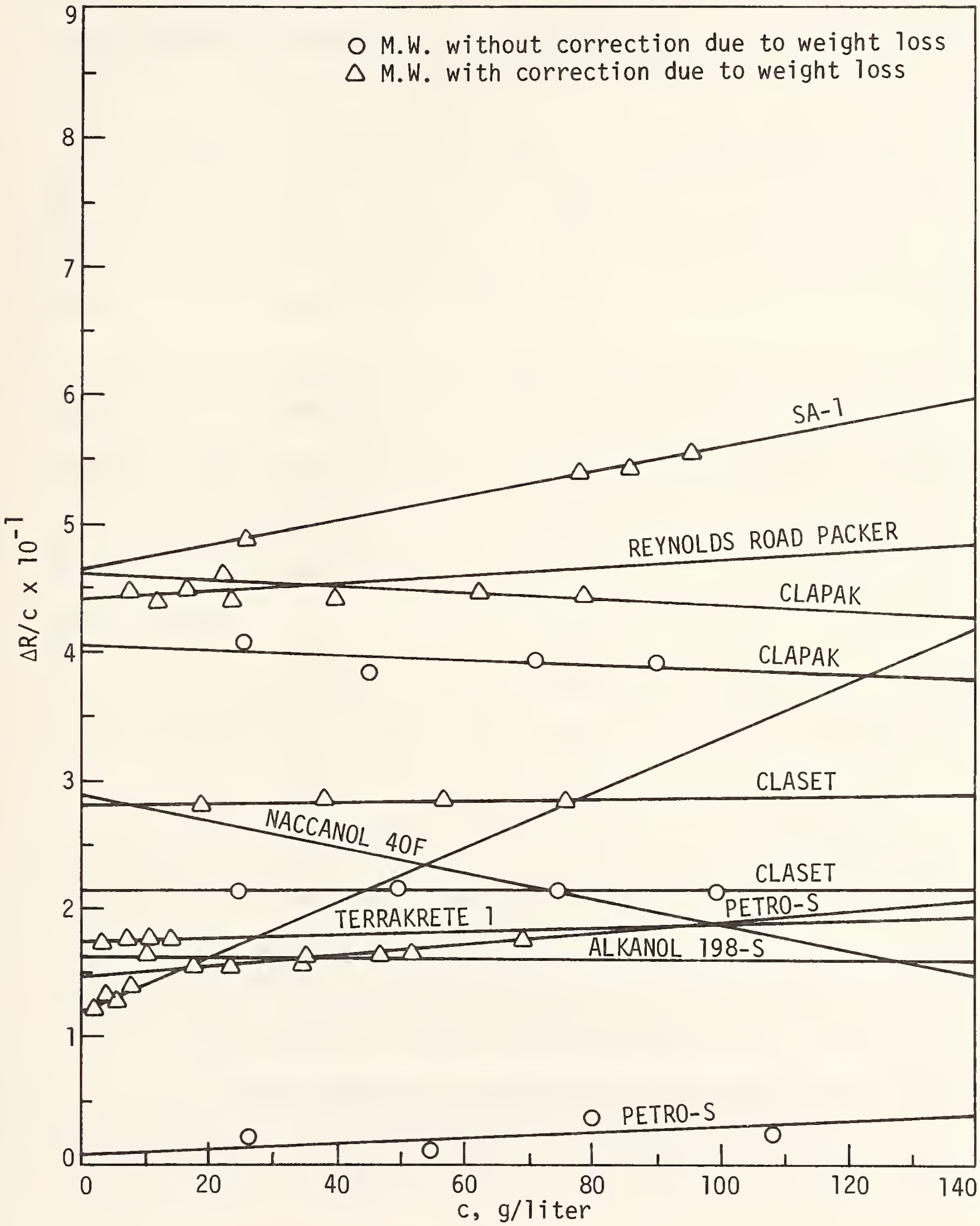

Fig. 89. ΔR/c vs. c of chemical compaction aids.

Table 43. Composite molecular weights as determined by vapor pressure osometer.

Chemical Product	Weight loss or gain at 105 °C, %	Molecular Weight, g/mole	
		A[a]	B[b]
Clapak	-12.6	87	76
Claset	-24.2	166	125
Petro-S	-30.1	346	244
SA-1	+ 4.1	76	76
SC-518	-69.5	10,695	3,359
Poly-Tergent B-300	0	12,940	12,940
Thinwater	-18.8	9,194	7,650
Tergitol 15-S-9	0	12,782	12,782
Terra-Krete 1	-86.3	1,480	202
Paczyme	-95.0	5,994	293
Alkanol 189-S	-53.1	453	213
Road Packer	-84.2	512	79
Aerosol OT 75%	-21.5	1,165	920
Naccanol 40F	-	120	-
RD-4482	-	3,882	-

[a] A = Molecular weight without correction due to weight loss.

[b] B = Molecular weight with correction due to weight loss.

while those in column B represent a molecular weight corrected for loss of all volatiles at 105 °C. Table 43 also presents the percentage weight loss of each product after being subjected to 105 °C for 24 hours. It is believed that the correct molecular weight of each chemical is somewhere in the range between the two estimated molecular weights A and B. There is one prime piece of evidence that supports this result. Literature provided us by manufacturers/distributors gives the molecular weight of the active ingredient of only one product listed in Table 43, Alkanol 189-S. According to E.I. DuPont de Nemours & Co., Inc., this product contains 31.5% sodium alkyl sulfonate at a molecular weight of 354 as the "active ingredient." The manufacturer's "Information Bulletin" contains no information on the inactive ingredient(s). Table 43 shows 53.1% volatile weight loss with molecular weights A and B of 453 and 213, respectively.

Although the vapor pressure osmometer is used to determine the average molecular weight of the solute, the complexity of the chemical compositions decrease accuracy of the results because the purer the tested substance, the more accurate the determined molecular weight. In spite of the errors in VPO results, it was the simplest, fastest, and only available method to determine molecular weight. Mass Spectrometry was attempted on five of the chemical compaction aids, but it did not give any results due to impurity of the chemicals, which also contaminated the column.

Zeta Potential

A clay suspension or clay-water-electrolyte system is considered to be a hydrophobic colloid. It is a two-phase system of small solid particles dispersed in liquid, which means a large interfacial area and a behavior dominated by surface forces.

Two forces exist between the particles in clay suspension: attractive and repulsive.[82] The attractive force is attributed to van der Waals attraction between all atoms of one particle and all atoms of another particle. Magnitude of the total attractive force depends basically on the size and shape of the particles. Particle attraction is counteracted by interparticle repulsive forces that are electrical in nature. When an electric field is applied to a clay suspension, the particles move, indicating that they carry an electric charge; this phenomena is called "electrophoresis."

A clay suspension does not have a net charge deficiency, so the particle charges must be compensated by opposite charges in the suspending medium. The internal balance of charges in a suspension is incorporated in the concept of the "double layer." The double layer

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[82] H. Van Olphen, An Introduction to Clay Colloids Chemistry. (New York: Interscience Publishers, John Wiley & Sons, 1963).

consists of the particle charge itself and an equivalent amount of opposing ionic charge accumulated in the liquid near the particle surface. The accumulated ions of opposite sign are called "counter-ions," which are electrostatically attracted by the charged clay surface. At the same time, the counter-ions diffuse away from the particle surface because of their thermal motion, forming a "diffuse layer."

Clay mineral particles carry a net negative charge that exists mainly on the flat surfaces of the particles. In contrast, the atomic structure of clay crystal edges is a patchwork of positive and negative charges, caused by discontinuities in the tetrahedral silica sheets and the octahedral alumina sheets, with unsatisfied primary bonds. On such surfaces, an electric double-layer is created by adsorption of peptizing or potential-determining ions, and there is the possibility that a positive double layer may exist on the exposed edges despite the fact that the net electrophoretic charge of the clay particle is negative.

Several observations support the concept of a positive edge charge. For example, clays show a certain anion adsorption capacity under certain conditions, which would be expected if there is a positive edge double-layer. Also, the positive edge double-layer would be responsible for electrostatic attraction between the edges and the negatively charged flat surfaces of the clay particles, resulting in the observable edge-to-face particle associations or "card-house structure" of flocculated clays. In natural soil clays, the double-layer of the clay particle must be quite complicated due to the differences in crystallography of the exposed edges and surfaces of the various clay particles.

Measurement of the Zeta Potential. Zeta potential is an electric potential within the double layer, actually at the interface between the particle as it moves in an electric field and the surrounding liquid. This is because the zeta potential is computed from the electrophoretic mobility of the suspended particles. Upon addition of a strong electrolyte, the zeta potential usually decreases, and at the flocculation value of the electrolyte, the zeta potential is considered to have reached a critical value below which the particle repulsion is no longer strong enough to prevent flocculation.

A Laser Zee Meter Model 400 was used to measure zeta potential of colloid particles in a number of soil-water suspensions. The suspension to be measured is placed in an electrophoresis cell consisting of two electrode chambers and a connecting chamber with length: 10 cm, width: 15 mm, and depth: 1.5 mm, for viewing the particles. A voltage is applied between two electrodes in the end chambers: the anode is molybdenum, and the cathode is platinum. The applied voltage produces a uniform electric field in the viewing chamber, and charged particles respond by moving toward one of the electrodes. The direction of movement indicates the sign of the charge, and particle speed is directly proportional to the zeta potential. In order to avoid complications from a reverse fluid flow (termed "elecroosmosis"), all measurements were made at the calculated height of the stationary layer which, for this particular unit, is at 212 µm from the top of the cell.

Once the microscope and laser are focused at the correct level, a zeta potential measurement is made by a unique, patented technique. By adjusting a prism-rotational control until the apparent motion caused by the prism exactly cancels the particle velocity caused by the applied field, the particles appear stationary in the field of view, and the zeta potential is displayed on a digital readout. The zeta potential reading is independent of the applied cell voltage which can be varied from 0 to 400 volts (200 volts is commonly used as the applied cell voltage), giving a field strength of 0 to 40 volts/cm. The range of zeta potential which may be measured is -100 to +100 mv with accuracy of ±5%. The measured zeta potential is corrected to a reference temperature of 20 ^{o}C by multiplying the measured value by (1 - 0.02T), where T is the degrees C above 20. This correction arises from particle surface potential being proportional to absolute temperature of the suspension.

The Laser Zee Meter also measures specific conductance of the colloid in the cell. Conductance (units in mhos) is the reciprocal of the resistance, (ohm). Specific conductance is the conductance per unit length, i.e. mhos/cm. The measurement range varies from 100 k µ mhos to 1 µ mho with accuracy ±10%.

Samples. Twelve of the soils used in the project research were studied for changes in zeta potential with chemical treatments. Three relatively pure mineral clays were used: Grundite that is predominantly illite, a Wyoming bentonite that is a sodium montmorillonite, and a kaolinite from Mesa Alta, New Mexico (Ward's Natural Science Establishment, Reference Clay No. 9). Seven chemicals were selected to treat the soils: Clapak, Claset, Petro-S, Thinwater, SA-1, Road Packer, and SC-518.

The first step in sample preparation was a sedimentation process which was carred out as follows:

1. 100 gm of soil was mixed with distilled water by a high-speed mixer until the soil was dispersed into its individual particles (approximately 10 minutes).

2. After mixing, the specimen was washed into a graduated cylinder, and distilled water was added to bring the level to the 1000 ml mark.

3. The soil and water were shaken in the graduated cylinder and allowed to settle for 20 hours.

4. After 20 hours, the upper part of the suspension, containing the particles of less than 2 μm in size (calculated from Stokes's Law) was carefully transferred into a large evaportaing dish and dried in an oven at 105 °C.

The object of the sedimentation process was to prepare a sample which included only the clay minerals and colloids of each soil. Several hundred grams of each soil, one hundred in each graduated cylinder, were used to prepare enough sample to carry out zeta potential experiments on untreated and chemically treated clay and colloid fractions.

Treatment of the clays was done as follows:

1. A chemical-water solution was prepared at a concentration of 1% using each of the seven chemicals and distilled water.

2. For each soil, 10 ml of the chemical-water solution were leached through a 1 gm sample of the soil clay (< 2 μm), held on Millipore filter paper (type vc, opening = 0.1 μm). A partial vacuum accelerated the process.

3. After leaching, half of the sample was oven-dried for 2 hours at 105 °C, and the other half was stored in wet condition in a closed container to be tested after 7 days.

At this point the sample was ready to be used in the electrophoretic experiment. To be tested in the Laser Zee Meter, the sample must exhibit a Tyndall effect, usually achieved by having a colloidal concentration in the range of 50 to 500 ppm. If the sample was too dilute, a few particles could be seen in the field of view at one time, increasing the time needed to make a measurement. Conversely, a too-concentrated suspension resulted in viewing hundreds of particles at once and caused light diffusion. A colloidal concentration of 200 ppm was chosen, and the experiment proceeded as follows:

1. A 0.1 gm of each sample was mixed with about 100 ml of distilled water in a 200 ml beaker, agitated for 10 minutes by means of a magnetic stirrer, and then transferred to a 500 ml graduated cylinder. Distilled water was added to give the required concentration.

2. The suspension was shaken, and about 20 ml was withdrawn by a syringe and placed into a beaker for measurement of pH. Additional suspension was withdrawn to fill the Laser Zee Meter cell.

3. After filling the cell and placing it in the Laser Zee Meter, zeta potential and specific conductance were measured by following the operating procedure of the device as specified by the manufacturer.

4. The sample was then emptied from the cell into a beaker, and temperature was measured using a special connection provided by the device.

The above procedure was used to measure zeta potential for each untreated soil and chemical-soil combination, immediately after preparation and 7 days after treatment.

Zeta Potential Results and Compaction Aid Effectiveness. Tables 44 through 54 present results of zeta potential measurements, plus predictions of compaction effectiveness based on increasing numerical values (i.e., more negative) of zeta potential from addition of chemicals. Also in the tables are the effectiveness ratings previously reported on the basis of M-D compaction tests.

Out of 52 soil-chemical combinations evaluated by both compaction tests and zeta potential measurements, agreement with the zeta potential prediction was noted 45 times, or an 88% compliance. For this comparison, combinations designated by 0 (partially effective) in the tables were considered as effective. Thus, the change in zeta potential is a fairly accurate predictor of compaction effectiveness and might be used as a relatively rapid and inexpensive screening test. That is, if the zeta potential of the soil is increased (becomes more negative) upon addition of a chemical, the chemical most likely will be partially to fully effective as a compaction aid. The main discrepancy was noted in the case of Clapak.

A more negative zeta potential should give lower strength because of increased particle repulsions. Ideally after compaction, strength must be regained which might correlate with a recovery in zeta potential with time. To test this, zeta potential measurements made after 7 days moist curing were compared with analogous changes in bearing capacities calculated from K-Test data. Of 25 combinations tested both ways, agreement was found for 24 cases, or a 96% compliance. Thus, a numerical decrease (less negative) zeta potential after 7 days signals an increase in strength, i.e. a strength improvement on curing. The converse also is true.

Of the 55 soil-chemical combinations noted in Tables 44-54, 30 indicate an improvement in strength with time, while 25 indicate a strength loss. The chemicals listed in decreasing order of strength-recovery effectiveness are as follows:

Table 44. Zeta potential (ZP), specific conductance, and pH of untreated and chemically treated Bearden series.

Chemical Compaction Aid	pH		Zeta Potential mv		Specific Conductance μ mhos/cm		Compaction Effectiveness at Maximum γ_d and OMC[a]	Expected Compaction Effectiveness According to ZP[b]
	at 0 time	after 7 days	at 0 time	after 7 days	at 0 time	after 7 days		
(Untreated)	7.65	7.65	-14.1	-14.1	12	12	/	/
Clapak	6.05	6.44	-18.1	-15.8	15	13	+	Z
Claset	6.48	6.42	-15.1	- 9.2	10	7	+	Z
Petro-S	7.61	7.00	-14.8	-13.1	12	11	+	Z
Thinwater	7.00	6.90	-14.6	-13.7	10	8	0	Z
SA-1	6.20	6.13	-13.7	-14.4	26	17	-	X

[a] + = fully to partially effective, 0 = partially effective, - = not effective.

[b] Z = expected to be effective, X = expected to be ineffective.

Table 45. Zeta potential (ZP), specific conductance, and pH of untreated and chemically treated Renohill series.

Chemical Compaction Aid	pH		Zeta Potential mv		Specific Conductance μ mhos/cm		Compaction Effectiveness at Maximum γ_d and OMC[a]	Expected Compaction Effectiveness According to ZP[b]
	at 0 time	after 7 days	at 0 time	after 7 days	at 0 time	after 7 days		
(Untreated)	5.80	5.80	-19.0	-19.0	8	8	/	/
Clapak	5.02	4.64	-28.6	-25.9	7	9	-	Z
Claset	5.57	5.70	-18.6	-19.4	5	4	-	X
Petro-S	6.30	6.42	-26.5	-22.4	4	4	0	Z
SC-518	6.55	6.22	-18.8	-17.0	4	4	-	X

[a] 0 = partially effective, - = not effective.

[b] Z = expected to be effective, X = expected to be ineffective.

Table 46. Zeta potential (ZP), specific conductance, and pH of untreated and chemically treated Rimrock series.

Chemical Compaction Aid	pH		Zeta Potential mv		Specific Conductance μ mhos/cm		Compaction Effectiveness at Maximum γ_d and OMC[a]	Expected Compaction Effectiveness According to ZP[b]
	at 0 time	after 7 days	at 0 time	after 7 days	at 0 time	after 7 days		
(Untreated)	7.00	7.00	-19.7	-19.7	7	7	/	/
Clapak	5.20	5.13	-24.2	-25.9	7	10	+	Z
Claset	6.55	5.32	-22.6	-21.9	6	8	0	Z
Petro-S	5.35	7.00	-17.9	-20.2	8	8	-	X
Thinwater	6.04	7.00	-19.1	-19.2	5	7	/	X
SA-1	5.00	4.90	-22.9	-20.6	15	22	+	Z

[a] + = fully to partially effective, 0 = partially effective, - = not effective.

[b] Z = expected to be effective, X = expected to be ineffective.

Table 47. Zeta potential (ZP), specific conductance, and pH of untreated and chemically treated Peavine series.

Chemical Compaction Aid	pH		Zeta Potential mv		Specific Conductance μ mhos/cm		Compaction Effectiveness at Maximum γ_d and OMC[a]	Expected Compaction Effectiveness According to ZP[b]
	at 0 time	after 7 days	at 0 time	after 7 days	at 0 time	after 7 days		
(Untreated)	5.20	5.20	-33.0	-33.0	4	4	/	/
Clapak	4.82	4.90	-22.8	-25.9	12	10	+	X
Claset	4.70	5.00	-18.6	-14.6	8	8	0	X
Petro-S	5.60	6.00	-38.2	-37.8	4	4	0	Z
Thinwater	5.78	5.60	-34.0	-31.3	2	2	++	Z
SA-1	4.75	4.75	-24.2	-21.4	12	12	+	X
SC-518	5.65	4.88	-34.2	-33.8	3	4	+	Z
Road Packer	5.20	4.82	-35.9	-29.4	4	5	+	Z

[a] ++ = fully effective, + = fully to partially effective, 0 = partially effective.

[b] Z = expected to be effective, X = expected to be ineffective.

Table 48. Zeta potential (ZP), specific conductance, and pH of untreated and chemically treated Marias series.

Chemical Compaction Aid	pH		Zeta Potential mv		Specific Conductance µ mhos/cm		Compaction Effectiveness at Maximum γ_d and OMC[a]	Expected Compaction Effectiveness According to ZP[b]
	at 0 time	after 7 days	at 0 time	after 7 days	at 0 time	after 7 days		
(Untreated)	8.95	8.95	- 9.3	- 9.3	17	17	/	/
Clapak	7.15	7.00	-11.8	-17.2	16	16	+	Z
Claset	7.00	7.60	-10.2	-13.0	12	12	+	Z
Petro-S	9.12	9.10	-12.3	-13.1	17	20	+	Z
Thinwater	8.80	9.00	- 9.3	-12.6	17	17	/	X
SA-1	6.00	6.20	-17.8	-14.5	21	21	++	Z

[a] ++ = fully effective, + = fully to partially effective.

[b] Z = expected to be effective, X = expected to be ineffective.

Table 49. Zeta potential (ZP), specific conductance, and pH of untreated and chemically treated Frederick series.

Chemical Compaction Aids	pH		Zeta Potential mv		Specific Conductance µ mhos/cm		Compaction Effectiveness at Maximum γ_d and OMC[a]	Expected Compaction Effectiveness According to ZP[b]
	at 0 time	after 7 days	at 0 time	after 7 days	at 0 time	after 7 days		
(Untreated)	5.50	5.50	-21.8	-21.8	3	3	/	/
Clapak	5.00	5.00	- 9.1	-14.2	8	6	-	X
Claset	5.10	5.00	-15.9	- 3.2	5	7	-	X
Petro-S	5.75	5.84	-31.9	-35.9	3	3	+	Z
Thinwater	5.00	5.65	-25.2	-30.3	3	3	+	Z
SA-1	4.85	5.05	-20.3	-21.4	6	5	-	X

[a] ++ = fully effective, + = fully to partially effective, - = not effective

[b] Z = expected to be effective, X = expected to be ineffective.

Table 50. Zeta potential (ZP), specific conductance, and pH of untreated and chemically treated Persanti series.

Chemical Compaction Aid	pH		Zeta Potential mv		Specific Conductance μ mhos/cm		Compaction Effectiveness at Maximum γ_d and OMC[a]	Expected Compaction Effectiveness According to ZP[b]
	at 0 time	after 7 days	at 0 time	after 7 days	at 0 time	after 7 days		
(Untreated)	6.00	6.00	-19.2	-19.2	3	3	/	/
Clapak	5.00	5.00	- 8.2	-12.6	9	6	0	X
Claset	4.48	5.20	- 2.0	- 4.2	5	6	-	X
Petro-S	5.85	5.95	-29.6	-26.7	3	3	+	Z
Thinwater	6.00	6.00	-20.4	-18.9	3	3	0	Z
SA-1	4.92	4.44	-13.8	-18.2	9	7	-	X
SC-518	6.00	6.00	-10.2	-10.8	3	3	-	X

[a] + = fully to partially effective, 0 = partially effective, - = not effective

[b] Z = expected to be effective, X = expected to be ineffective.

Table 51. Zeta potential (ZP), specific conductance, and pH of untreated and chemically treated Nappanee series.

Chemical Compaction Aid	pH		Zeta Potential mv		Specific Conductance µ mhos/cm		Compaction Effectiveness at Maximum γ_d and OMC[a]	Expected Compaction Effectiveness According to ZP[b]
	at 0 time	after 7 days	at 0 time	after 7 days	at 0 time	after 7 days		
(Untreated)	7.82	7.82	-19.4	-19.4	12	12	/	/
Clapak	6.45	6.45	-19.2	-19.8	18	18	-	X
Claset	6.65	6.65	-10.9	-14.2	8	6	-	X
Petro-S	8.65	9.00	-19.0	-18.0	13	13	-	X
Thinwater	8.82	8.90	-17.0	-18.8	14	15	/	X
SA-1	6.00	6.80	-21.7	-20.8	25	20	+	Z

[a] + = fully to partially effective, - = not effective.

[b] Z = expected to be effective, X = expected to be ineffective.

Table 52. Zeta potential (ZP), specific conductance, and pH of untreated and chemically treated Vergennes series.

Chemical Compaction Aid	pH		Zeta Potential mv		Specific Conductance μ mhos/cm		Compaction Effectiveness at Maximum γ_d and OMC[a]	Expected Compaction Effectiveness According to ZP[b]
	at 0 time	after 7 days	at 0 time	after 7 days	at 0 time	after 7 days		
(Untreated)	9.00	9.00	-12.9	-12.9	15	15	/	/
Clapak	6.27	6.10	-20.8	-20.7	18	18	0	Z
Thinwater	9.00	9.00	-19.0	-12.4	15	19	+	Z
SC-518	9.00	9.00	-16.9	-10.5	15	15	0	Z
Road Packer	8.75	8.50	-12.4	-14.1	13	11	-	X
Petro-S	9.15	9.15	-17.9	-10.9	20	20	+	Z
SA-1	6.00	6.00	-19.0	-16.3	38	38	0	Z

[a] + = fully to partially effective, 0 = partially effective, - = not effective.

[b] Z = expected to be effective, X = expected to be ineffective.

Table 53. Zeta potential (ZP), specific conductance, and pH of untreated and chemically treated Melbourne series.

Chemical Compaction Aid	pH		Zeta Potential mv		Specific Conductance µ mhos/cm		Compaction Effectiveness at Maximum γ_d and OMC[a]	Expected Compaction Effectiveness According to ZP[b]
	at 0 time	after 7 days	at 0 time	after 7 days	at 0 time	after 7 days		
(Untreated)	5.88	5.88	-19.6	-19.6	4	4	/	/
Clapak	4.91	5.00	-13.8	-14.5	10	7	0	X
Claset	5.00	5.00	-14.7	- 9.0	4	5	+	X
Petro-S	5.86	5.15	-34.7	-23.3	4	3	+	Z
SC-518	5.10	5.76	-25.6	-19.6	4	2	0	Z
SA-1	4.85	4.42	-20.5	-20.0	10	12	+	Z

[a] + = fully to partially effective, 0 = partially effective.

[b] Z = expected to be effective, X = expected to be ineffective.

Table 54. Zeta potential (ZP), specific conductance, and pH of untreated and chemically treated Shelby series.

Chemical Compaction Aid	pH		Zeta Potential mv		Specific Conductance μ mhos/cm		Compaction Effectiveness at Maximum γ_d and OMC[a]	Expected Compaction Effectiveness According to ZP[b]
	at 0 time	after 7 days	at 0 time	after 7 days	at 0 time	after 7 days		
(Untreated)	7.00	7.00	-19.9	-19.9	5	5	/	/
Claset	5.43	5.79	-21.0	-27.3	5	7	+	Z
Thinwater	6.22	6.22	-20.5	-24.8	4	4	+	Z

[a] + = fully to partially effective.

[b] Z = expected to be effective.

	Percent of soil-chemical combinations with strength recovery predicted, %	Percent of soil-chemical combinations predicted effective %
SC-518	80	60
Petro-s	70	80
SA-1	67	56
Road Packer	(50)[*]	(50)[*]
Thinwater	44	67
Claset	40	40
Clapak	30	50

[*] Insufficient data fo fully evaluate

In most cases, chemicals below the dashed line were deleterious to strength, at least over the period 0-7 days after mixing. On this basis, it would appear that only SC-518, Petro-S, and SA-1 would be acceptable for use on widely variable soils.

The above speculation is supported by field test data for Claset and Thinwater treated Shelby soil. Both chemical treatments resulted in an increase in density, consistent with the zeta potential data of Table 54. After 10 months, field densities showed a further increase, and strength was further reduced, also predictable from the change in zeta potential with time.

Pure Clays. Parallel zeta potential measurements on the highly illitic Grundite clay, on a sodium montmorillonite, and on a kaolinite, indicate that Clapak, Claset, Petro-S, Thinwater, or SA-1 all should be effective compaction aids for the Grundite, while none should be effective with the montmorillonite or kaolinite. Only the Grundite was actually compaction tested (Phase I), and no chemicals were found to be effective. Thus, zeta potential criteria may not apply to pure clays, perhaps because other factors such as structure dominate.

A prime purpose in testing the relatively pure clays was to ascertain if any changes that occurred through chemical treatment might be detectable in the infrared spectra or x-ray diffraction. Soils analyzed by infrared must have a particle size smaller than the wavelength of the rays in order to eliminate scattering and reflection. Clays separated by sedimentation for the zeta potential experiments were of suitable size for the infrared study. The pellet method of preparation was selected to prepare the samples: 10 mg of soil--either treated or untreated--were mixed with an excess of KBr (in a ratio of 1 to 500). After drying the mixture at 120 °C, it was pressed, in a die for 1 minute at about 10 ton/cm^2, into a transparent pellet 10 mm in diameter and about 1 mm in thickness. A reference pellet with only KBr was used in the reference beam.

Figures 90, 91, and 92 show the infrared spectra of Grundite, kaolinite, and bentonite, respectively, for both untreated soils and soils treated with Clapak, Claset, Petro-S, Thinwater, and SA-1 immediately after mixing and at 7 days. There was little difference between the treated and untreated soil spectra, the main functional groups being present in every spectrum. Thus, no significant change could be inferred related to isomorphous substitutions by the chemical additives. Only minute shifts in the frequencies of vibrations and minor differences in the treated soil intensities were observed when comparing with the untreated soil spectra.

Some of the natural soils were also tested by the infrared technique. These included Bearden, Renohill, Rimrock, Peavine, Marias, Frederick, Nappanee, and Melbourne series. In each, no significant differences were noticed between the infrared spectra of the untreated and those of the chemically treated soil.

Figures 93, 94, and 95 present the x-ray diffraction patterns of untreated and chemically treated bentonite (sodium montmorillonite), kaolinite, and Grundite soils, respectively. The chemicals selected for treatment were Clapak, Claset, Petro-S, Thinwater, and SA-1, the same chemicals as used in the infrared spectroscopy.

X-ray diffraction patterns for the untreated and treated kaolinite and illite clays (Figs. 94 and 95) show virtually no changes which indicates no appreciable reactions affecting crystal structures. The 10 Å illite peak was flatter upon treatment with Thinwater, which suggests some possible expansion; however, the second- and third-order reflections from this spacing, at 5 and 3.3 Å, remained sharp. In the case of the montmorillonite clay (Fig. 93), the air-dry basal 12 Å spacing was diminished in intensity by treatment with Clapak, Claset, and SA-1, all of which are strongly acidic and may degrade the clay mineral or decrease uniformity of the interlayer spacing. Treatment with Thinwater gave a large, sharp peak at 16 Å, suggesting that molecules of this chemical penetrate and stabilize the interlayer region. Thinwater has the highest molecular weight of the five selected chemicals. From a compaction standpoint, interlamellar adsorption is believed to be deleterious since it removes chemicals from the double layer system.

Discussion and Conclusions. Several observations may be made with regard to reaction mechanisms of the chemical compaction aids:

1. The quantities of chemicals used are far below the ion exchange capacities of the soils. Compaction effectiveness, therefore, does not appear to relate to ion exchange saturation, although ion exchange may occur.

2. Different soils react differently with a given chemical, even though the predominant clay minerals and exchangable cations may be the same. Because of the small chemical amounts used, it

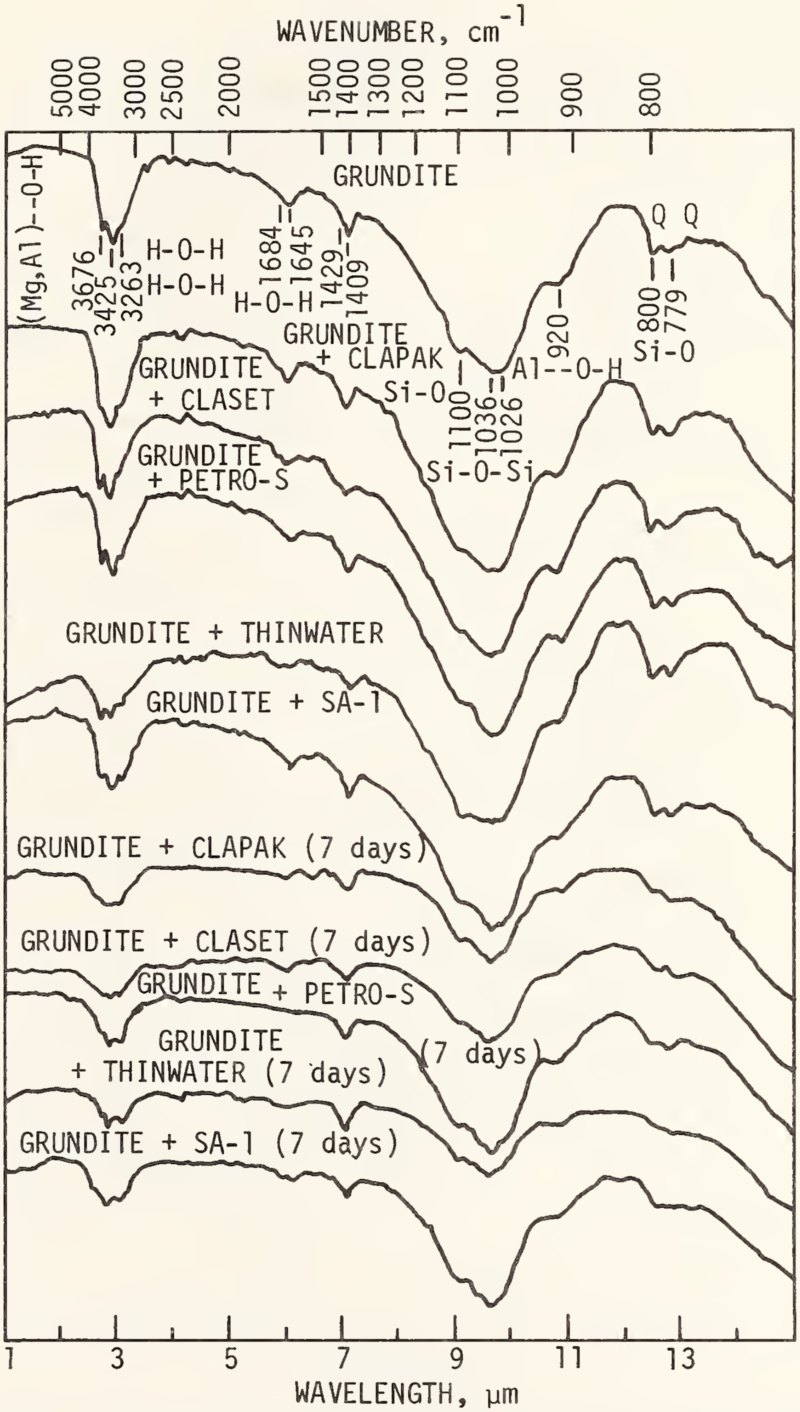

Fig. 90. Infrared spectra of untreated and treated Grundite.

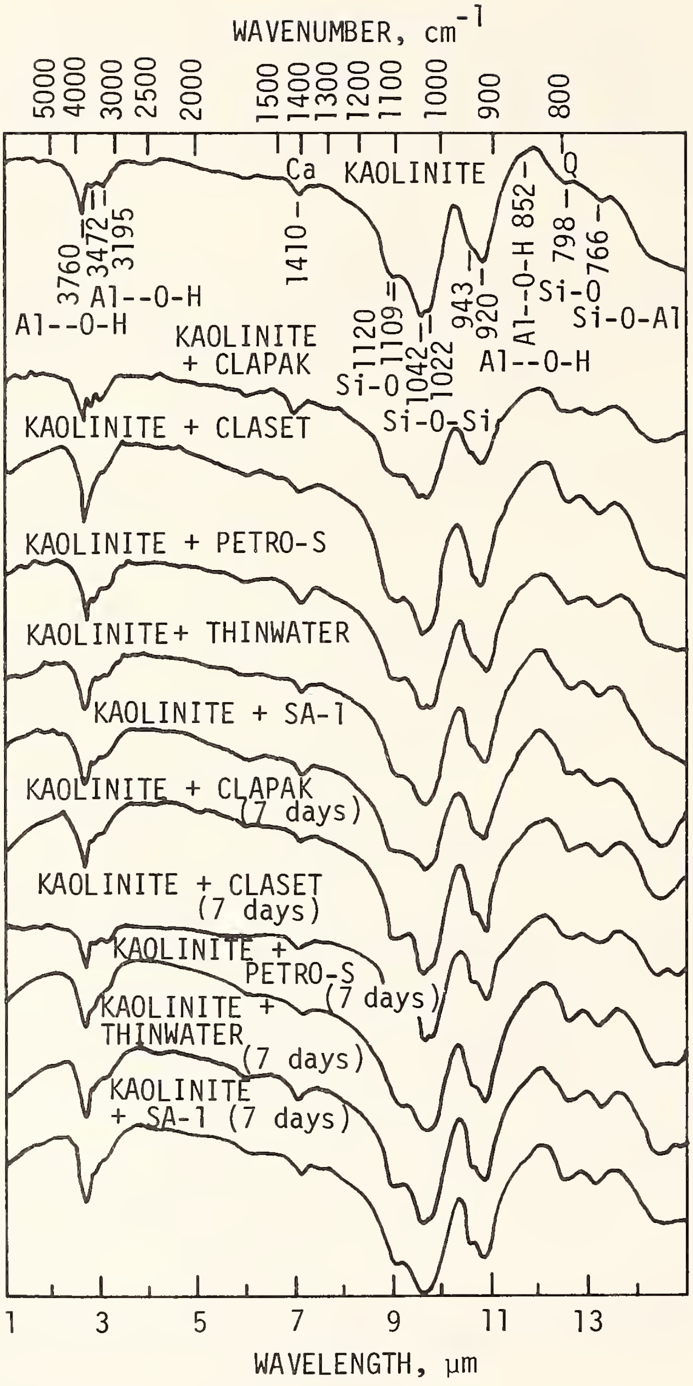

Fig. 91. Infrared spectra of untreated and treated Kaolinite.

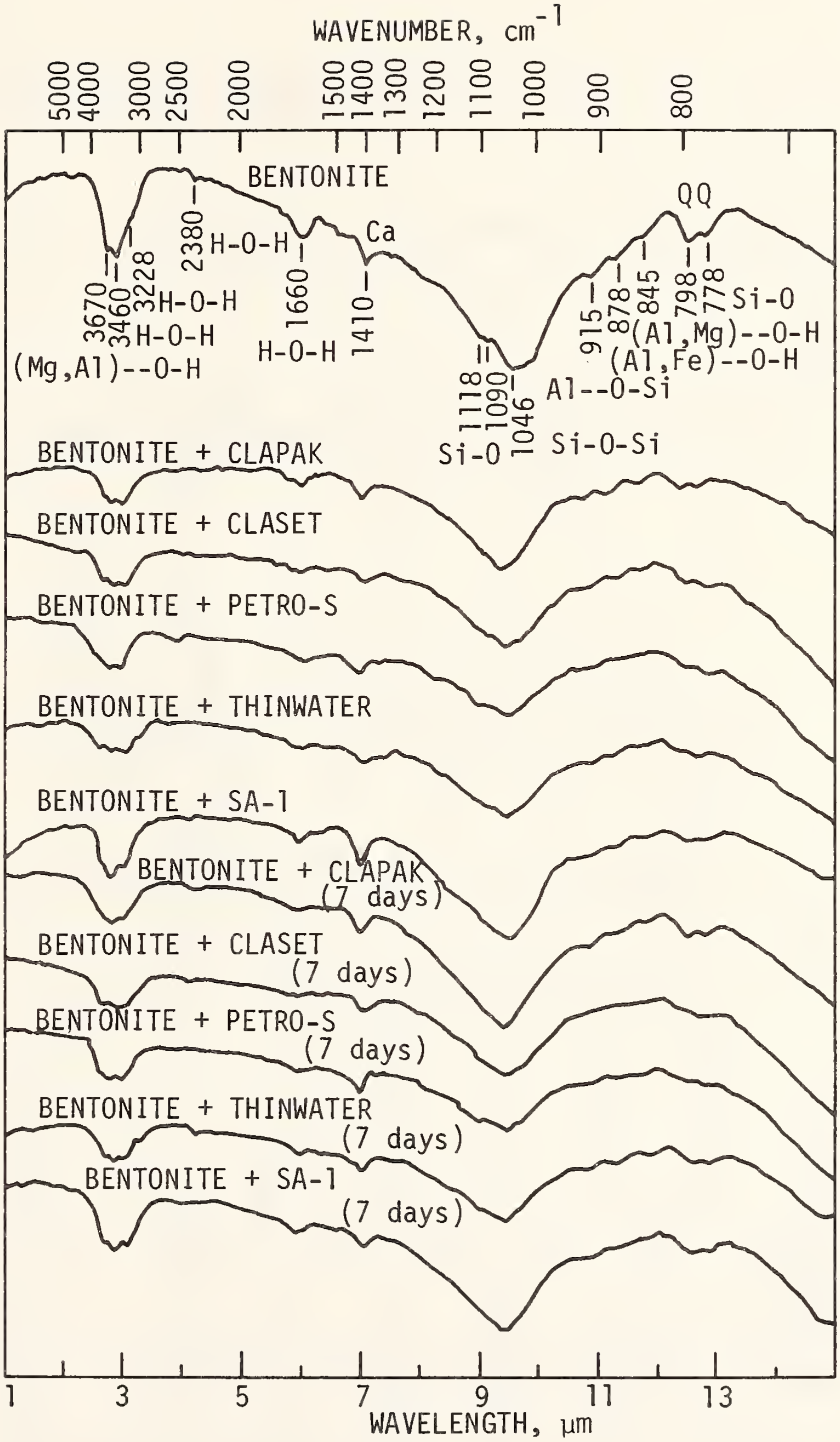

Fig. 92. Infrared spectra of untreated and treated Bentonite.

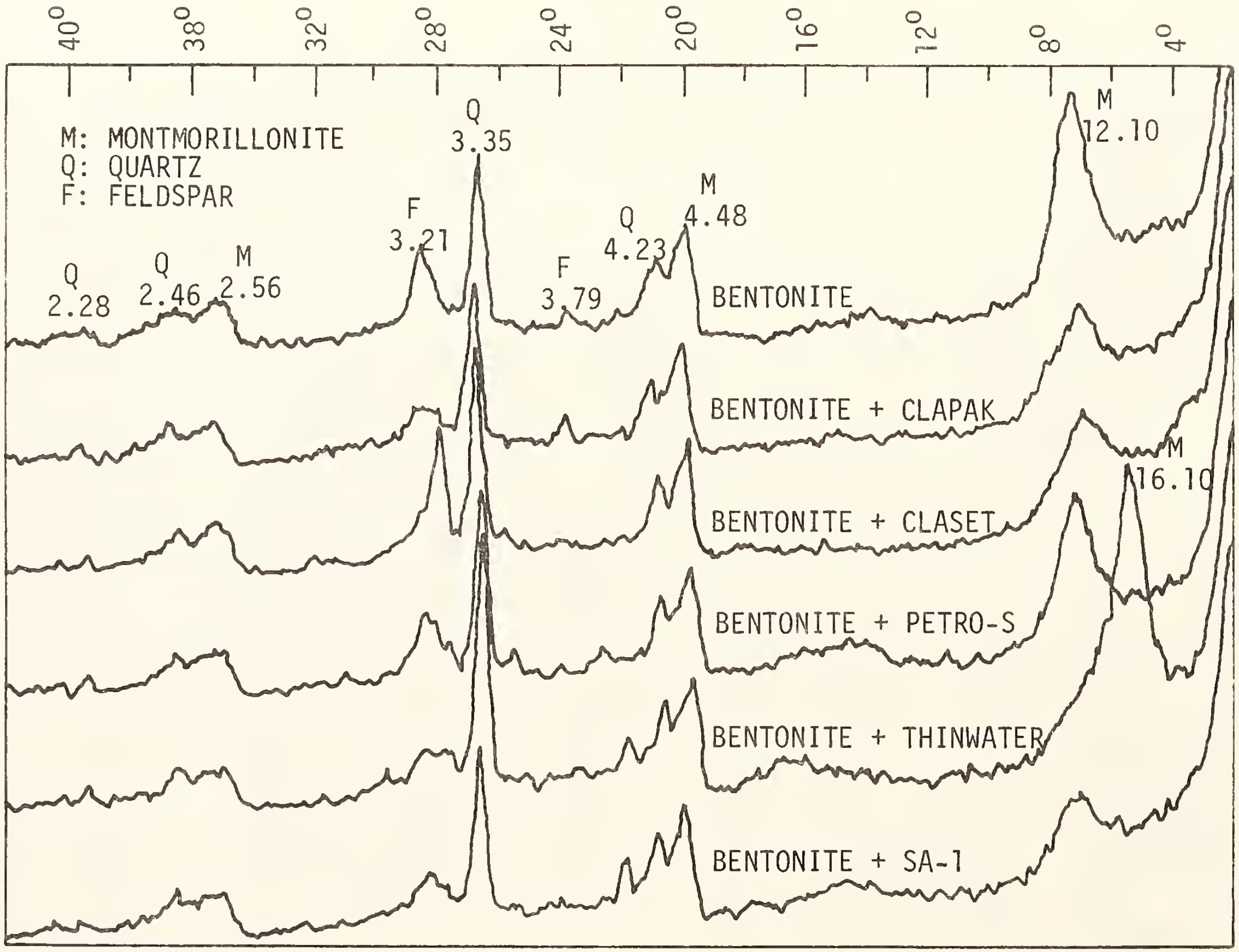

Fig. 93. X-ray diffraction of untreated and chemically treated Bentonite.

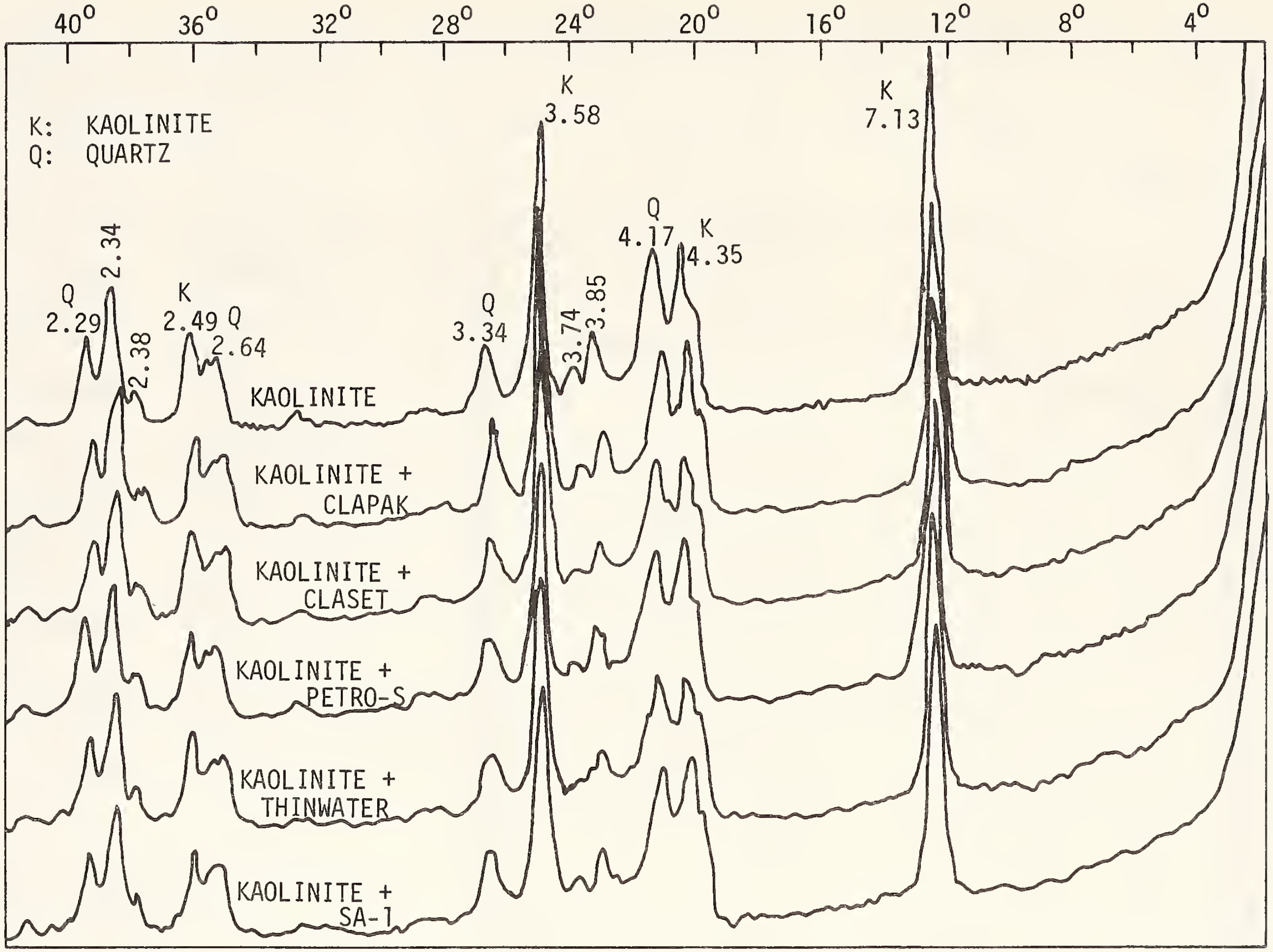

Fig. 94. X-ray diffraction of untreated and chemically treated Kaolinite.

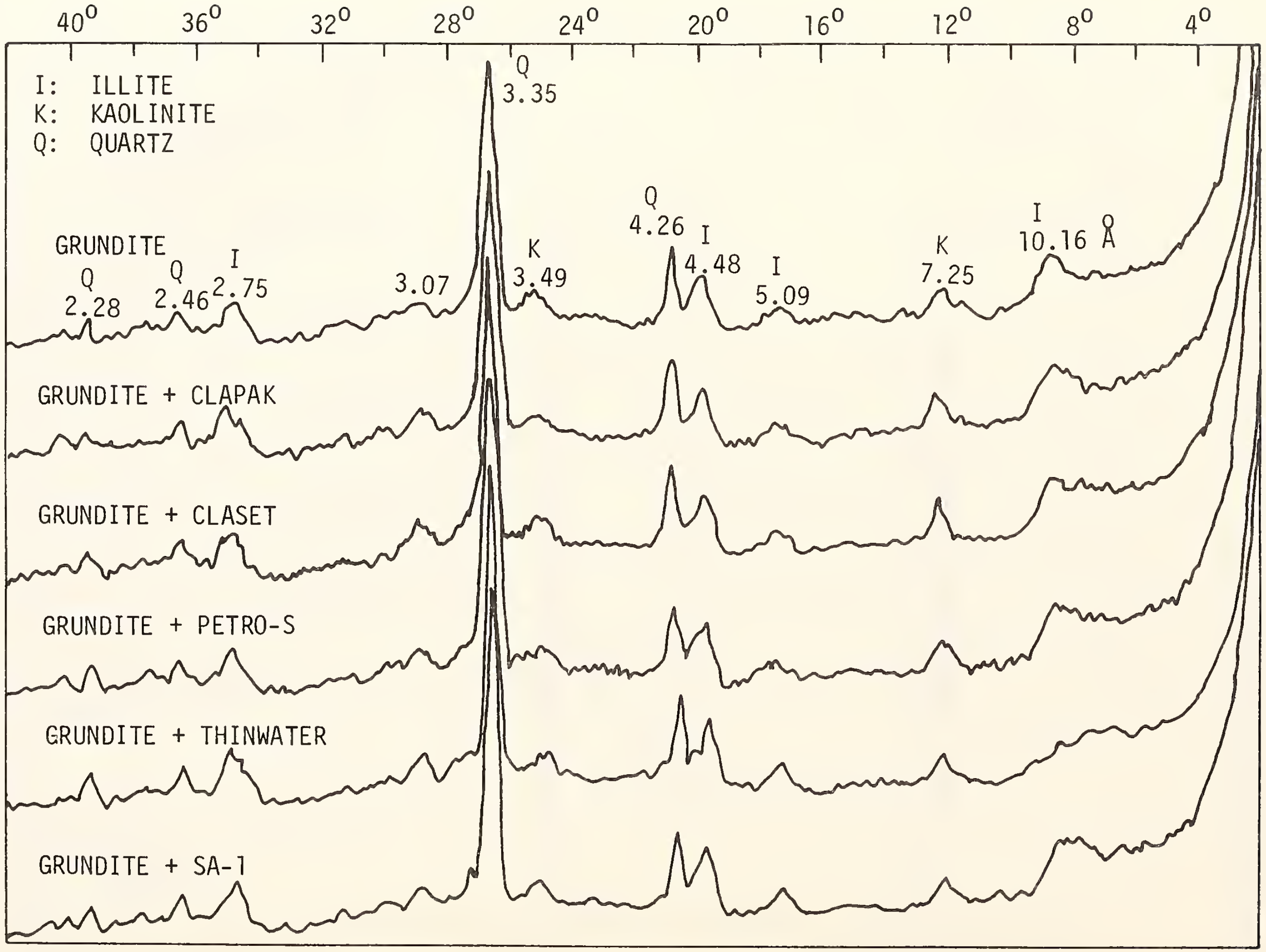

Fig. 95. X-ray diffraction of untreated and chemically treated Grundite.

appears that relatively subtle differences in the soil physico-chemical makeup may create large differences in effectiveness of a chemical compaction aid.

3. Compactability effectiveness of various soil-chemical combinations was positively correlated with numerically increased (i.e., more negative) zeta potential of the clay fractions.

4. Numerical increase in zeta potential of the clays also correlated with a decrease in strength.

5. For some soil-chemical combinations, increased zeta potential, increased compactability, and decreased strength tend to meliorate with time. This is an advantage because, in these instances, the soil in effect was chemically weakened for easier compaction but then regained strength. However, with some combinations, the reverse was true; the soil actually became weaker with time, which is of course deleterious.

Mechanisms

Since the amounts of chemicals used are so small compared to the ion exchange capacity of the soils and yet the effective chemicals strongly affect the soil zeta potential, and since the effectiveness is so sensitive to type of soil, we can speculate that reactions must be occurring at critical key sites on the clay particles. Such sites could be the clay particle edge positions involved in edge-to-face flocculation. A positive edge-to-negative face attraction would be diminished through preferential edge adsorption of anions, which would tend to create a negative double-layer at the edges. The tendency then would be for dispersion or peptization which would weaken the clay and make it easier to compact. There also would be a corresponding reduction in zeta potential. The adsorption capacity of clay for anions is small; hence, only trace amounts of anionic chemicals would be required to be effective.

Most of the chemical compaction aids contain considerable amounts of organic compounds which is indicated from their infrared spectra and high molecular weights. The mechanism of peptization is essentially the same as for inorganic chemicals; however, organic compounds with long-chain macromolecules and ionized groups along the chain would have a tremendous peptizing action provided that, in the case of layer expansive clays such as montmorillonite, the molecules do not readily penetrate the interlayer.

Sensitivity of the treatment to soil composition, even when the predominant mineralogy is the same, may relate to clay peptization being staged at the edges, which is caused by chemisorption of the peptizer anions to the exposed octahedral cations. Soil clays with the same mineralogy still differ in kinds and amounts of substituting ions in the octahedral sheet; therefore, in different soils, different cations will be exposed at the broken edges. This could affect specific adsorption reactions.

The effect of too much chemical could be to further compress the double layers until Van der Waals attractions would tend to flocculate the system, making the chemicals less effective. Thus, an optimum amount of chemical should exist that is dependent on the particular soil-chemical combination. This tendency also was observed in the physical testing.

Specific conductance of the solutions was measured but revealed no consistent relationships with effectiveness. Generally, specific conductance increased with increasing chemical concentration as would be expected for ionic solutions.

Several of the compaction aids were strongly acidic, but this did not appear to enhance their effectiveness. One effect of pH is to change the net negative charge of the clay by either supplying or removing H^+ ions. In addition, a very high or very low pH will tend to chemically degrade the clay; a pH above about 10.5 causes pozzolanic reactions that are cementitious, and a pH below 2 or 3 hydrolyzes and removes aluminum and may cause flocculation.

Ideal Compaction Aid

In summary, based on the above observations and speculations, an "ideal" chemical compaction aid can be proposed:

1. Such an ideal additive should contain molecules that adsorb on clay surfaces but, because of the molecules' potentially large size and configuration, should not invade between the layers of montmorillonitic clay. Such molecules of practical necessity will be organic which will supply a beneficial secondary effect, that of decreasing surface tension.

2. For the ideal additive, it will be found that, as a consequence of chemisorption of the organic molecules, the zeta potential of the soil clay will become more negative. This also will temporarily lower the soil shearing strength.

3. Because of the above requirements, the ideal chemical most likely will be neither strongly acidic nor strongly basic.

4. After compaction, the effect of the chemical must not last; i.e., the chemical must degrade or become more fully adsorbed for zeta potential and strength recovery.

5. Unfortunately, because of the highly sensitive nature of the zeta potential response to chemisorption of trace amounts of chemicals, it is extremely doubtful that any single chemical will be found which is a panacea working with all soils in a readily specified optimum amount. On the contrary, results show that identity and optimum amount of an effective chemical compaction aid depends, to a large extent, on the kind of soil and is not predictable from the soil clay mineralogy or other compositional data yet obtained. Furthermore, if edge-adsorption is the responsible mechanism, it is unlikely that any reasonable

compositional test will yield the required information. Thus, the best way to evaluate a potential soil-chemical combination is to prepare a trial batch and measure the change in zeta potential compared to a control. Based on the data thus obtained, effectiveness may correctly be predicted about 85-90% of the time. For a better prediction, actual compaction tests should be used.

PHASE III - FIELD EVALUATION

The purpose of this phase was to design and construct a series of field experiments to evaluate several of the more promising chemical compaction aids. From this phase of the project, it was hoped that a comparison of lab and field test results might provide answers to questions concerning both the adequacy of the laboratory techniques to fairly evaluate effectiveness of the chemicals and whether such techniques would fully and fairly represent field compaction, strength, and other mechanisms important to the integrity of the roadway structure.

Tentative field site selection, preparation, and testing criteria included the following:

1. Fine-grained roadway embankment soils with minimum length section of 1000 ft per chemical used, plus adjacent 1000 ft control section (water only). A minimum of three 6 in. compacted lifts per section were desirable.

2. Normal construction procedures for the participating agency relative to their equipment, number of passes, density requirements, etc., per section.

3. Chemically treated and control sections to be constructed under as closely identical conditions as possible, including mixing operations (chemical or water added), equipment used, passes per lift of compaction unit, time of operation, etc.

4. Chemical selection to be based on laboratory tests previously described in this report, performed on soil samples submitted by the participating agency.

5. In-situ tests during construction to include compaction-growth (i.e., moisture-density values at selected numbers of passes per lift) and removal of Shelby tube samples for field K-Test evaluation.

6. In-situ tests to begin immediately following construction, and to include moisture-density, K-Tests on Shelby tube specimens, Benkelman beam deflection, and spherical bearing values (SBV) tests.

The above criteria were tentative in anticipation that some changes might be necessary in order to provide a degree of flexibility when negotiating with potential participating agencies, yet remain within the context of the research objectives.

Through the FHWA Contract Manager, as well as the principal investigators, numerous contacts were made. Interest was expressed by agencies in Iowa (two sources), Idaho, New Mexico (two sources), Louisiana, and Georgia. Field test possibilities in each of the above states ranged from good to bad. For various reasons, the sites narrowed to one each in Iowa, New Mexico, and Louisiana, and soil samples were either obtained or received from each location. Numerous laboratory moisture-density, K-Test, and compaction growth tests and evaluations were conducted, and chemicals were ultimately selected and recommended for each site. However, it was discovered that the Louisiana site was actually more sandy than the samples tested and was beyond even a borderline fine-grained criterion. Through the extremely cooperative efforts of the Louisiana Department of Highways (and in particular, Mr. James Melancon), additional sites were explored, but field tests in Louisiana were eventually abandoned. Thus, field tests were finally conducted near Knoxville, in Marion County, Iowa, and in Villanueva, New Mexico.

Marion County, Iowa, Test Sections

Marion County had scheduled construction of a 3/4 mile long grade, located about 15 miles southwest of Knoxville, Iowa (1.5 miles west, 1 mile south of Melcher, Iowa), using their own maintenance crews. Site examination indicated that about a 1500 ft portion of the grade would be built from a borrow pit within a Shelby series soil, the same soil series used earlier in this investigation. Based on laboratory moisture-density and K-Tests of the Shelby series, several Phase I and II chemical compaction aids were tested using the on-site soil which had nearly duplicate properties to those noted in Table 7. Claset, SC-518, and Thinwater appeared promising. Since Stabilization Chemicals (manufacturers of SC-518) were out of business, Claset and Thinwater were considered for use in conjunction with a single control section.

Final test sections consisted of (a) 500 ft length untreated control section which received water only, (b) 500 ft length Claset section treated at 0.01% dry soil weight, and (c) a 250 ft length Thinwater section treated at 0.0034% dry soil weight. The test sections were located within the roadway embankment fill, averaging about 5 ft in thickness. Each test section consisted of the last three 6 in. compacted lifts. Therefore, the embankment was brought up to about 1.5 ft from final grade prior to start of the test lifts.

Construction was performed by a Marion County maintenance crew in August 1976. Equipment consisted of three blade graders, one self-loading scraper pulled by a D-8 tractor, one D-4 dozer, one sheepsfoot compactor, and a hydroseeder. The hydroseeder was used for circulatory pump mixing of chemical and water, as well as for spray application of water or chemical solutions. Mixing of water or chemical solution with the soil was accomplished with the blade graders; a combination scarification/blading of each untreated or treated lift was used until desired moisture and texture was achieved. Figures 96 and 97 show portions of the construction.

Moisture contents and densities were obtained every 2 to 5 passes of the compactor for evaluation of compaction growth. A Troxler nuclear M-D unit was used for primary M-D determinations but was also supplemented with sand-jar cone and rubber balloon density measurements. Speedy moisture meter as well as sealed moisture can samples, the latter being field laboratory oven-dried at a constant temperature of 105-110 °C, were used for supplementary moisture determinations.

During construction of the third lift, 4 in. diameter Shelby tube samples were removed through the full depth of lift thickness, extruded, cut and trimmed to 4.56 in. height, weighed and measured, and field K-tested for evaluation of M-D and K-test parameters. Following construction, Spherical Bearing Value (SBV) and Benkelman Beam Tests were conducted on the completed surface of the third lift, with the beam tests conducted under a single axle load of 17,300 lb (18,000 lb Iowa maximum), or 8650 lb per each pair of dual tires.

Construction of the control and treated sections was good though somewhat slow due to type and quantity of equipment used. One significant problem relative to evaluation of the treated sections occurred at five passes on the first lift of the Thinwater section when the frame of the one-and-only sheepsfoot compactor of Marion County broke. As a consequence, no compaction growth data were obtainable within the Thinwater section.

About one month after construction, the County applied a light spread of crushed stone surfacing throughout the total 3/4 mile length of the project, including the three test sections.

Figures 98, 99, and 100 present compaction growth data of the untreated control, and the Claset-treated sections, in the first, second, and third lifts respectively. Dry density within these figures is based on moisture and density obtained with the nuclear unit. In analyzing the data, it should be understood that the County crew used no compaction control on any of the embankment fill underlying the three test sections.

Within the first lift, Fig. 98, the control section showed greater density regardless of number of passes. With the compactor used, maximum density was achieved in both sections at about 15 passes, with little or no increase in density of either section up to 25 passes.

In the second lift, Fig. 99, the Claset treatment provided greater density than the untreated control section, both sections being of generally higher density than the first lift. Both effects probably

Fig. 96. General view, Marion County, Iowa, Test sections.

Fig. 97. Application of chemical, Marion County, Iowa, test section.

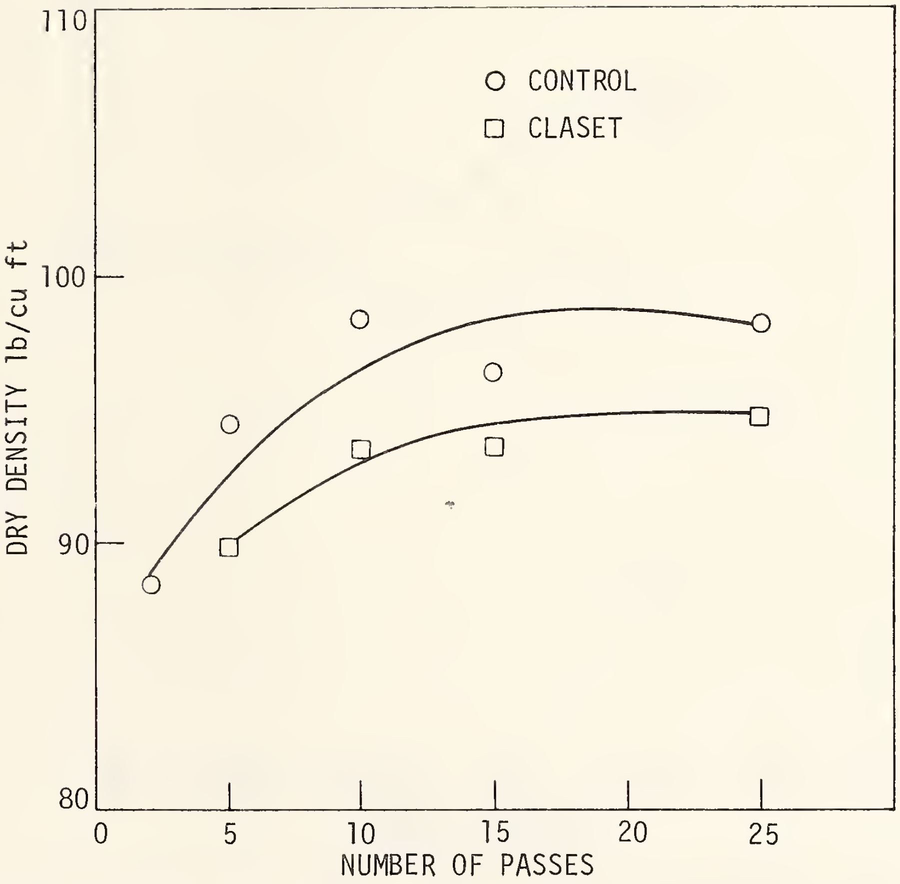

Fig. 98. Field compaction growth, first lift, Marion County, Iowa.

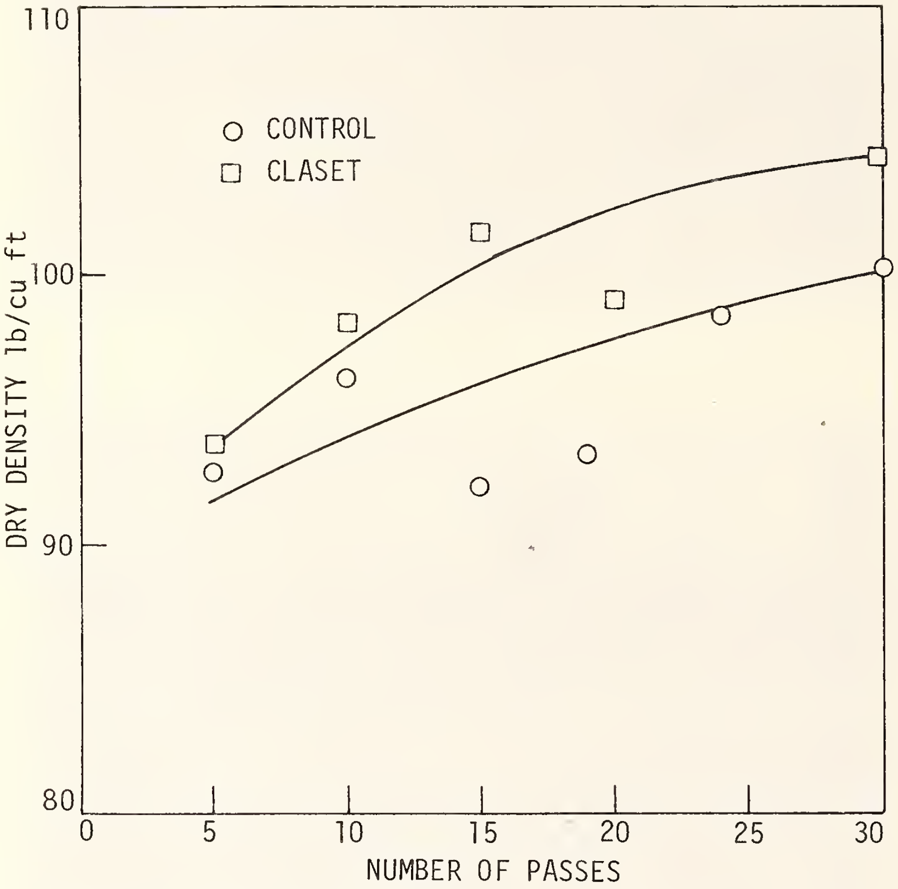

Fig. 99. Field compaction growth, second lift, Marion County, Iowa.

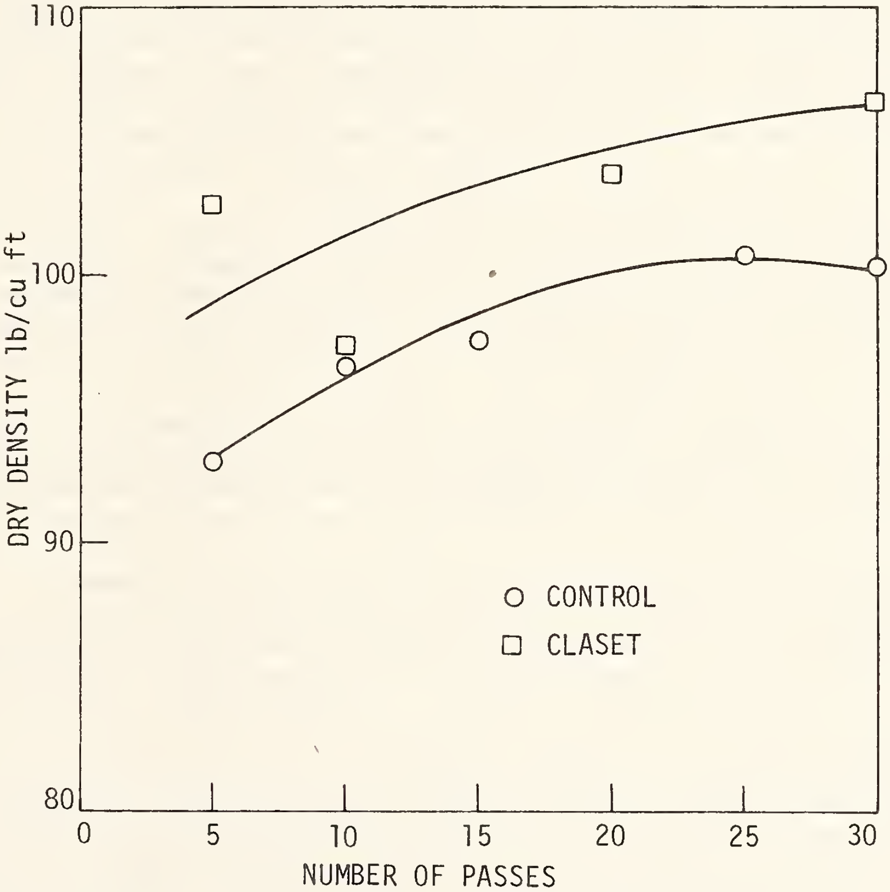

Fig. 100. Field compaction growth, third lift, Marion County, Iowa.

result from the first lift developing as a compaction platform immediately above the non-compacted fill. In general, compaction was still occurring at 30 passes in each section, as compared with attaining a maximum at about 15 passes during compaction of the first lift.

At 15 passes, density of the Claset during second lift construction was about equal to that of the control section at 30 passes, a savings of about 50% compactive effort.

In the third lift, Fig. 100, the Claset treatment again provided greater densification than the untreated control section, and again both sections were generally of higher density than the second lift. Maximum density of the control section appeared at about 25 passes, while the Claset-treated section appeared as still gaining density up to 30 passes. Density of the Claset section, equivalent to maximum density of the untreated control section at 25 passes, was achieved between 5 and 10 passes, a savings of compactive energy of about 70%.

In-place moisture contents of the test sections consistently ranged from about 1 to 4% higher than lab-determined optimums. As a consequence, 100% of lab standard γ_d was not achieved in any of the lifts, primarily due to partial lack of spread control of water or solution through the hydroseeder, coupled with a probable lack of adequate contact pressure of the compactor, and weakness in the lower fill. For example, maximum γ_d and OMC of the control section was 107.3 pcf at 18.4% respectively, while that of the Claset section was 109.9 pcf at 16.6%. Maximum γ_d of the Thinwater was nearly identical to that of the control with less than 1% reduction in OMC.

Each plotted point of dry density vs. number of passes, Fig. 98-100, is the mean of not less than four M-D determinations. The regression line, plotted for each section/lift, is fairly smooth and represents a generalization of compaction growth. In observing each set of plotted points, however, it is noticeable that some fracturing and remolding may have occurred within each section and lift. For example, during compaction growth of the second lift, control section mean density of about 96 pcf was observed at 10 passes but then dropped to about 92 pcf at 15 passes, increasing to above 93 pcf at 19 passes, above 98 pcf at 24 passes, and ending above 100 pcf at 30 passes. The second lift Claset growth increased steadily to 15 passes, dropped at 20 passes, and increased to a maximum at 30 passes.

Lab compaction growth studies conducted on the Marion County soil, treated and untreated, represent a condition of overcompaction as presented earlier in this report. For example, field M-D and K-Test results with the untreated control section soil indicated a lessening of rate of density increase between 60 and 80% T-99 compactive effort, coupled with a bearing capacity reduction from 60 to 80% compactive effort, followed by a slight increase in q_o from 80 to 100% compactive effort. Thus, some fracturing and remolding, if not overcompaction, appears to have been created within the field test sections.

Figure 101 presents mean ultimate bearing capacities of the third lift Claset and control sections vs. number of passes, as calculated from field K-Test data during construction. In general, there appears to be little variation in q_o between the untreated and Claset-treated soil between 5 and 20 to 25 passes. At 30 passes, however, the control section increased to about 40 psi greater than the Claset. Interpretive analysis of each plotted point again indicated possible fracturing and/or remolding of both the treated and untreated soil during field compaction.

Figures 102 and 103 present a descriptive portion of the SBV test data (range of hydraulic gage pressure, in pounds, vs. range of deflection [penetration] of the 6 in. diameter sphere) for each of the three test sections. Penetration of the sphere into the Claset-treated section at any load was greater than the control section (Fig. 102). Sphere penetration into the Thinwater section was less than or similar to that of the control section up to about 1000 lb of gage loading (Fig. 103). Calculated Spherical Bearing Values indicated the control section to have a higher bearing capacity than the Claset-treated section immediately following construction (following the pattern of the calculated third-lift field K-Test bearing capacities). Spherical bearing values of the Thinwater section were similar to, or of slightly higher capacity, than the untreated control section.

Table 55 presents Benkelman Beam maximum deflections immediately following construction. Relative stiffness values in kips/inch are included and were calculated as the dual tire loading of 8.65 kips divided by maximum deflection. The data within this table support previously noted observations from the field K-Tests and SBV evaluations. Maximum deflections of the control section were less than, and average relative stiffness values were greater than, those within the Claset-treated section. Values of maximum deflection and relative stiffness with the Thinwater section would be considered similar to those of the control section.

During and immediately following construction, the Claset section thus produced greater density but lower bearing capacity and general stability of the Shelby soil as compared to the control (water only) section. Similar observations were predicted from the laboratory M-D, compaction growth, and K-Tests. Even without field compaction growth data, it therefore appears highly likely that the Thinwater section would have produced densities, strength, and stability properties somewhat similar to that of the control, as indicated by laboratory data of the field site soil.

In November 1976, approximately three months after construction, additional Shelby tube samples were removed from each test section for moisture content, density, and field K-Test evaluation. Table 56 presents a summation of the test results over the depth of the three compacted lifts. Densities and moisture contents of the control and Claset sections were very similar. Moisture content of the Thinwater

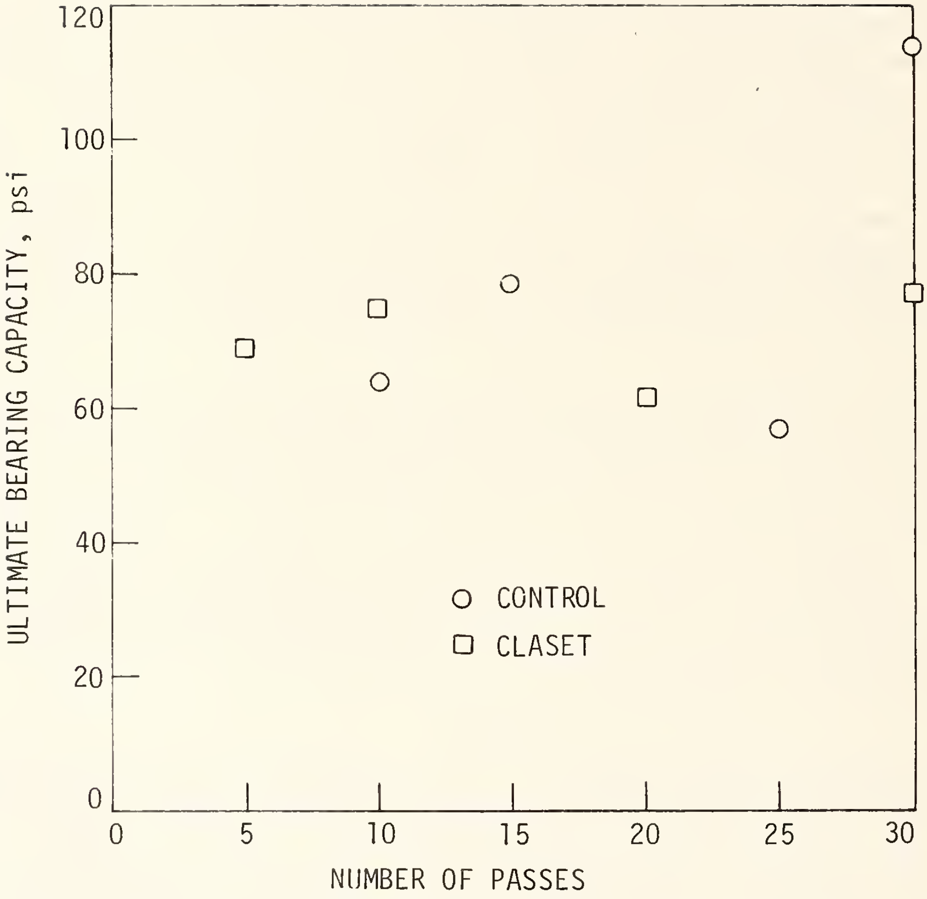

Fig. 101. Ultimate bearing capacities, third lift, Marion County, Iowa.

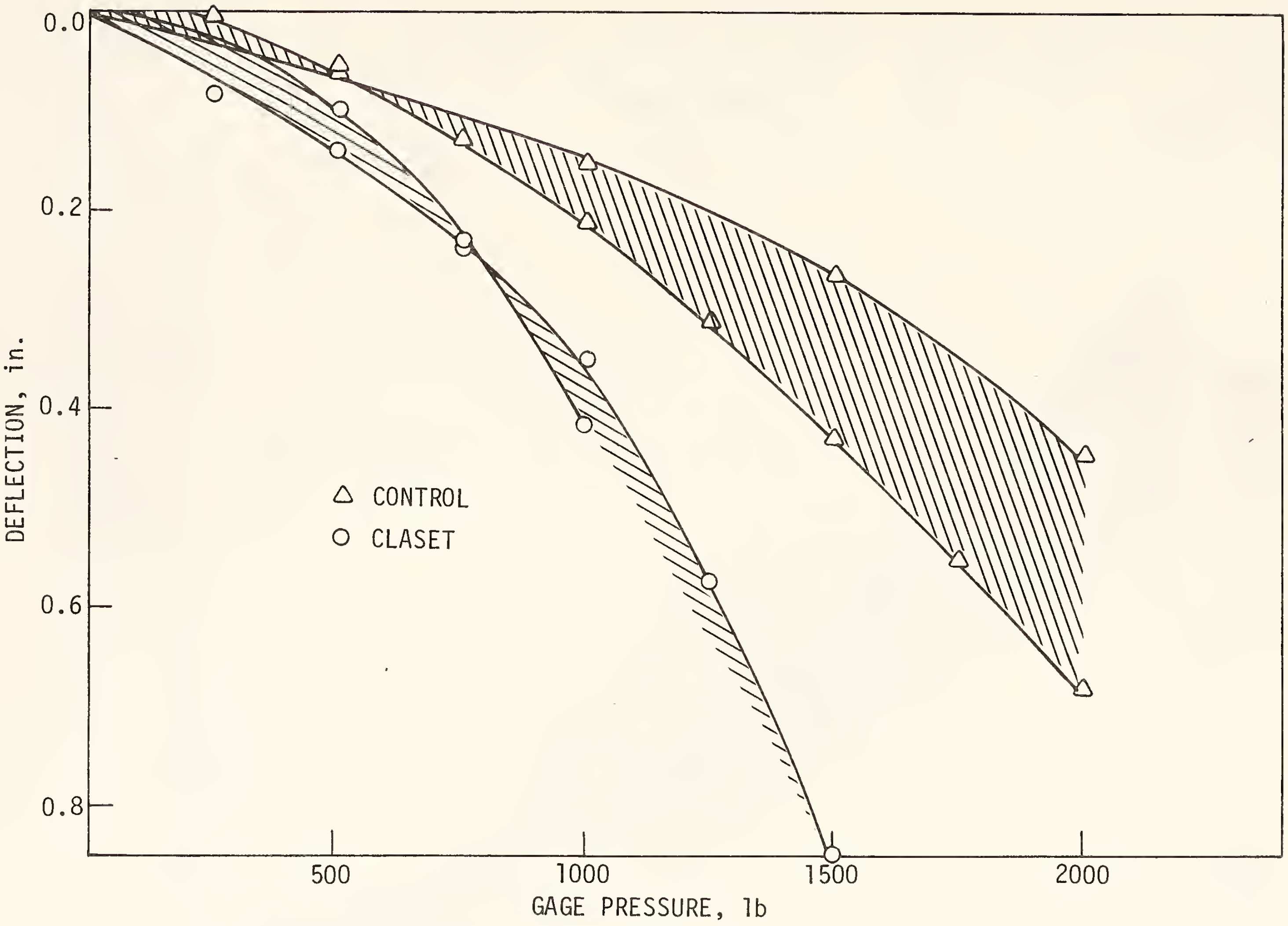

Fig. 102. Pressure vs. deflection, Marion County, Iowa

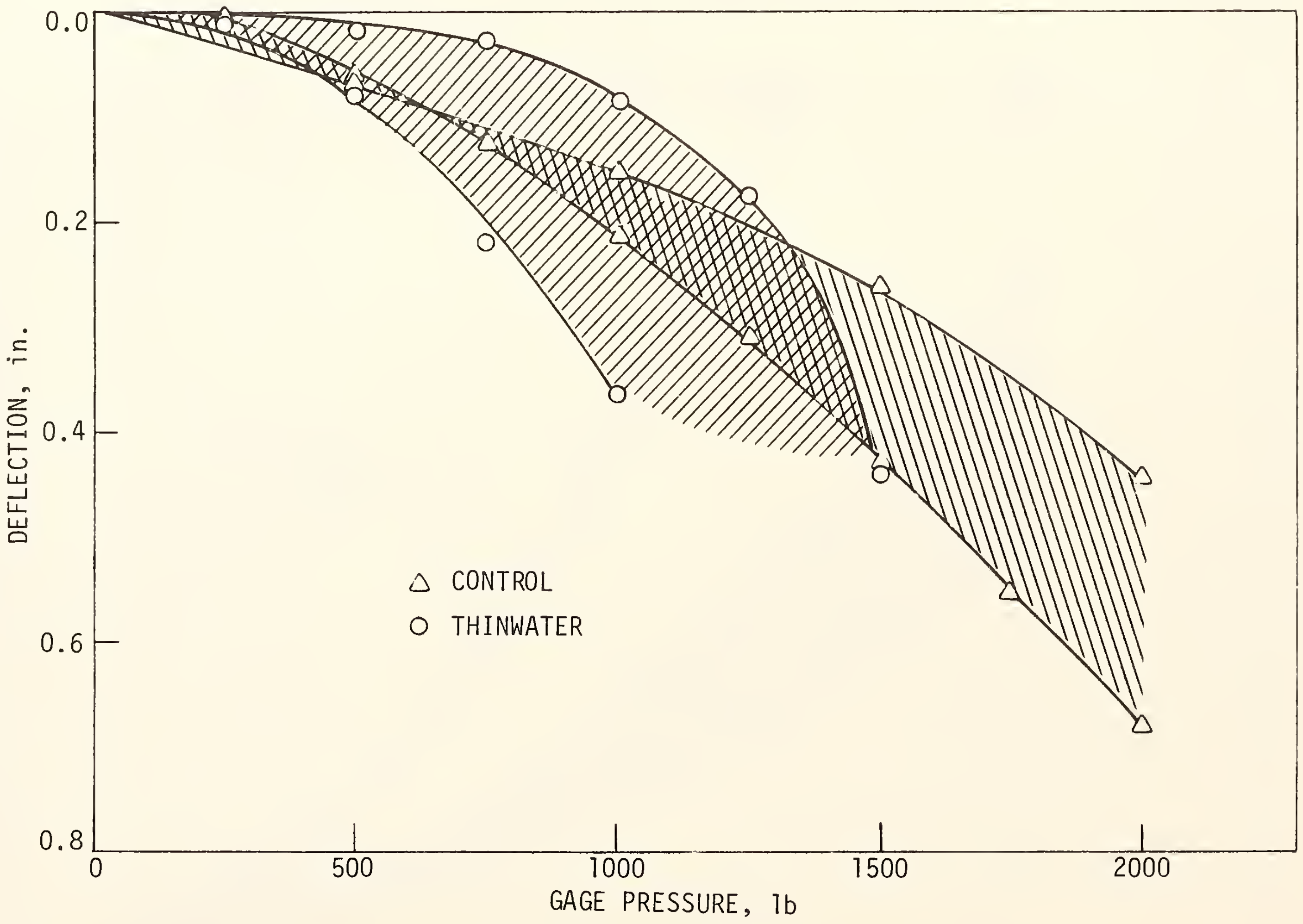

Fig. 103. Pressure vs. deflection, Marion County, Iowa.

Table 55. Benkelman beam results immediately following construction.

Section, station, and location*	Maximum Defection (in.)		Relative stiffness (kips/in.)
Control			
Sta. 1 + 50			
WIWT	0.080		108
WOWT	0.081		107
Sta. 3 + 50			
EIWT	0.036		240
EOWT	0.050		173
		Average	157
Claset			
Sta. 7 + 00			
EIWT	0.122		71
EOWT	0.148		58
Sta. 8 + 50			
WIWT	0.060		144
WOWT	0.130		67
		Average	85
Thinwater			
Sta. 11 + 100			
WIWT	0.050		173
WOWT	0.058		149
Sta. 12 + 00			
EIWT	0.080		108
EOWT	0.064		135
		Average	141

*WIWT = West lane, inside wheel track
WOWT = West lane, outside wheel track
EIWT = East lane, inside wheel track
EOWT = East lane, outside wheel track

Table 56. Mean density, moisture content, and K-Test results, about three months after construction, Marion County, Iowa.*

Section	Dry density, pcf	Moisture content, %	Angle of internal friction, degrees	Cohesion, psi	Ultimate bearing capacity,** psi
Control	109.0 ± 8.0	15.8 ± 1.6	21.1 ± 4.1	18.3 ± 7.2	219
Claset	108.2 ± 7.1	16.0 ± 0.9	20.4 ± 6.8	13.6 ± 6.7	163
Thinwater	113.5 ± 3.7	14.7 ± 2.5	19.9 ± 3.3	15.2 ± 1.8	182

*± indicates one standard deviation from the mean.
**q_o of mean c and ϕ values only.

was still less than the control section, but density was surprisingly 4.5 pcf greater. Comparing the density results to Fig. 100, γ_d of the Claset section was still similar to that produced at 30 passes of the compactor during construction, while the control section had increased about 9 pcf. Median angles of internal friction determined from the K-Tests for each section were very similar, while values of cohesion gave ultimate bearing capacities consistent with other field tests during or immediately following construction, as well as with laboratory results.

In February 1977, about six months after construction, an inspection was made of each of the test sections. Air temperature was above 40 °F, snow was entirely off the section surfaces and melting in the ditches and on the backslopes, but probing indicated that frost was still about 4 in. below the road surface. Typical winter formations of 1/2 to 3/4 in. wide transverse dessication cracks, spaced about 8 to 10 ft apart, were obvious in the control section and were observed from ditch line up the foreslope and across the shoulder. As the cracking approached the center line, there was a definite abatement. Transverse cracks within the Claset section were non-existent, being replaced, however, with very fine alligatoring, forming surface peds of 3 to 6 in. diameter. Subtle color differences were also noted between the Claset and control sections, the latter being slightly darker.

Some transverse cracking was also noticeable in the Thinwater section and was of similar width though of lesser magnitude (about 12 to 15 ft apart) than in the control section. Had full control of compaction occurred during construction of this section it is possible that such cracking may have been prevented.

Soil texture differences were visually obvious, particularly between the Claset and control sections. During probing in the control section, typically heavy Shelby soil clods were noticeable. These were dry and difficult to break up by hand. Breaking out the peds within the Claset section indicated that each was exceedingly friable and would easily crumble when hand-squeezed. The Thinwater section was more similar to the cloddy texture of the control section but less difficult to break when squeezed.

Traffic rutting was quite evident in the Claset section and only slightly noticeable within the Thinwater and control sections, appearing to at least visually correlate with the prior strength/stability lab and field test data.

Low strength subgrade soils normally show penetration of surface-applied aggregate and/or migration of subgrade fines into the aggregate surface. This phenomenon was apparent in the Claset section, partially noted in the Thinwater section, but not noted within the control; these again concur with the previously described shear parameters.

In mid-June 1977, about 10 months after construction, a final series of Shelby tube specimens were removed from the full depth of the three lifts of each Marion County test section for additional moisture-density and K-Tests. Benkelman beam and SBV tests were also performed. Table 57 presents the mean and one standard deviation of density, moisture content, and K-Test data. Table 58 presents the average Benkelman beam deflections and relative stiffness values, plus spherical bearing values for each section.

As may be seen from Tables 57 and 58, 10 months after construction the Thinwater section produced the lowest bearing capacity, relative stiffness, and SBV but still showed the highest density and lowest moisture content of the three sections. Lateral stabilities of the three sections were very similar and, though the mean q_o of the Thinwater was less than the nearly identical q_o's of Claset and control sections, the variability of the Thinwater was less than half that of the other sections.

Comparisons of the ultimate bearing capacities in Fig. 101 and in Tables 56 and 57 show a general increase in magnitude from time of construction to about 10 months after construction; the control and Claset sections bearing capacities increased to more than twice that achieved immediately after 30 passes of the compactor. This phenomenon represents the so-called "tightening" of a constructed embankment or other pavement material with time.

No direct correlation is possible between q_o, SBV, and maximum beam deflection or relative stiffness since each is produced from a different mode of testing. That is, q_o, determined on tube specimens via the K-Test, represents a mean ultimate bearing capacity of the lift materials only, while each of the other parameters also reflects

Table 57. Mean density, moisture content, and K-Test results about 10 months after construction.

Section	Dry density, pcf	Moisture content, %	Angle of internal friction, degrees	Cohesion, psi	Lateral stress ratio, K_i	Ultimate bearing capacity, psi
Control	105.3 ± 6.0	17.6 ± 2.2	21.3 ± 3.3	11.7 ± 3.2	0.396 ± 0.057	257.8 ± 115.9
Claset	109.8 ± 6.4	16.2 ± 2.1	19.9 ± 7.9	12.4 ± 2.7	0.419 ± 0.118	264.8 ± 117.3
Thinwater	114.5 ± 3.9	14.0 ± 1.5	21.6 ± 6.5	10.8 ± 2.5	0.401 ± 0.077	232.6 ± 47.5

[*] ± indicates one standard deviation from the mean.

Table 58. Average Benkelman beam deflection, relative stiffness, and spherical bearing values, about 10 months after construction, Marion County, Iowa.

Section	Maximum deflection, in.	Relative stiffness, kips/in.	Spherical Bearing Value, psi
Control	0.064	135	569
Claset	0.081	108	448
Thinwater	0.113	77	334

properties of the subgrade underlying the three lifts.

From the evidence obtained from the three Marion County, Iowa, test sections, the following conclusions appear appropriate:

1. Claset and Thinwater, in general, improved M-D relations over a period of time; i.e., they reduced moisture and increased density compared to a similarly constructed control section.
2. Claset and Thinwater did not improve in-situ strength and stability properties of the Shelby series soil with time.
3. Ultimate bearing capacity and stability estimates of the three sections, as based on measurement of c-ϕ-K values, indicate only small variations between the sections after 10 months in place.
4. Thinwater and Claset may act as dispersing agents, as evidenced from the densities and textures achieved with time in each section.

Villanueva, New Mexico, Test Sections

This test site was located about 5 miles south of Villanueva, New Mexico, on State Road 3. A new grade, several miles in length, previously had been constructed out of the predominantly caliche material of the adjacent right-of-way and surfaced with aggregate from two pits near the site. In 1976, a 1 mile section of the soil-aggregate surface had been ripped, and SA-1 was applied in anticipation that the approximate 6 in. compacted lift would be a low-cost base for future surfacing. The New Mexico State Highway Department was intensely interested in pursuing similar types of low-cost chemically stabilized construction which could be accomplished by their own maintenance forces. While this section did not meet the tentative three-lift criteria for the test sections, it did provide a desirable length, and other sections could be constructed in a region where water for any format of roadway construction was at a premium.

A composite site soil sample was obtained and shipped to us by the District 4 laboratory, Las Vegas, New Mexico. X-ray diffraction analysis indicated the soil was dominantly of calcite ($CaCO_3$) and quartz mineralogy. Cation exchange capacity and pH of the soil were 11.5 m.e. per 100 g and 10.54, respectively, placing the material at the lower end of CEC and above the high end of the pH range of Phase I and II samples (Tables 7 and 8, Volume I). By the Unified classification system, the soil was identified as an SC having a liquid limit of 32 and plasticity index of 11%, thus placing the material within the range of engineering properties exhibited by the Phase I and II soils.

In order to select a few chemicals for laboratory testing, a review was made of the various chemical treatments utilized on Phase I and II soils that had alkaline pH values and contained calcite. SA-1, Clapak, Claset, Petro-S, and Coherex appeared as potential candidates. Table 59 presents the laboratory M-D K-Test results of the most beneficial chemical percentages as determined on the composite site soil. It will be noted that the Clapak and Claset were used in combination at 0.005% dry soil weight each, totaling 0.01%.

Due to severe limitation of quantity of sample, no laboratory compaction growth studies were performed with the SA-1. In addition, such tests would not have provided comparative field compaction growth since SA-1 had already been applied on site. However, in-situ density, bearing, and other tests were conducted on the previously constructed

Table 59. Laboratory standard density, optimum moisture, and K-Test results of Villanueva, New Mexico, sample.

Product	Dry soil weight, %	Dry density, pcf	Optimum moisture content, %	K-Test parameters at γ_d and OMC: c, psi	ϕ, degrees	K_i
Water	----	105.9	17.7	4.4	37.1	0.227
Clapak + Claset	0.01 (0.005 each)	108.1	15.9	5.5	36.8	0.226
Petro-S	0.10	107.6	17.4	2.1	38.5	0.224
Coherex	0.70	104.6	17.3	4.3	37.0	0.228
SA-1	0.01	110.1	16.2	7.4	28.7	0.313

SA-1 section, and the lab M-D K-Test data were useful for long-term comparative analysis.

Figures 104 and 105 present the lab compaction growth data of dry density (γ_d) and ultimate bearing capacity (q_o) vs. percent of standard T-99 compactive effort for the untreated and chemically treated Villanueva specimens at their respective laboratory OMC's. Also included are results of specimens compacted at 100% T-99 effort but tested following 7-day moist curing at 72 ^{o}F and near 100% relative humidity. Though density of the untreated soil increased with increased compaction, the bearing capacity (q_o) remained nearly constant at about 200 psi and dropped to near 50 psi after 7-day moist curing. Densities of the Clapak + Claset and Petro-S treatments were equal to or exceeded the untreated at about 60% compaction energy, while the Coherex was continuously less than the corresponding untreated soil. Density growth was reflected in q_o of the Petro-S specimens, nearly doubling that of the untreated at the 80% energy level but decreasing to about 320 psi at 100% compaction and dropping to about 80 psi after 7-day moist curing (which possibly reflected the drop in γ_d following the moist cure period). Bearing capacity of the Clapak + Claset increased to about four times that of the untreated at the 80% energy level, dropping and becoming about equal to the untreated at 100% but increasing again to 350 psi after 7-day moist curing. At 100% compactive effort, q_o of the Coherex-treated specimens was approximately equal to the untreated but then doubled following the moist cure period.

Based on what cost data were available, an estimate was made of chemical costs only, assuming a 1000 ft length, 28 ft width, and 6 in. compacted thickness roadway, at the respective γ_d and percentages of chemicals noted in Table 59. Calculated costs were about $260 for the Clapak + Claset combination, $800 for Coherex, $980 for Petro-S, and $415 for SA-1.

On the basis of the above analyses, the Clapak + Claset combination and Petro-S were selected and recommended to the New Mexico State Highway Department for field trial. Through generous cooperation of the manufacturers, each product was donated for the project. Petro-S is normally supplied in a water-based solution, but due to shipping costs, it was supplied in a dry bagged form, in a quantity equivalent to the 0.10% wet form for the test section. No tank mixing difficulties were encountered in the field.

Final test sections began at the south end of the previously constructed SA-1 section and consisted of (a) 1000 ft untreated control (water only) section, (b) 1000 ft Clapak + Claset section treated at 0.005% dry soil weight each, and (c) 1000 ft Petro-S section treated at 0.10% dry soil weight.

Construction was performed by a New Mexico Department of Highway Maintenance crew June 6 to 10, 1977. Equipment consisted of a dozer-ripper, three blade graders, three water tankers, a grid roller, and a self-propelled (8 ton, 100 psi tire pressure) pneumatic-tired roller. Sequence of construction was as follows:

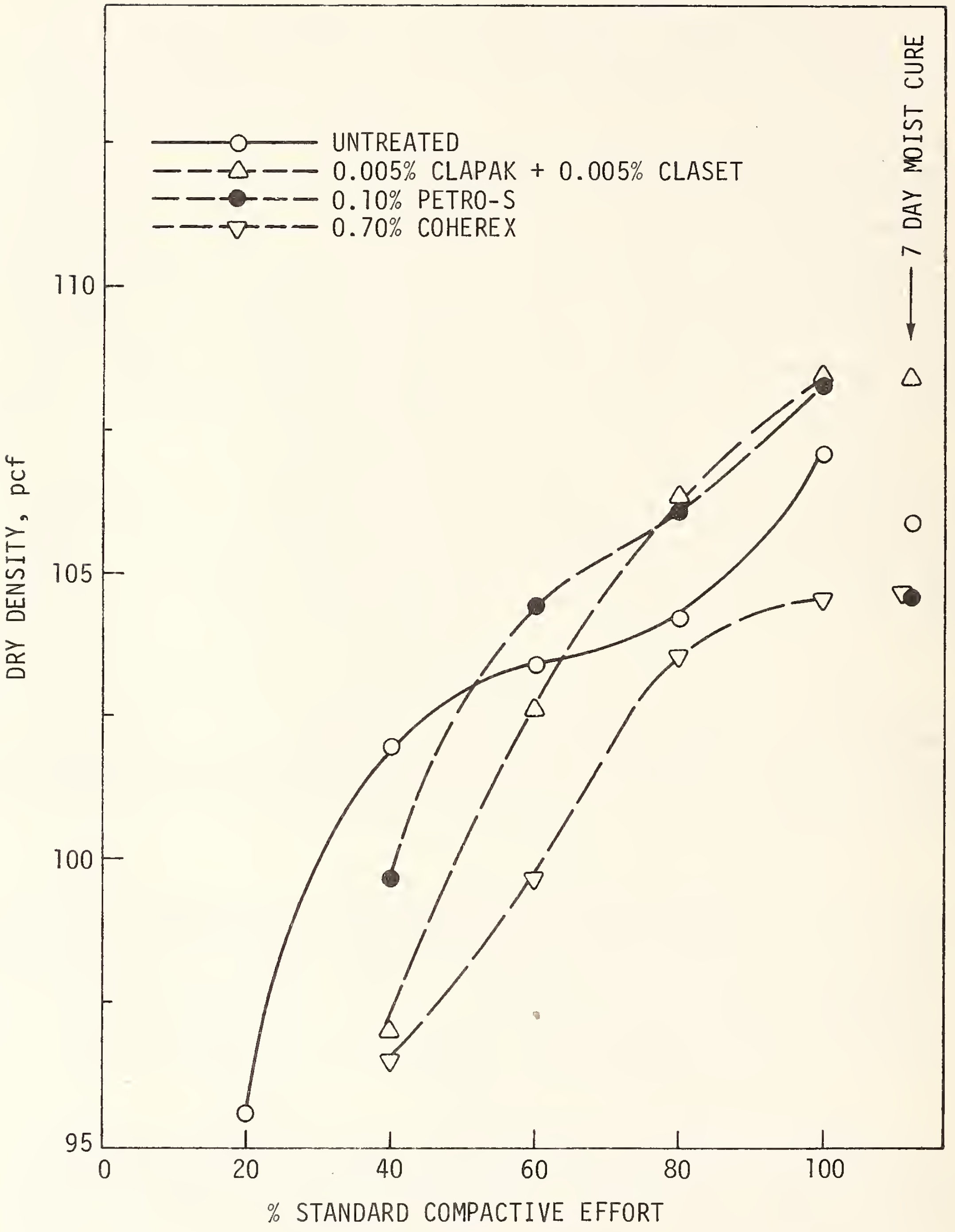

Fig. 104. Laboratory compaction growth, Villanueva, New Mexico, soil.

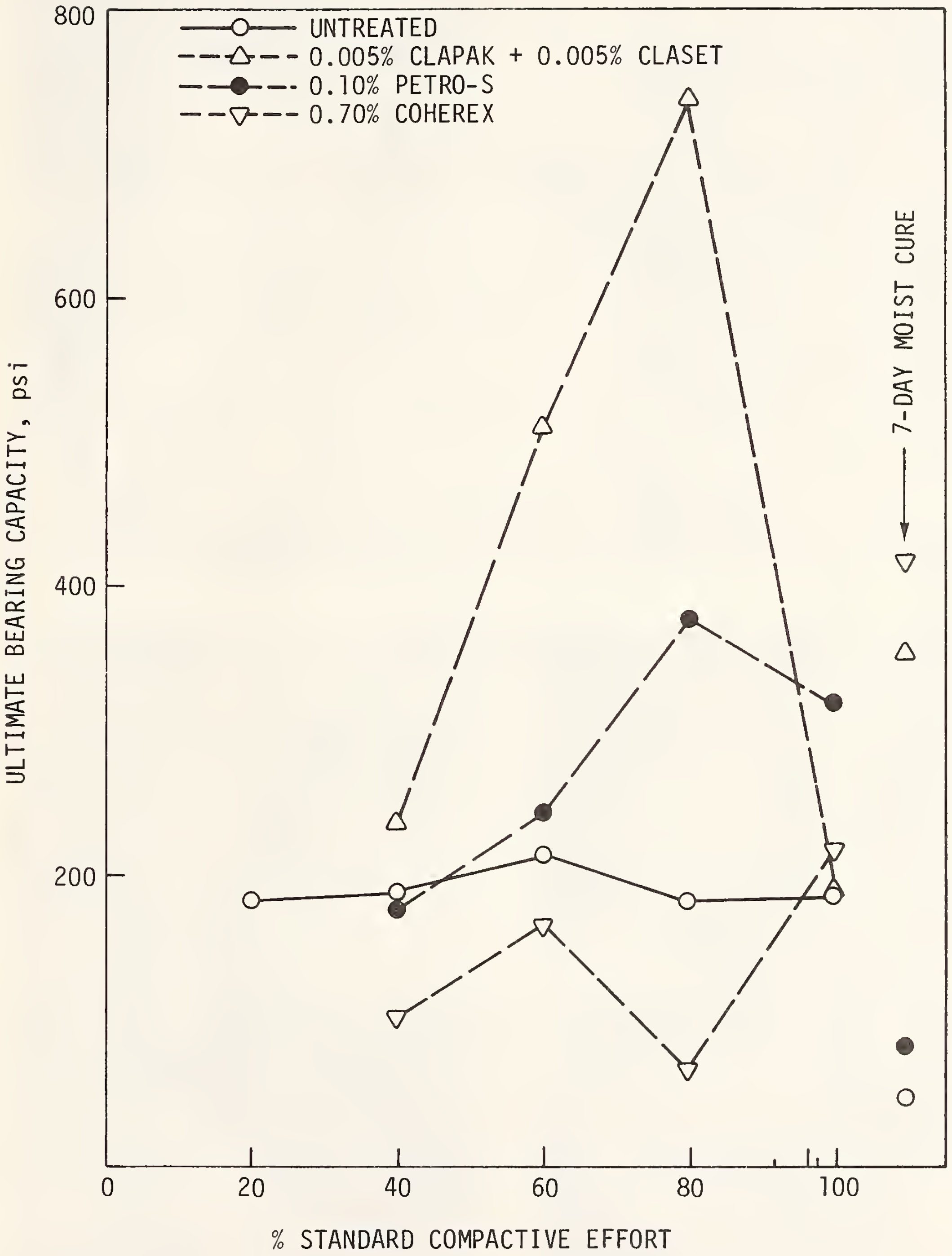

Fig. 105. Laboratory bearing capacity growth, Villanueva, New Mexico, soil.

1. The existing soil-aggregate surface material was scarified with the ripper to desired depth.

2. The loose material was blade-mixed and windrowed, and aggregations of the material were pulverized with the grid roller.

3. Moisture contents of the pulverized windrowed-soil were measured.

4. Water, or chemical in water solution, was sprayed on the windrowed soil, followed immediately by blade mixing, and then re-windrowed.

5. Upon completion of mixing, the material was bladed across the roadway in thin lifts and compacted with the pneumatic-tired roller, all soil being placed by the third or fourth pass of the roller.

Figure 106 presents several typical views of the construction operation.

The quarter-points of each section were selected and marked for in-situ tests, thus giving a minimum of three points per section. Moisture-density determinations were conducted at 1, 2, 3, 4, 5, 7, and 10 passes of the compactor in each section, plus 15 passes in the Clapak + Claset section, by means of a nuclear densometer supplied by the New Mexico Department of Highways. Each nuclear densometer test was accompanied by a speedy moisture test, the latter previously calibrated by the conventional oven-drying method to the soil, water, and chemical used. Comparison of moisture procedures indicated variations of 1.0% dry soil weight or less. Following construction of the sections, a series of density measurements were made with the nuclear densometer and a large rubber balloon volumeasure. Densities thus obtained varied by as much as 5 pcf but were far more consistent with the nuclear unit. Therefore, all in-situ densities and moisture contents reported herein for compaction growth are from the nuclear data.

Benkelman beam deflection measurements, spherical bearing value tests, and K-Tests of Shelby tube samples were conducted on all test sections (including the nearly one-year old SA-1 section) immediately following test section construction and up to 2.5 months thereafter, through the excellent cooperation of the District 4 Materials Lab. Nuclear moisture and density tests were also performed on all sections up to 2.5 months following construction.

Figure 107 presents compaction growth density vs. number of passes for the several sections. Each data point is the average of a minimum of three tests. The method of construction is reflected in the growth data; after the first pass, more material was spread from the windrow, and densities decreased. By the third to fourth pass, all soil was essentially in place. Due to the dry desert-like atmosphere, compaction proceeded at a rapid pace in order to minimize drying. Even

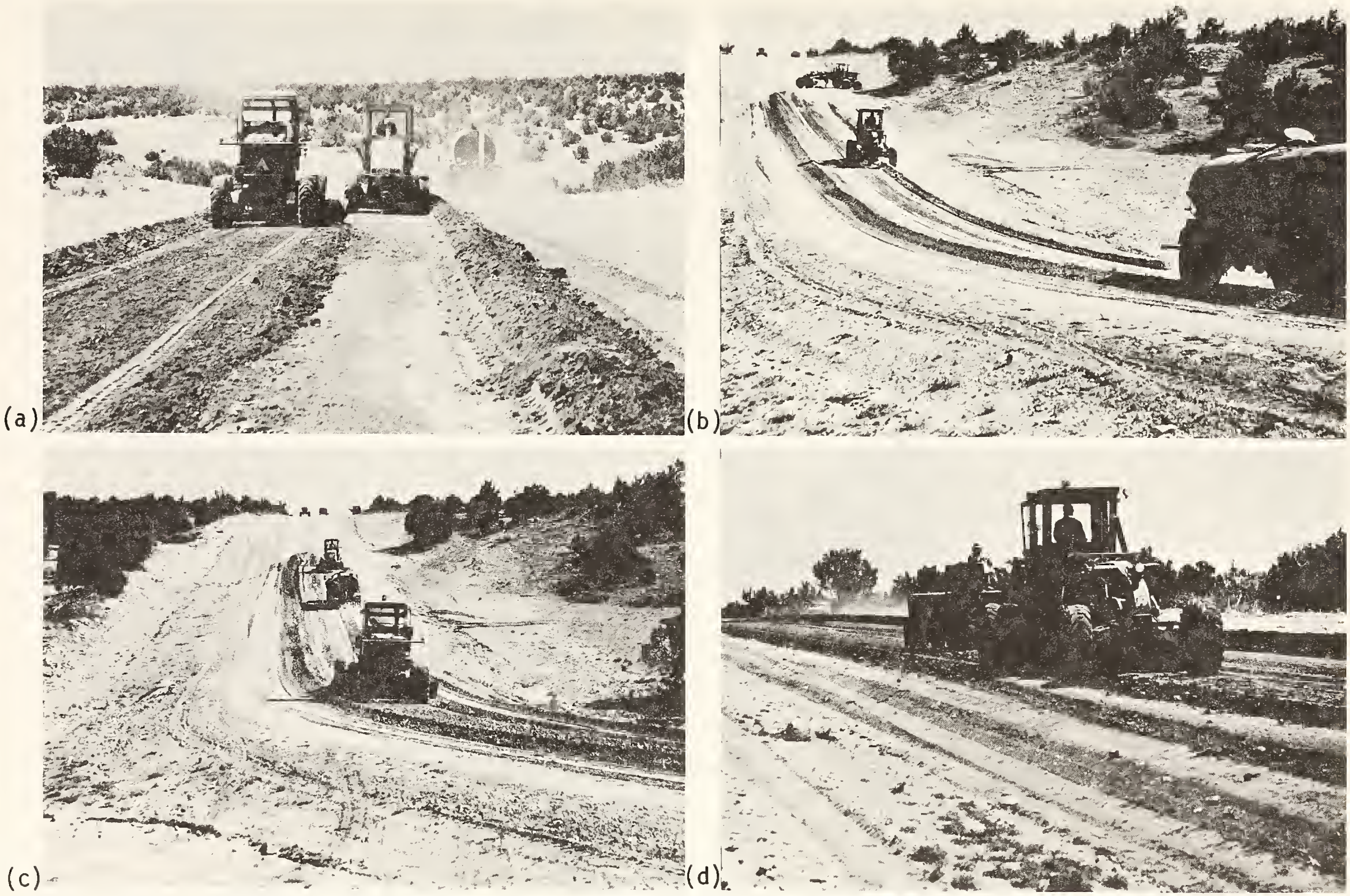

Fig. 106. Villanueva, New Mexico: (a) Blade mixing and windrowing following scarification and pulverization; (b and c) Sequence of chemical and/or water application plus blade mixing; (d) Spreading of mixed soil followed by pneumatic-tired roller compaction.

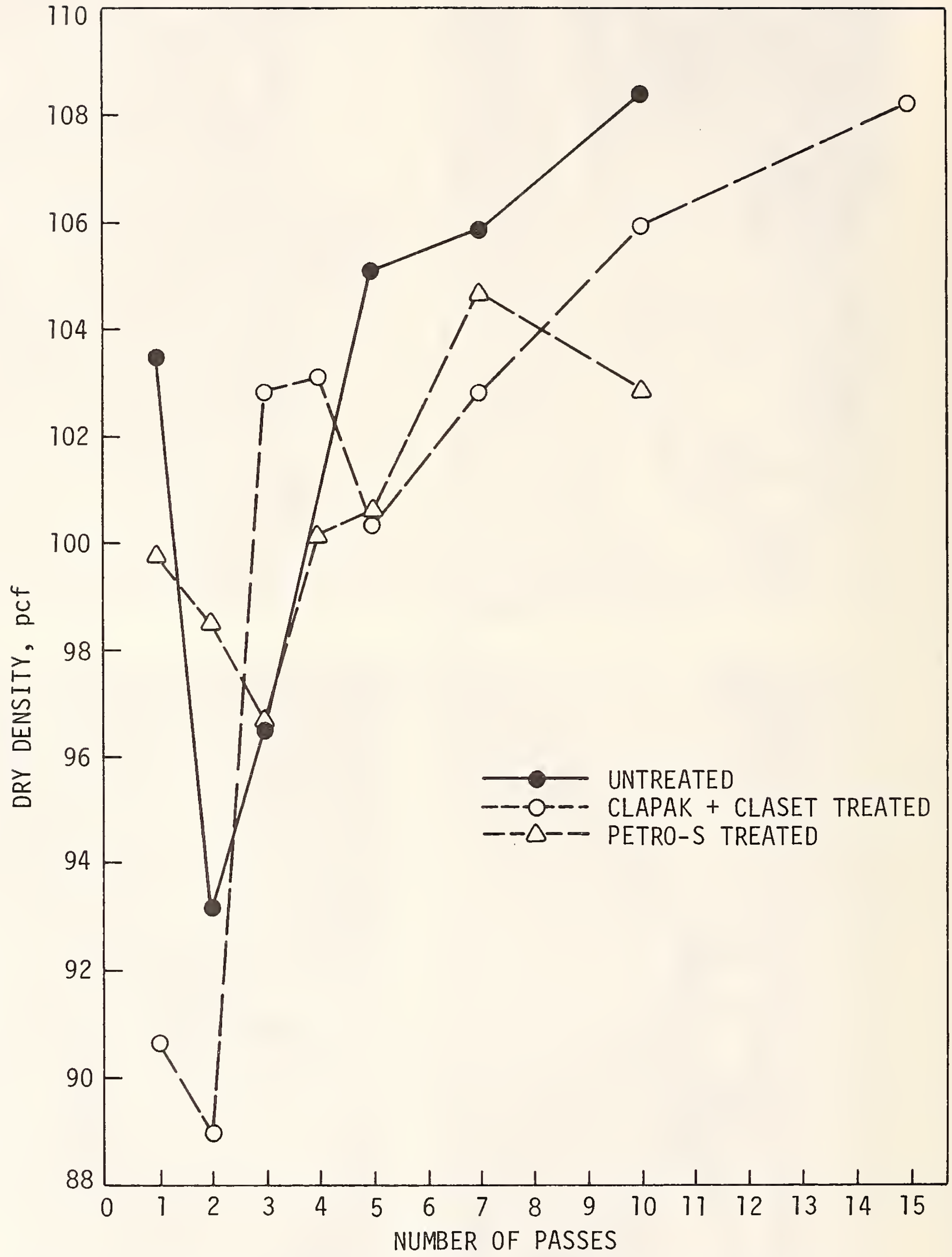

Fig. 107. Field compaction growth, Villanueva, New Mexico.

though allowances were made by holding the initial moisture contents above optimum on all sections, it was necessary to spray water on the Clapak + Claset section between the fourth and fifth passes. A quick, but heavy, rain shower occurred between passes 2 and 3 within the Petro-S section. Both waterings increased the respective section moisture content at the point of time and thus reduced γ_d. Assuming such watering had not occurred, it may be hypothesized, at least, that densities of the two treated sections may have projected above the untreated at about 5 passes. Such a hypothesis is also reflected in the M-D data of Table 60.

Table 60 presents the in-situ nuclear densometer moisture and density data at end of construction and after 1 and 2.5 months. Relatively minor changes of γ_d occurred within the control section over the 2.5 month period. At 2.5 months, however, γ_d of the Clapak + Claset section had increased about 4 pcf, exceeding γ_d of the untreated control, and γ_d of the Petro-S section had increased over 10 pcf, exceeding the control section by 4 pcf. All three sections thus showed signitifcantly increased densities above those anticipated from the laboratory studies (Table 59). The SA-1 section (approximately 1 yr old) showed densities about as anticipated from the laboratory study.

In-situ SBV tests were performed only at the end of construction. As shown in Table 61, this test mode indicated a decreasing magnitude of bearing values, from the highest (control) to the lowest (Petro-S), for the just-completed test sections. However, average SBV of the nearly one-year old SA-1 section was somewhat greater than the control section.

Average Benkelman beam maximum deflections immediately following construction (Table 62) produced orders of values similar to the SBV's, i.e., the control section indicated less deformation characteristics under a moving load than that of the Clapak + Claset treated sections, while SA-1 was somewhat more stiff than the control.

Table 60. Average in-situ moisture-density tests, Villanueva, New Mexico.

	Average dry density, pcf, and (moisture content, % dry soil weight)		
Section	End construction	1 month	2.5 months
Control	108.4 (13.0)	110.6 (6.0)	109.4 (8.0)
Clapak + Claset	108.2 (9.9)	107.9 (6.5)	112.0 (6.3)
Petro-S	102.8 (9.1)	106.2 (5.3)	113.4 (4.4)
SA-1 (~ 1 yr old)	---	109.6 (7.2)	109.6 (9.5)

Table 61. Average end-of-construction Spherical Bearing Values, Villanueva, New Mexico.

Section	SBV, psi
Control	679
Clapak + Claset	490
Petro-S	311
SA-1 (~ 1 yr old)	729

Immediately following construction, and again after one month, Shelby tube samples were taken from the quarter-points of each section. Table 63 presents the average moisture-density and K-Test parameters obtained from these samples. Moisture contents of the materials at end of construction were fairly consistent with those determined by the nuclear densometer (Table 60). One month later, however, a fairly wide variation between the two moistures existed, obviously affecting density but apparently not affecting the c-ϕ-K_i-q_o values from the K-Test. Angles of internal friction (ϕ) were reasonably consistent over the month time span, but values of cohesion (c) definitely changed with reduction in the control, Clapak + Claset, and SA-1, while that of the Petro-S nearly doubled. Variations in c-ϕ values over the period resulted in significantly decreased q_o for the control section and some reduction for the Clapak + Claset section. However, the SA-1 section showed definite improved ultimate bearing, while q_o of the Petro-S section had more than doubled. The q_o values, if viewed in the context of tube sample density as a percentage of laboratory density (% compactive effort), Fig. 105, indicate that both the Petro-S and Clapak + Claset sections should have been greater than the untreated control. If compared to the laboratory q_o at OMC as moist-cured for 7 days, q_o of the Clapak + Claset section should have been considerably greater than that of the untreated. Comparison of K-Test values of the laboratory M-D specimens at lower than OMC with the end-of-construction K-Test parameters indicate a distinct similarity of c-ϕ-K_i-q_o values. Thus, moisture variations, accented in arid region field K-Test values, may be more closely represented by lab M-D K-Tests than compaction growth and K-Tests, particularly after 7-day moist curing. This indicates some possibilities that the 7 day lab growth specimens should (a) first be air-dried for a short period and then moist-cured for the remainder of the 7 days for moisture equilibration, or (b) cured at a relative humidity more consistent with the field site.

Table 62. Average maximum Benkelman beam deflections and relative stiffness values, Villanueva, New Mexico.

Section	Maximum deflection, in.			Relative stiffness, kips/in.		
	End construction	1 month	2.5 months	End construction	1 month	2.5 months
Control	0.045	0.037	0.040	183	298	295
Clapak + Claset	0.067	0.047	0.042	194	299	332
Petro-S	0.067	0.057	0.041	157	222	271
SA-1 (~ 1 yr old)	0.040	0.023	0.037	260	970	341

Table 63. Moisture-density and K-Test results on Shelby tube specimens, Villanueva, New Mexico.

Section	Moisture content, %	Dry density, pcf	ϕ, degrees	c, psi	K_i	q_o, psi
			End of Construction			
Control	9.5	110.3	40.5	7.4	0.186	789
Clapak + Claset	11.0	98.2	39.6	8.4	0.204	708
Petro-S	9.9	102.8	39.9	8.5	0.189	901
SA-1 (~ 1 yr old)	8.0	102.8	40.7	8.7	0.182	969
			One Month After Construction			
Control	8.4	105.9	39.5	3.1	0.215	289
Clapak + Claset	10.9	98.9	36.9	6.8	0.238	502
Petro-S	6.6	104.9	41.5	16.7	0.145	1896
SA-1 (~ 1 yr old)	10.3	105.4	42.1	6.8	0.180	1226

Data gathered from the Villanueva, New Mexico, test sections indicate the following conclusions:

1. Clapak + Claset and Petro-S improved M-D relations of the soil over a period of time, reducing moisture and increasing density as compared to a similarly constructed control section.

2. Petro-S and the Clapak + Claset combination did not improve deflection and stiffness characteristics of the sections up to 2.5 months following construction.

3. Clapak + Claset and Petro-S appeared to improve shear strength and stability characteristics of the soil up to 1 month after construction.

4. Recommended laboratory investigative procedures for chemically treated soils in an arid region should probably be modified to include a curing condition more consistent with on-site relative humidity.

5. Chemical products may be suitable for low-cost, low traffic volume roadway base construction in New Mexico.

CONCLUSIONS

The study documented herein was necessitated by a need for unbiased, rational, and objective evaluations of chemical "compaction aids" for fine-grained soils, for providing increased densification and/or ease of compaction, and for improving desirable engineering qualities of soil. Previous standardized laboratory testing of such chemicals generally have not produced noticeable, desirable effects. The present study was accomplished in accordance with the folloiwng objectives:

1. To determine the feasibility of improving compaction characteristics of a wide variety of representative fine-grained soils by chemical treatment.

2. To measure the effects of selected chemical compaction aids on moisture-density relationships and other engineering properties of soils, such as strength, plasticity, and stability characteristics, using modified tests and soil handling procedures which better simulate field processing and environments.

Three investigative phases were established:

Phase I - Literature Review (Task A) and Pilot Laboratory Study (Task B)

Phase II - Laboratory Study

Phase III - Field Evaluation

Through the above objectives and investigative phases, the study has developed a fuller understanding of the mechanics of compaction and suggests several pertinent and meaningful measurements for evaluation of compaction aids.

Though each section of Volumes I and II of this report present their respective detailed conclusions, the major findings achieved in relationship to the above objectives are as follows:

1. Chemicals which reduce surface tension of water or interrupt continuity of clay-water bonding should reduce the criticality of optimum moisture content for compaction.

2. A chemical compaction aid which decreases sliding friction between particles may increase density. However, a permanently reduced sliding friction produces a weaker soil with less bearing capacity and lateral stability.

3. Most emphasis and claims in the literature appear related to action of chemical compaction aids as surfactants, reducing surface tension of water. Virtually none of the literature explained the mechanics of compaction, and no attention was given to clay mineralogy or to soil-clay or clay-water interactions. Nevertheless, the literature reviewed herein indicated many chemical products as having created improvements in laboratory densification, coupled with improved strength, compressibility, and other properties of fine-grained soils, for reasons that basically remained obscure and unknown.

4. Surface tension reduction of a chemical in water solution alone did not correlate with improved soil compaction. However, surface tension of leachate, derived by passing diluted chemicals through selected soils, indicated a 97% probability of correlation with compaction effectiveness. Reduction of surface tension of the soil leachate also produced a 90% probability of a strong, positive correlation with an empirically derived rating system for reduction of OMC.

5. Chemical product effectiveness appears related to the soils' percent clay and clay mineralogy but is not predictable on the basis of the dominant clay mineral.

6. High density in a compacted soil does not necessarily yield superior strength, suggesting that strength of a compacted soil is not solely related to either density or tightness of the soil mineral skeleton. Such characteristics were confirmed and illustrated for the untreated and chemically treated soils. For example, laboratory spherical bearing value (SBV) for effective chemical compaction aids were generally lower than SBV's of chemical products not effective in improving density.

7. Surfactant chemicals may be attracted to a clay surface, depending on the soil-chemical compatability of charges. Cationic (+) chemicals attracted to negatively charged clay surfaces create a flocculated structure, in turn reducing compacted density (γ_d) and usually increasing optimum moisture content (OMC). Anionic (-) products, if finding a positively charged surface, may create limited dispersive characteristics, increasing moisture-density (M-D) effectiveness. Nonionic chemicals may reduce surface tension. Products analyzed in this study appeared to contain one or more of the three forms of surfactants.

8. Soil flocculation-dispersion characteristics produced by a chemical product varied with the soils tested, illustrating the interdependence of clay mineralogy and additive effectiveness. Products that were strong flocculants were not good compaction aids but often increased strength. Products also may not have to disperse soil-aggregations to improve compactibility of a soil. Products that "texturize" (produce size variances with apparent well-graded size distribution) fine-grained soils improve γ_d and OMC for better compactibility as well as strength.

9. Atterberg limits tests were inconclusive with regard to defining the role of chemical aids to compaction, except that chemicals which caused a large change in Atterberg limits of a particular soil did not significantly aid compaction of that soil.

10. Comparison of dispersion indices (DI), as determined from dielectric dispersion measurements, indicated no relationship to changes in OMC. A 94% probability that a negative correlation existed between DI and γ_d was shown. Correlation between DI and SBV produced a 96% probability that the positive relationship was not due to chance and corroborated dispersion soil-structure SBV observations.

11. Within the limits investigated, pH of a chemical did not appear related to M-D effectiveness as a compaction aid.

12. Zeta potential (ZP) is an electric potential existing at the interface between a particle as it moves in suspension in an electric field. If ZP of the soil is numerically increased (more negative) upon addition of a chemical, the chemical most likely will be partially to fully effective as a compaction aid (88% compliance). A numerical decrease (less negative) in ZP after 7 days signals an increase in strength, i.e., strength improvement with curing, (96% compliance). The converse of each observation is also true. Thus, a ZP test procedure should correctly predict product effectiveness about 85 to 90% of the time. For superior prediction, ZP should be coupled with actual compaction tests.

13. Because of the small amounts of chemicals used, relatively subtle differences in the soil physico-chemical makeup may create large differences in chemical compaction aid effectiveness.

14. The manner in which fine-grained soils are prepared for laboratory compaction for M-D or strength and stability studies significantly affect the data. Laboratory samples should not be fully air-dried and pulverized preparatory to such testing. By maintaining near natural moisture contents and particle aggregations, laboratory results appear to more closely simulate field behavior. Initial moisture content is extremely critical. A reduction in initial moisture content frequently brought about a reduction in OMC and a corresponding increase in γ_d, with no chemical effect whatsoever. This phenomenon may explain some of the inconsistent results cited in the literature. A suitable method for laboratory preparation, mix design, evaluation, and cost effectiveness is outlined in the body of this report.

15. Use of laboratory techniques and evaluative procedures studied and recommended within this report appear likely to forecast field performance of chemical compaction aids. Further laboratory/field comparisons should be conducted, however, prior to general acceptance of the procedures. If properly evaluated, and not misued, chemicals may be effective low-cost aids for improving compaction, strength, and stability characteristics of fine-grained soils in roadway structures.

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FEDERALLY COORDINATED PROGRAM OF HIGHWAY RESEARCH AND DEVELOPMENT (FCP)

The Offices of Research and Development of the Federal Highway Administration are responsible for a broad program of research with resources including its own staff, contract programs, and a Federal-Aid program which is conducted by or through the State highway departments and which also finances the National Cooperative Highway Research Program managed by the Transportation Research Board. The Federally Coordinated Program of Highway Research and Development (FCP) is a carefully selected group of projects aimed at urgent, national problems, which concentrates these resources on these problems to obtain timely solutions. Virtually all of the available funds and staff resources are a part of the FCP, together with as much of the Federal-aid research funds of the States and the NCHRP resources as the States agree to devote to these projects.*

FCP Category Descriptions

1. Improved Highway Design and Operation for Safety

Safety R&D addresses problems connected with the responsibilities of the Federal Highway Administration under the Highway Safety Act and includes investigation of appropriate design standards, roadside hardware, signing, and physical and scientific data for the formulation of improved safety regulations.

2. Reduction of Traffic Congestion and Improved Operational Efficiency

Traffic R&D is concerned with increasing the operational efficiency of existing highways by advancing technology, by improving designs for existing as well as new facilities, and by keeping the demand-capacity relationship in better balance through traffic management techniques such as bus and carpool preferential treatment, motorist information, and rerouting of traffic.

3. Environmental Considerations in Highway Design, Location, Construction, and Operation

Environmental R&D is directed toward identifying and evaluating highway elements which affect the quality of the human environment. The ultimate goals are reduction of adverse highway and traffic impacts, and protection and enhancement of the environment.

4. Improved Materials Utilization and Durability

Materials R&D is concerned with expanding the knowledge of materials properties and technology to fully utilize available naturally occurring materials, to develop extender or substitute materials for materials in short supply, and to devise procedures for converting industrial and other wastes into useful highway products. These activities are all directed toward the common goals of lowering the cost of highway construction and extending the period of maintenance-free operation.

5. Improved Design to Reduce Costs, Extend Life Expectancy, and Insure Structural Safety

Structural R&D is concerned with furthering the latest technological advances in structural designs, fabrication processes, and construction techniques, to provide safe, efficient highways at reasonable cost.

6. Prototype Development and Implementation of Research

This category is concerned with developing and transferring research and technology into practice, or, as it has been commonly identified, "technology transfer."

7. Improved Technology for Highway Maintenance

Maintenance R&D objectives include the development and application of new technology to improve management, to augment the utilization of resources, and to increase operational efficiency and safety in the maintenance of highway facilities.

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* The complete 7-volume official statement of the FCP is available from the National Technical Information Service (NTIS), Springfield, Virginia 22161 (Order No. PB 242057, price $45 postpaid). Single copies of the introductory volume are obtainable without charge from Program Analysis (HRD-2), Offices of Research and Development, Federal Highway Administration, Washington, D.C. 20590.