BULLETIN NO. 124

LIME STABILIZATION OF CLAY SOIL

by

Bob M. Gallaway
Assistant Research Engineer

and

Spencer J. Buchanan
Research Engineer

THE TEXAS A. AND M. COLLEGE SYSTEM
GIBB GILCHRIST, *Chancellor*

TEXAS ENGINEERING EXPERIMENT STATION
H. W. BARLOW, *Director*
ARTHUR W. MELLOH, *Vice-Director*
LOUIS J. HORN, *Supervisor of Publications*
College Station, Texas

Research directs progress.

PUBLISHED IN 1951

FOREWORD

Use of lime as an admixture was investigated by the Texas Engineering Experiment Station in view of the tremendous quantities of readily available soils being required in present day highway development, particularly for the embankments and subgrades. Ideal soils are not always available at construction sites, and use of the less desirable ones is sometimes necessitated by reasons of economy or procurability. Some such soils need to be improved by physical or chemical means for suitability in construction.

The Station's experimentation has provided data on lime stabilization of clay soils. Such data are presented in this publication as a contribution to the technical literature of the road-building and construction fields.

ACKNOWLEDGMENT

Sincere appreciation for helpful assistance is expressed to members of the engineering staff of the Texas Highway Department in Austin, Texas; Dr. John B. Page of the Department of Agronomy, A. and M. College of Texas; and the student assistants who performed the laboratory tests under the direction of Mr. Gallaway.

CONTENTS

SECOND PHASE OF RESEARCH

LIME STABILIZATION OF CLAY SOIL

SUMMARY

Lime as an admixture has been employed in agriculture to improve clay soils in workability, plant sustaining qualities, and transmission of surface waters. Highway engineers in Texas and other places have found that in proper mix ratio, various clays react with lime to produce improvement in load bearing capacities.

The Texas Engineering Experiment Station found it feasible to conduct experimentation on lime stabilization of clay soils. As a result of this work, a number of conclusions were drawn.

The stabilizing reaction of lime with clay soils is chemical in nature. It is the result of the replacement of the weaker positively charged metallic elements by the stronger positively charged calcium cations of the lime which, in turn, influence the thickness of the adsorbed halo-like moisture films on the exterior of the clay grains. The plasticity of clay soils, which is in effect a rough measure of their stability, is considered to be a function of the thickness of the water films.

It was learned that the chemical reaction caused by the lime is not restricted to a specific group of the clay family, but rather it occurs with all of the Texas natural surface and subsurface soils used in the experiments. Consequently, the application range of the lime method of improving the engineering properties of clays appears to be very broad.

The identification of members of the clay family; namely, kaolinite, illite, and montmorillonite by the differential thermal analysis was indicated to be satisfactory. However, the results of such identification were indicated to be of general rather than specific value as regards lime stabilization. It did not appear possible to identify the sodium cation from the calcium cation montmorillonite clays by this method.

The identification of members of the clay family by the X-ray method is possible, but at present it does not appear to be feasible for engineering purposes.

The unreliability of the benzidine color reaction test for identification of montmorillonite was confirmed.

The identification of clay soils, without regard to classification by groups, susceptible to favorable reaction with lime on the basis of the Total Base Exchange capacity, appears to be valid

for the small number of soils examined. The classification of the groups of the clay family on the basis of the Base Exchange ranges does not appear to apply to Texas natural soils or to laboratory mixtures of inert silt with commercial grade of montmorillonite. In addition, the correlation of the Plasticity Index with this Base Exchange, as developed for both laboratory and natural soils, appears to be reasonable and permits ready identification of the clay soils which would react favorably with lime as a stabilizing admix.

The research gave evidence of a minimum reaction time of 24 hours for lime and clay soil, as regards the influence of the lime on the plasticity characteristics of the clays concerned. No consideration was given in this research to the influence of cementation, caused by the lime admixes, on the properties of the clays studied.

Clay-like soils having a PI or Base Exchange capacity of less than 20 experienced negative to slight or insignificant reaction; soils possessing a value of these factors in the range from 20 to 40 experienced a moderate reaction; and soils possessing values of 40+, without exception, experienced a significant improvement of their plasticity characteristics.

INTRODUCTION

Soil and means of improving its natural condition have attracted man's attention since the beginning of civilization. Early interest was confined largely to means of improving the soil's ability to support vegetation for human and animal uses. This interest has broadened with the progress of mankind. The highways of the world are transportation elements vital to world development, and soils are one of the most important materials required for them. Means of improving the natural condition of the soils for the betterment of their stability have been explored to various degrees since highways have become avenues of commerce.

Clay soils predominate in the habitable and arable areas of the earth, where the need for highways is greatest. In many instances, the most desirable and readily available soils have been used for highway construction in the past. Further, greater quantities of materials, particularly for the embankments and subgrades, are now required for the extensive and broad highways of a modern era. To meet the current dictates of economy may require the use of the less desirable soils, some of which may need improvement of their physical properties by physical or chemical means in order to serve the intended purpose. In agriculture, one of the early means discovered for improving clay soils was by the admixture of small amounts of lime which resulted in the improvement of the workability of the soil, the ability to support plant life, and the penetration of surface waters into the material treated. This same method has been used on occasions by highway engineers in Texas who have commented as follows: "The experience of the Texas Highway Department and others with the use of lime as an admixture, has shown that various clays react with lime (when used in reasonable and comparable quantities) to produce various degrees of improvement in load bearing capacities."

The general objective of the research described in this publication was to gain an understanding of the primary changes wrought in plastic clays by the admixture of lime so that an explanation of the erratic reaction could be obtained. It was realized at the outset that the full understanding of the problem might not be achieved. The specific objective of the research was to explore the problem to ascertain three things—(1) a reasonable explanation of the process, (2) a relatively simple yardstick for determining the reaction that could be anticipated for the typical Texas plastic clays, and (3) the approximate range and influence on the engineering properties of lime admixture required so that the feasibility of this method of stabilization can be evaluated to better advantage. Although cementation of lime treated soils both plastic and nonplastic is admittedly of considerable import, this branch of the research was not investigated. An excellent treatment of this phase of the effect of lime on Texas natural soils is given by McDowell.[22]

PRELIMINARY BASIC CONSIDERATIONS

Understanding of some of the effects of lime admixture with clay soils is best gained by a brief review of the properties of the clay minerals. The properties are influenced to a large extent by the minerals present which are complex compounds of silica, iron, magnesium, potassium, sodium, calcium, aluminum, and oxygen. Mineralogically, the clay soils are divided into three groups: namely; montmorillonite, illite, and kaolinite. A laminated crystalline structure is characteristic of all of the groups; however, the properties of each group vary because of the difference in their surface activity phenomena. This phenomena is greatest for the montmorillonite and least for the kaolinite. This variation in activity is generally attributed to the influence of the electrical charges carried by the mineral particles and their surrounding moisture films, the nature of the exchange ions present, and the crystalline structure of the mineral particles.

In the soil mechanics and soil science fields, it is generally accepted that each mineral particle of a soil is covered by films of water molecules. The first film about each mineral grain is bound to the grain so tightly as to be termed "solid water" by Terzaghi, and its molecules are oriented in a manner similar to the electrical field of the grain. Each successive film is influenced at a progressively decreasing rate by this binding phenomena so that the bound water films blend into free water films to form a halo-like jacket around each clay particle. The inner film or films of the water-halo are termed "adsorbed layers." These layers contain positively charged elements termed ions, while the clay or mineral particles are negatively charged. The intensity of the bond between the two depends upon the atoms composing the molecules of the clay particles and the arrangement of these atoms. The negatively charged clay particles and the positively charged cation of the water film result in a electromotive force generated by the dissociation of the two opposite charges. It is natural that the cations contained in the halo-like water film are attracted by the oppositely charged mineral particle to hold the water film about the particle. The characteristics of the adsorbed complex depend upon the cation present and its strength. The process by which cations of one kind replace those of another in the adsorbed layer of moisture on a clay particle and thus alter the properties of the mass is known as Base Exchange. Further understanding of the matter may be gained from the remarks of Dr. R. E. Grim, Illinois Geological Survey, which are quoted as follows: "Base Exchange can be illustrated by the zeolite or permutite water softeners which make use of this phenomenon. Water is hard when it contains calcium compounds. As hard water passes through the softener, the calcium of the water is exchanged for the sodium which the zeolite contains, i.e., sodium goes from the zeolite to the water in exchange for the calcium which goes from the water to the zeolite, thereby softening the water. When the softener is no longer effective, sodium salt is run through it, reversing the process and rendering it effective again."[6]

The research of others, principally Dr. Grim, shows the Base Exchange capacities of the three basic members of the clay family are as shown in Table 1.

Table 1[7]

BASE EXCHANGE CAPACITY

(In milliequivalents per 100 grams)

Montmorillonite	60 to 120
Illite	20 to 40
Kaolinite	3 to 15

The contents of Table 1 may be taken as an indication that possibly the Base Exchange capacity of a clay soil may be considered as an index of favorable reaction of a soil with lime admixes; that is, the degree of favorable reaction may be of the order of the Base Exchange capacity.

Relation Between Crystalline Structure and Base Exchange

The crystalline structure of almost all clay particles is lamellar with the aggregates bound together rather weakly. This type of structure is known as the layer-lattice type. Substitution of cations is indicated to occur within the crystal lattice. This substitution is frequently reported[1] to cause the presence of electrostatic charges on the structure, which in turn are responsible for the adsorption of layers of water and cations.

The plasticity of the clays is considered to be a function of the uncompensated electrostatic charges on the structure and the thickness of the adsorbed water films held to the particles. For example, if the water films are relatively thick, the clay particles are shielded so as not to come in intimate contact with their neighbors. The mass they form under this circumstance possesses low stability, and a very plastic state prevails. The presence of an uncompensated electrostatic charge in the mineral lattice results in a high surface charge which appears to influence the stability and thickness of the water films so that it is a factor influencing the plasticity and stability of a mass of clay particles.

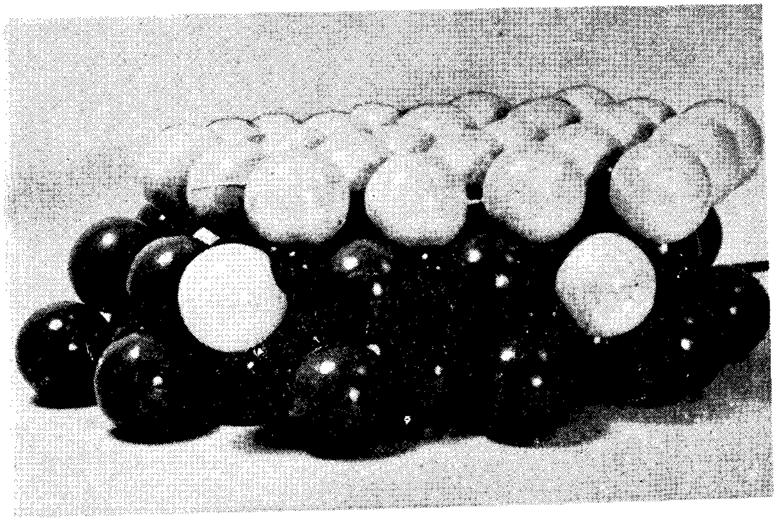


Figure 1. View of kaolinite structure normal to the A-axis. Oxygen, hydroxyl, and potassium are represented by large gray, white, and black balls respectively. Small white balls represent silicon atoms and small black balls, aluminum atoms.

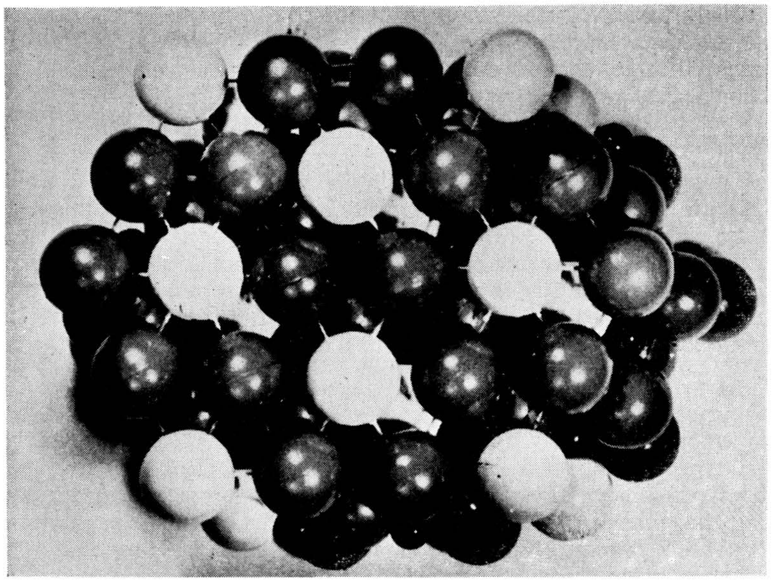


Figure 2. Lower three sheets (tetrahedral layer plus third "sheet") of the montmorillonite structure.

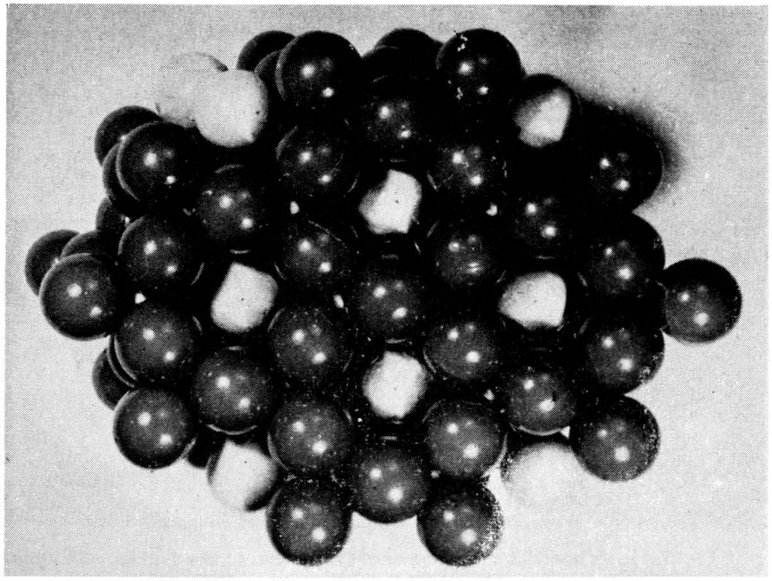


Figure 3. View of the montmorillonite structure normal to the C-axis with the fourth "sheet" added.

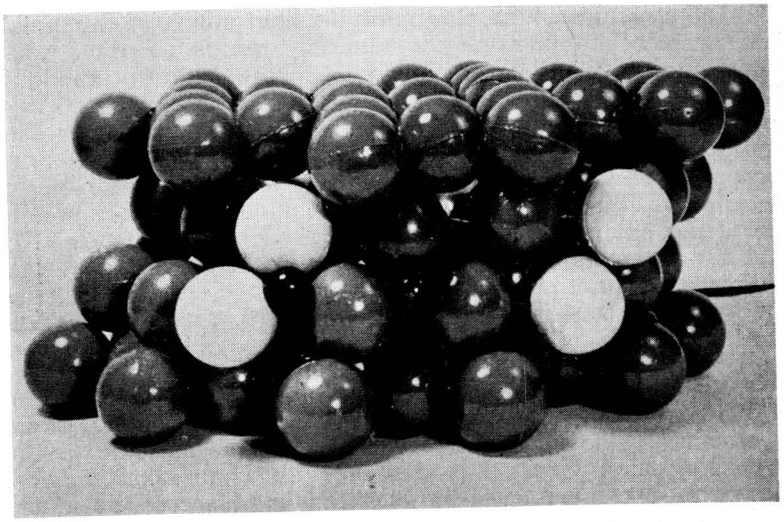


Figure 4. View of montmorillonite structure normal to A-axis.

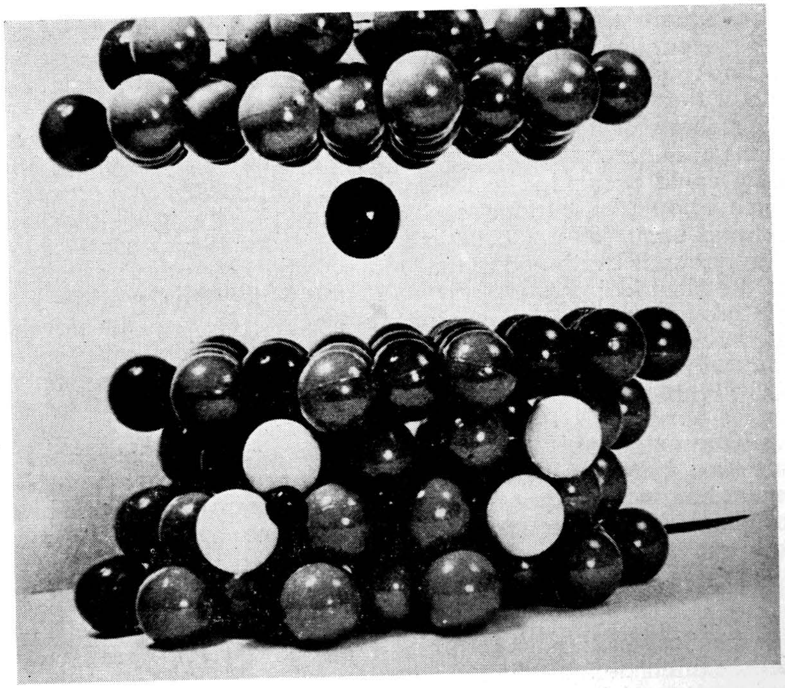


Figure 5. Expanding lattice of the montmorillonite structure.

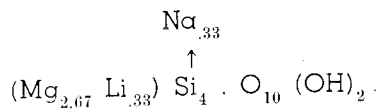
The structure of the clay minerals warrants brief discussion. The grains of the illite and kaolinite clay groups are of the layer-lattice type. This is illustrated by the photograph of a model in Figure 1. The electron micrographs of Shaw and Humbert[28] show this is the structure for nontronite and beidellete as well as illite. The grains of the clay soils in general are plate-like in shape and extremely thin as indicated by the large ratio of diameter to thickness. The halo-like adsorbed films of water are formed about the exterior of the grains, as previously described. The stability of the electrical charge of the adsorbed water and that of the grains has not been established for these clays, it is believed. It is possible that they may be unstable in some instances in nature and subject to stabilization by the use of admixes, as will be discussed later.

The structure of the grains of the montmorillonite clay group is essentially the layer-lattice type, also. The structure is illustrated by photographs of models shown in Figures 2, 3, 4, and 5. However, this member of the clay family possesses the unusual ability of taking molecules of water into the "structure to be adsorbed on the basal surfaces to a considerable degree."[4] The unusual property of taking molecules of water into the structure apparently causes the layers to expand so that it is termed the "expanding-lattice" type. Each grain may be compared to a book containing many pages of extremely thin crystals with the water entering between each page causing an increase of the volume of the grain. The great variation of the volume of a mass of this clay group with moisture content is many times more than could occur due to the formation of the halo-like adsorbed films about the surface of the particles. The great plasticity (Liquid Limit 700 per cent and Plastic Limit 10 per cent) of this clay group is attributed to this unusual phenomena. The stability of the electrical charges carried by the water films and layers of the grains may be very low for this group. Likewise, the stability or replaceability of the elements comprising the minerals may be low, which circumstance would lend itself to improvement by the use of admixes.

The extensive work of Ross and Hendricks[24] is important in showing how the replaceability of elements may occur. Examination was made of a platy silicate mineral which exhibited no Base Exchange properties and whose composition is as follows:

$$Mg_3\ .\ Si_4\ .\ O_{10}\ .\ (OH)_2\ .$$

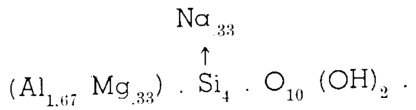
Similar examinations were made of a Hector clay which does exhibit definite Base Exchange properties and whose composition is as follows:



$$(Mg_{2.67}\ Li_{.33})\ \overset{\overset{Na_{.33}}{\uparrow}}{Si_4}\ .\ O_{10}\ (OH)_2\ .$$

It is significant that although the structure of the silicate layer has not been altered, the physical properties have been, simply by the substitution of one Mg ion in nine by lithium. This substitution also admits an interlayer of water and permits colloidal dispersion, which is another property not displayed by the platy silicate mineral.

The somewhat complicated composition of montmorillonite bears a striking similarity with the previously described Hector clay, as may be noted from the following formula:



$$(Al_{1.67}\ Mg_{.33})\ .\ \overset{\overset{Na_{.33}}{\uparrow}}{Si_4}\ .\ O_{10}\ (OH)_2\ .$$

The foregoing composition of montmorillonite was selected because the sodium cation on the surface of the clay particle is replaceable, as has been reported by many investigators. The relative order of replacement, as reported by Grim and others[6, 8, and 9] is as follows:

$$Li^+ > Na^+ \ldots K^+ > Rb^+ > Cs^+ > Mg^{++} > Ca^{++} > Sr^{++} > Ba^{++} > H^+.$$

The order of enumeration is that of generally increasing difficulty of replacement, or, in other words, the order of increasing stability. The opinion of Dolch[4] is that "an ion is held more securely the greater its ionic size, with the charge effect predomination."

The replaceability of ions and the order of relative stability is indicated to be a vital factor in the stabilization of clay soils with lime (Ca) or other cations high on the scale. It is evident that an exchange may occur when the metallic ion of a natural soil, which is one of the elements low on the scale, is treated by an admixture containing an element higher on the scale. The list of elements mentioned above is considered low, i.e., has low bonding power on the Li^+ end of the scale. It is also possible that partial replacement of cations in a natural soil which is low on the scale of replaceability may have been accomplished, and by the addition of a limited quantity of the proper admix, the reaction may be completed.

Relation of Cation Exchange Capacity and Coagulation

The plasticity of soils, especially clays, is a function of the relative thickness of the halo-like moisture film and the degree with which the film is bound to the mineral particle. The influence of both of these factors on the plasticity increases tremendously with the decrease in the size of the particles, so that for clays whose particles are of colloidal size, the influence is very significant. The writing of Dolch, summarizing the research of others, shows that, in the instance of Ca added to Na-ion montmorillonite, a coagulation of the particles would be expected.[4] The result of the coagulation is to reduce the plasticity considerably for the clay so treated. It is further indicated by Dolch, "that precise information is obscure regarding the concentration of the calcium ion required to effect coagulation of soil colloids because of their variable nature. However, the quantity of calcium used currently for soil stabilization probably suffices for accomplishing the coagulation." It is possible that other admixes of positively charged metallic elements high on the scale of increasing stability may accomplish the same effect.

FIRST PHASE OF RESEARCH

The preliminary study of the problem indicated that the major benefit of stabilization of clay soils with lime would be confined to the montmorillonite group, provided no consideration is given to the influence of cementation. As often prevails at the outset of research, this thought was inferred because of knowledge limited largely to the replaceability of the Na-cation of some of the montmorillonites by the Ca-cation of lime. The study of some typical Texas clay soils indicated that the improvement of the plastic properties was apparently not so restricted. However, major attention during the early phase of the study was directed toward various methods of positively identifying the montmorillonite group and particularly the clays of this group in which the Na-cation predominated. The differential thermal analysis, X-ray analysis, benzidine color indicator, and Total Base Exchange methods were considered to be best suited for this purpose. Brief descriptions of the use of these methods are given in the following paragraphs.

The discussion of the differential thermal analysis method for identifying the Na-cation montmorillonite group of clays will be limited to the results rather than discussion of the fundamental principles of the method, equipment, and other matters.

Five samples of Texas soils were selected for examination. Four of them were surface soils from areas exhibiting known detrimental swelling in the subgrades, and the fifth was from a position about five feet beneath the footings of Guion Hall on the A. and M. College of Texas campus. The last sample was obtained during under-pinning and repair of the building. The samples were subjected to the differential thermal analysis method in the laboratory of the School of Mineral Industries of the Pennsylvania State College during early 1947. The results of the tests, interpreted to within 3 to 5 per cent, are given in Table 2.

Table 2

MINERAL IDENTIFICATION OF TEXAS SOILS BY DIFFERENTIAL THERMAL ANALYSIS

Sample No.	Montmorillonite Per Cent	Quartz Per Cent	Calcite Per Cent	Feldspar Per Cent
1	40	15	40	5
2	38	27	20	15
3	5	20	75	0
4	10	55	25	10
5	50	45	0	5

The report of the examination of the samples showed that because of the different clay minerals mixed in with the montmorillonite group, it would be desirable to make a qualitative study of all of the clay minerals in the soils of Texas so as to establish their type and characteristic thermal curves. Then, unknown soils could be analyzed qualitatively in order to determine the nature of the clay mineral for comparison with the established types, so as to ultimately establish its identity.

The net result of the foregoing approach to the problem would involve extensive analytical analysis with the final result obtained by a series of comparisons. It was evident that differentiation between the sodium and calcium cation montmorillonite soils was not possible by this method at that time. However, general identification could be gained; accordingly, no further consideration was given the method.

The same group of five soil samples was examined by the X-ray method at the School of Mineral Industries, Pennsylvania State College with practically the same results as obtained by the differential thermal analysis method. The accuracy of the X-ray method depends on such factors as particle size, overlapping of the diagnostic peaks, number and nature of the minerals present, and other variables. To further explore the feasibility of the X-ray method for identifying and separating the montmorillonite group into the two desired subdivisions, a study of the problem was undertaken by LeRoy Holmes Simons, a graduate student of the Department of Physics, A. and M. College of Texas. In June of 1949, a report of the study was presented in the form of a thesis for a Master of Science degree. This was entitled "X-ray Analysis of Soils for Montmorillonite." The X-ray diffraction method was used for the thesis study. The study indicated that "by means of this method it is possible to identify various components of a given crystalline mixture and to obtain precise information about the distribution of atoms in a crystal.

To obtain the latter information, the symmetry of the crystal must be high, or single crystals of about 100 microns in length (actual diameters are 0.1 to 0.05 microns) in at least one direction must be available. Clay minerals satisfy neither of these requirements; hence, their atomic arrangements cannot be determined in complete detail, but much structural information can still be derived." It was concluded by Simons that the X-ray diffraction method was time-consuming because of the procedure required for the proper conditioning of the samples. It is posisble that the procedure could be redesigned and improved in the event the method was to be used extensively. The equipment used for this research may not have been as well suited for the purpose as some other equipment available commercially or custom made for the specific purpose. Nevertheless, the research indicated that even if the equipment and procedure were both greatly improved, the method would require technicians possessing a high degree of skill and a high level of education, with the latter applying particularly to the interpretation of the results. Therefore, the method would not be entirely feasible for an operating soil laboratory unless urgent necessity dictated its use. The thought prevailed that there must be an easier and less expensive means of securing the information.

The review of literature showed that some attention has been given by other investigations to the use of benzidine or its hydrochloride to produce an identifying blue color on inorganic montmorillonite types of clay.[14] The feasibility of such a simple determination was very appealing. It was thought that a calibrated color scale could possibly be developed for use in identifying the montmorillonite clay group which eventually might be used in the field economically and to advantage. Provision was made for this determination of the selected test soils during the early part of the investigation.

Subsequent search of literature, coupled with the consultation of Dr. J. B. Page, Texas Agricultural Experiment Station, showed the benzidine test to be unsatisfactory.[24] One of the conclusions formed by Dr. Page is quoted as follows: "It was demonstrated that montmorillonite is not essential to the reaction, that the proper oxidizing conditions though sometimes present are not always associated with montmorillonite, and that the oxidizing agents may also be associated with other clay constituents of soils. It is concluded that this test cannot be considered as specific for montmorillonite." The foregoing conclusion is concurred in by the writers.

In view of the established ranges of Base Exchange capacity in units of milliequivalents per 100 grams for all of the clay groups by Grim, and because one of the major factors involved in the stabilization of clays by chemical means is the exchange of cations of the water film electrolyte, it was evident that the determination of Total Base Exchange capacity in the foregoing indicated units was desirable. If this capacity is large, it was reasoned that the replaceable ion concentration would be large, and this would serve as an index of susceptibility to improvement of soils by the Base Exchange process. This determination for a soil would serve further to permit identification as to the clay group, and to obtain a relative measure of the chemical reaction potential. It was realized that the determination probably would not serve to differentiate between the Na-cation and the Ca-cation montmorillonite. However, it was thought that this apparent shortcoming could be overcome by another means, as will be discussed later.

A study was made of the methods described in technical literature for determining the Total Base Exchange in milliequivalents per 100 grams of soil so that the method best suited for the purpose could be selected. The basic method described by Schollenberger and Simon[27] and modified by Peach[25] was selected. Some further modifications of a minor nature were made as dictated by the conditions of the tests, as the research progressed. Full description of the procedure used is contained in the Appendix. This method of testing proved satisfactory and, by means of it, the desired results were obtained. The test can be performed satisfactorily by an average analytical chemist in a normally equipped commercial chemical laboratory. The normal soil laboratory is not so equipped nor staffed, so that constant attention during the research was given to the matter of correlating the Base Exchange information with the physical characteristics of soils as usually determined. This was done in hopes that an index could be established which would enable a soil engineer to roughly evaluate soils considered for earthwork, foundation, or highway development, insofar as the swell and shrinkage characteristics and the susceptibility to improvement by chemical means of these physical characteristics is concerned. This recognition is considered to be an important factor in the research, for not only should the soil engineer understand the factors which cause clays to possess low stability and how these factors may be controlled, but also how the troublesome clays can be recognized readily from usual soil test information.

Means of identifying the troublesome clays, such as mineralogical, petrographic analysis, or special X-ray analyses, may have their advantages. However, their use involves expensive highly specialized equipment and lengthy techniques. Further, such methods are not commonly available to soil engineers in practice; consequently, major effort was made to use such facilities as are usually at hand.

Selection of Typical Surface and Subsurface Texas Clay Soils for Study

Interest in the research was shared by the Road Design Division of the Texas Highway Department. The Texas Highway Department assisted in the program by supplying a number of natural topsoils for the study. The soils were selected because of their satisfactory, questionable, or unsatisfactory record as subgrade or embankment materials. The identifying numbers and locations from which the surface samples were secured are given in the Appendix. The subsurface soil samples were obtained from an auger boring located near the center of the site for the New Science Building on the A. and M. College of Texas campus. The selection of this source for subsurface soil samples was predicted on the knowledge that the preliminary research involving the trial of the differential thermal and X-ray analysis had shown a concentration of approximately 50 per cent montmorillonite in the subsurface soils of the campus.

The selection of surface and subsurface soils was advantageous, because they represent natural materials used both for natural subgrades and for embankments formed from excavated borrow areas or cuts in highway construction.

The plasticity characteristics of all soils used in this research were determined so as to establish their classification according to soil engineering procedure, and for the purpose of obtaining a measure of the improvement of their engineering characteristics caused by chemical treatment. The Atterberg Limits (Liquid Limit, Plastic Limit, and Plasticity Index) were used to establish the plasticity characteristics. The procedure and equipment used were those reported by A. Casagrande in PUBLIC ROADS, October 1932. The compaction characteristics of the raw and treated soils were determined using the equipment and procedure as set forth in Technical Bulletin No. 107 (1948) of the American Road Builders Association, pp. 65-71. Special attention was given to the preparation of the clay soil specimen for the compaction testing so as to assure the uniform distribution of moisture. This was accomplished by thorough mixing of each specimen when the increments of required water were added followed by storage of the specimen in air-tight containers in a humid room with subsequent additional mixing at intervals of several days until a uniform distribution was achieved.

The grain-size distribution determinations by the hydrometer method were made of most of the Texas natural topsoil samples and of selected samples of the subsurface soils. The purpose of these determinations was to secure general information about the soils used for the research.

The results of all of the determinations, except those of the compaction tests, are summarized in Table 3 for the topsoils and in Table 4 for the subsurface soils.

Study of the plasticity characteristics of both the topsoils and subsurface soils, as tabulated in Tables 3 and 4, shows that the normal range of clay soils was fully represented by the samples selected for the research. This is shown by the fact that the Liquid Limits varied from 0 to 102, and the Plasticity Indices varied from 0 to 66. It is realized that some soils, having Liquid Limits and PI's greater than the values indicated may be encountered, and it would be these unusual soils which would probably benefit most from chemical treatment. A possible solution to such a problem is treated later in this report.

The results of the determinations of Total Base Exchange and plasticity characteristics were studied so as to ascertain whether or not a correlation could be established between the two. Such a correlation would be very desirable, because the plasticity characteristics are established as a routine matter and could possibly serve as a yardstick for measuring susceptibility to chemical treatment in much the same manner as they serve for the identification of soils for engineering purposes. The best correlation that could be developed for all of the samples tested (Tables 3 and 4) was between the PI, plotted as the ordinate to a logarithmic scale, and the Total Base Exchange, plotted as the abscissa to an arithmetic scale, as shown by Figure 6. The significant portion of the curve representing the average relation is shown as a solid line through the central portion of the figure. The dashed-dot portion of the curve, for the range of PI's of 3 to 15 and Base Exchange of 3 to 13, is not considered to be too important. However, as the PI increases from the value of about 15 upward, the need for improvement increases proportionally. It appears reasonable that for this range of PI, the curve can be considered to be a straight line which may be projected from the point having the maximum coordinates up to at least a value of 100 for the PI. It would be rare for the last mentioned value to be exceeded in the usual highway development, particularly in Texas.

It may be recalled that a range of Base Exchange values for each of the members of the clay family has been established by Grim (See Table 1). The values for each of the clay groups have been plotted on Figure 6. The initial impression one may gain from a comparison of the test results and the limits for each group is that all of the soils fall either in the kaolinite or illite groups. This is not believed to be true for the following reasons:

a. The differential thermal analysis of a soil sample from the

Table 3

PROPERTIES OF THE TEXAS NATURAL TOPSOILS EXAMINED

Sample Number* (1)	Grain Size Reference (2)	Liquid Limit (3)	Plastic Limit (4)	Plasticity Index (5)	Total Base Exchange (6)	Benzidine Color Test† (7)
TNS-1-T	Fig. 1 App.	NP	NP	NP	0.7	s-p
TNS-2-T	Fig. 1 App.	18	15	3	3.5	n
TNS-3-T	Fig. 1 App.	23	20	3	4.2	n
TNS-4-T	Fig. 2 App.	25	19	5	4.5	s-p
TNS-5-T	Fig. 2 App.	22	19	3	6.0	n
TNS-6-T	Fig. 1 App.	60	29	31	30.0	n
TNS-7-T	Fig. 2 App.	49	20	29	31.0	s-p
TNS-8-T	Fig. 2 App.	63	20	43	45.0	s-p
TNS-9-T		25	22	3	1.4	n
TNS-10-T		19	15	4	5.0	n
TNS-11-T	Fig. 3 App.	30	20	10	10.0	n
TNS-12-T		50	16	34	15.0	p
TNS-30-T	Fig. 6 App.	63	20	43	45.0	p

* Sample number is laboratory designation. See Appendix for description of location.
† Degree of color reaction: s = slight; p = positive; n = negative.

Table 4

PROPERTIES OF TEXAS NATURAL SUBSURFACE SOILS AT ONE LOCATION ON CAMPUS AT VARIOUS DEPTHS

Sample Number* (1)	Grain Size Reference (2)	Liquid Limit (3)	Plastic Limit (4)	Plasticity Index (5)	Total Base Exchange (6)	Benzidine Color Test† (7)
TNS-13-5	Fig. 4 App.	44	21	23	21	p
TNS-14-7	Fig. 5 App.	51	25	23	25	p
TNS-15-3	Fig. 4 App.	53	19	34	26	p
TNS-16-9		54	24	30	27	p
TNS-17-19	Fig. 6 App.	53	23	30	27	p
TNS-18-21	Fig. 6 App.	71	25	46	30	p
TNS-19-15	Fig. 3 App.	68	27	41	31	p
TNS-20-23	Fig. 5 App.	73	24	49	32	p
TNS-21-5A§	Fig. 6 App.	70	22	48	34	p
TNS-22-17	Fig. 4 App.	78	37	41	35	p
TNS-23-13		63	34	29	36	p
TNS-24-8§	Fig. 4 App.	70	22	48	36	p
TNS-25-2		98	31	67	38	s-p
TNS-26-26	Fig. 5 App.	72	21	51	40	p
TNS-27-2§	Fig. 3 App.	64	20	44	41	s-p
TNS-28-25		84	25	59	42	p
TNS-29-11		53	32	22	44‡	s-p
TNS-31-4A§		96	35	61	45	s-p
TNS-32-8		102	36	66	47	p

* Sample designations as follows: TNS = Texas Natural Soil; First Number = Sample Number; Second Number = Depth below Surface.
† Degree of color reaction as follows: s = slight and p = positive.
‡ Sample contained appreciable organic matter; consequently, results were not used.
§ Sample of Taylor Marl from indicated depth, as supplied by the Texas Highway Department.
‖ Sample of Beaumont Clay from indicated depth, as supplied by the Texas Highway Department.

foundation of a nearby structure showed that it contained approximately 50 per cent montmorillonite (See Sample 5, Table 2) with no indications of the presence of kaolinite or illite. Accordingly, it is reasonable to consider that the clay portions of the subsurface samples tested were principally montmorillonite.

b. The grain-size distribution curves of representative samples (Appendix) show that from 20 to 80 per cent of the grains of the soils used are of the clay size (0.002 mm) or smaller. The coarse-grained portions of the samples would so alter the characteristics of the pure clay portions as to preclude applying criteria for pure clays to the normal soils encountered in earth work construction. This is a modification of a thought previously expressed; however, Total Base Exchange should serve as an indicator of susceptibility to treatment of a soil.

The color reaction of the soil samples to treatment with benzidine is reported in Column 7 of Tables 3 and 4. Review of the results, as shown in Column 7 of Table 3 for samples 1, 4, 7, and 8 shows all to have a slight-to-positive reaction, although the respective values of Liquid Limit clearly represent a broad range of plasticity from nonplastic to 25, 49, and 63 and the PI's likewise from nonplastic to 5, 29, and 43. It is possible of course, for a series of soil samples to contain a trace of montmorillonite so as to give the slight-to-positive color reaction; however, for the range of plasticity enumerated it is not probable that the same quantity of montmorillonite would exist in all such samples. The same inconsistency appears to apply to samples 25, 27, 29, and 31 of Table 4 except for a higher range on the plasticity scale. In view of the unreliability of the color reaction determination with benzidine for montmorillonite, as reported by Dr. Page, further use of this test was discontinued.

Brief recapitulation of the foregoing shows that, for the series of surface and subsurface soil samples selected for study, a correlation was found between the PI's and Total Base Exchange of the soils that appears reasonable. The correlation appears to be valid for the normal range of plastic soils (Plasticity Index of 20 to 70) and may be extended to the range of Plasticity Index of 15 to 100. The correlation shows that for the Texas natural soils, classification on the basis of Total Base Exchange is not feasible because of the normal contamination of the clay grains by the coarse grains (sand and silt sizes) usually existing in clays. The study of the plasticity and base exchange characteristics does not give any indication of the concentration of any of the three basic groups of clays contained in a natural soil.

Influence of Montmorillonite on Inert Soil

To explore the influence of montmorillonite on the plasticity and Total Base Exchange capacity of an inert soil, a series of laboratory prepared samples was formed so as to contain known proportions of each.

The inert soil selected was an inorganic alluvial silt from the recent flood plain of the Brazos River near Navasota, Texas. This natural silt was found to have LL of 30, PL of 20, PI of 10, and a Total Base Exchange of 10 milliequivalents per 100 grams. It was readily available in the desired quantities.

The montmorillonite used was commercial grade known as "Volclay," which is produced by the American Colloid Company of Chicago from reportedly relatively pure natural deposits in Wyoming. This material was found to have a LL of 710, PL of 10, PI of 700, and Total Base Exchange of 90. It is interesting to note that the Base Exchange value of 90 lies at the middle of the range for montmorillonite as established by Grim[7] and shown in Table 1.

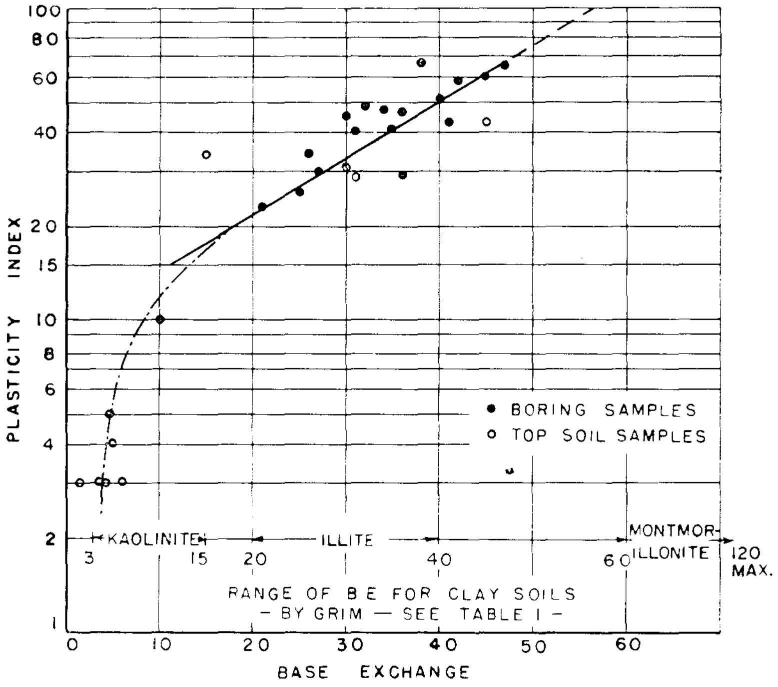


Figure 6.

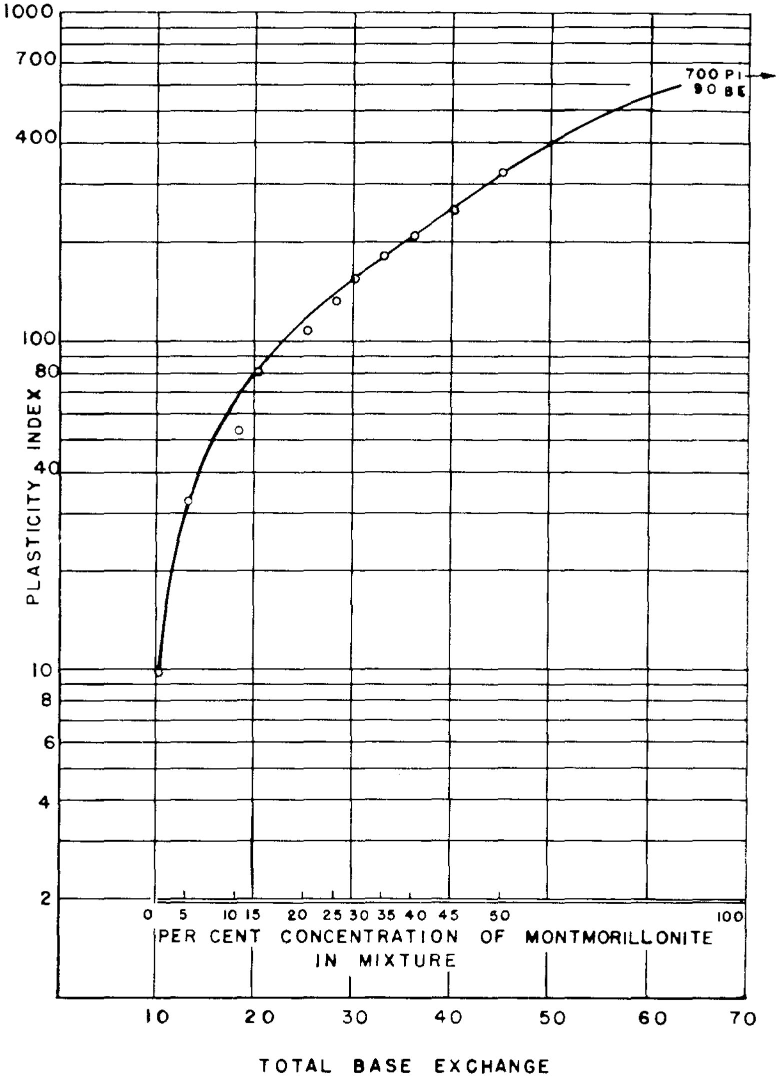


Figure 7.

Table 5

PLASTICITY AND TOTAL BASE EXCHANGE CHARACTERISTICS OF NAVASOTA SILT AND MONTMORILLONITE

Sample Number* (1)	Liquid Limit (2)	Plastic Limit (3)	Plasticity Index (4)	Total Base Exchange (5)
LM-0-0	30	20	10	10
LM-1-5	56	23	33	13
LM-2-10	82	27	55	18
LM-3-15	108	25	83	20
LM-4-20	134	25	109	25
LM-5-25	159	25	134	28
LM-6-30	185	26	159	30
LM-7-35	210	25	185	33
LM-8-40	236	25	211	36
LM-9-45	277	24	253	40
LM-10-50	354	24	330	45
LM-11-100	710	10	700	90

* Explanation of sample numbering code: "LM" indicates laboratory mixture; the first number designates the the sample number of this series; and the second number indicates per cent of commercial montmorillonite.

The two materials were combined to form ten laboratory samples. The first sample was made to contain 95 per cent silt and 5 per cent montmorillonite, the second 90 per cent silt and 10 per cent montmorillonite, and so on by 5 per cent increments with the final sample containing equal parts of both materials. The raw soil was pulverized prior to being combined with this commercial grade montmorillonite, which had been obtained in pulverized form. The proportioning was on the basis of the air dry weight of the solids.

The plasticity and Total Base Exchange characteristics of each of the ten samples were determined by the procedures previously described. The results of the determinations are summarized in Table 5.

Review of the LL and PI determinations shows the influence of the tremendous increase of surface area per unit volume accompanying the increase of concentration of montmorillonite. This is in accordance with previous discussions wherein it was pointed out that as the size of the grains decreased, the surface area per unit of volume increased. Further, it was explained that the minerals and structure of the montmorillonite group possessed the unusual ability to take molecules of water into their structure. The net effect is for the halo-like adsorbed moisture films to form about and between the grains to increase the plasticity of the material. It may be noted from Table 5, Columns 2 and 4, that both the LL and PI increased 1200 per cent and 3300 per cent respectively by the addition of 50 per cent montmorillonite to the silt.

The graphic relationships between PI, Total Base Exchange, and per cent of montmorillonite contained in laboratory prepared samples are shown by Figure 7. This figure presents these relationships in the same manner as was used for the Texas natural soils, Figure 6. The lower portion of the curve of Figure 7 reflects a rapid change of plasticity (PI of less than 160) with a small increase of the percentage of montmorillonite. This rapid change is attributed to the relative pureness of the montmorillonite used and the absence of other minerals such as would be the normal case for natural soils. It may also be noted that the concentration

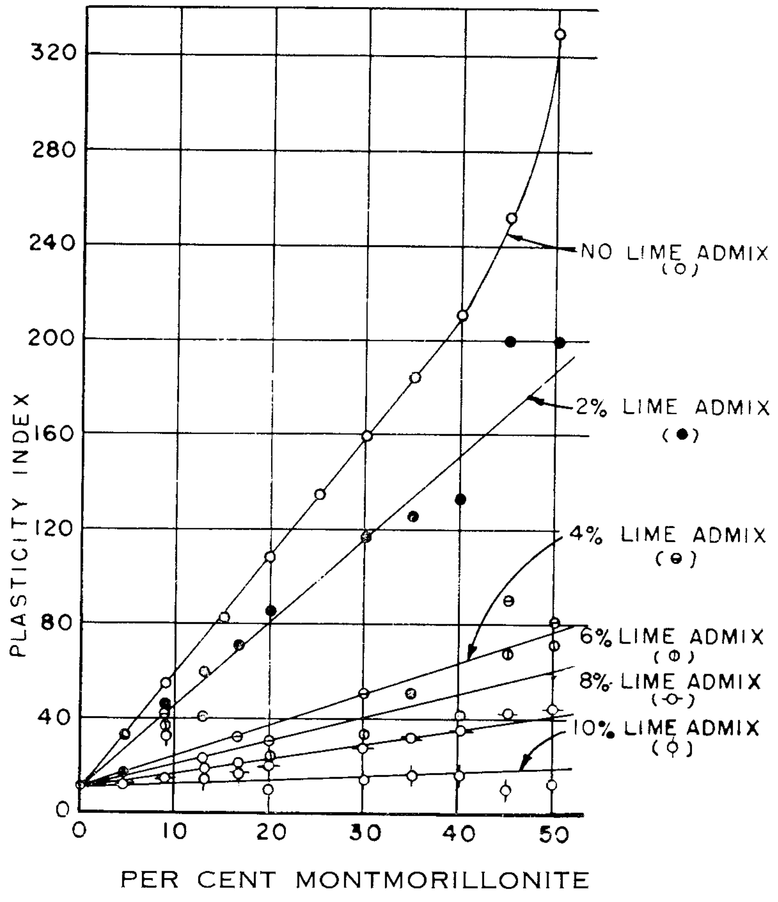


Figure 8.

of montmorillonite was increased from 0 to 30 per cent, so that in effect characteristics of the silt were predominating. For the tangent portion of the curve, where the concentration of the montmorillonite exceeded 30 per cent, the characteristics of the silt were obscured because the silt grains were dispersed in the other material. Accordingly, this latter part of the curve may be considered to represent the maximum relation that may be expected between PI and Base Exchange for soils encountered in nature. The upper portion of the curve is for illustrative purposes only and is not considered significant. The experimental data from which the curve was plotted shows three points, namely the 10, 20, and 25 per cent montmorillonite, to lack agreement. This is thought to be caused by experimental error in determining the Total Base Exchange, for had the Base Exchange been slightly less, each point would fall on the curve. As a result, the scales of per cent concentration of montmorillonite and Total Base Exchange would be more proportional and nearly arithmetic.

It is realized that there are many subdivisions of the montmorillonite group of clays, as there are of the other two groups; namely, kaolinite and illite. It would not be possible in a report of this nature to investigate all of the various subdivisions of the clay groups.

SECOND PHASE OF RESEARCH

Influence of Lime on Plasticity Characteristics of Some Laboratory Controlled Clay Soils

In view of the uniformity of the laboratory prepared inert silt and montmorillonite mixtures and the broad ranges of plasticity and Base Exchange of the materials mixed in the previously enumerated proportions, treatment of them with lime was experimented with initially. No simple means was found during the first phase of the research for identifying the predominating ionic size or charge of the natural or laboratory prepared soils. However, the magnitude of the Total Base Exchange was indicated to be a measure of replaceability of the cation in the soil or mixture. Inasmuch as Ca^{++} is available from lime and is relatively near the top of the scale of increasing difficulty of replaceability, it was reasoned that knowledge as to the exact identification of the cation of the soil or mixture may not be necessary. Further, it may be recalled, that in the order of replacement, only Strontium (Sr), and Barium (Ba), which are not common in soils, outrank Calcium (Ca); consequently, it is reasonable to assume the lime would serve to replace all of the more common cations of lower order.

The desired reaction of lime or other stabilizing materials that may be used with clay is fundamentally chemical by nature. Accordingly, the rate at which the reaction occurs depends upon the dispersion of the reagent in the clay soil treated, surface area per unit of volume, moisture available, and temperature. The first three of the foregoing factors are of primary significance, because the soils requiring chemical treatment are fine-grained, cohesive, relatively impervious, and their capillary moisture causes these soils to form clods which are difficult to pulverize. The surface area per unit of volume of these clods is many times less than the total surface area per unit of volume for the individual grains.

Table 6

INFLUENCE OF REACTION TIME ON BASE EXCHANGE AS REFLECTED BY ATTERBERG PLASTICITY TESTS

Sample Plus Admix (1)	Liquid Limit			Plastic Limit			Plasticity Index		
	Series 1*		Series 2†	Series 1		Series 2	Series 1		Series 2
	Virgin (2)	0.5 hours (3)	24 hours (4)	Virgin (5)	0.5 hours (6)	24 hours (7)	Virgin (8)	0.5 hours (9)	24 hours (10)
2 per cent	56	57	46	23	26	28	33	31	18
4 per cent	56	54	41	23	31	30	33	23	11
6 per cent	56	54	42	23	30	30	33	24	12
8 per cent	No appreciable change above 6 per cent.								
10 per cent									

* Series 1 reaction time 0.5 hours.
† Series 2 reaction time 24 hours.

The Base Exchange process affects only the surface area and must affect the aggregate surface area of the mass; consequently, it would appear that a lapse of time must be allowed for the lime and its accompanying water to permeate the mass. To ascertain the influence of time so that a reasonable criterion for subsequent testing could be established, ten samples of the inert silt were prepared with about 5 per cent of montmorillonite, and admixtures of 2, 4, 6, 8, and 10 per cent of lime were added to form two series of like samples. The Atterberg Limits were determined for the first series of samples following a lapse of 30 minutes after mixing, and for the second series a lapse of 24 hours was allowed after mixing. The results are given in Table 6.

The significance of allowing a reasonable time lapse for the lime-bearing water to soak through the soil and affect the Base Exchange of the halo-like moisture films on the grains is evidenced by comparison of the values summarized in Table 6. The significance is esepcially evident by comparing the values shown in Columns 9 and 10. Accordingly, for the subsequent testing an interim of 24 hours was made to elapse between the introduction of the admixture of lime with thorough mixing before the desired tests were made, thus assuring that the chemical reaction would be reasonably complete. It is probable that the chemical reaction continues with time, so that the benefits may be greater than those indicated by the 24-hour period maintained in this research. Allowance of relatively long reaction time would have been necessary if consideration had been given to the effect of cementation in this program.

To explore further the influence of lime on the plasticity characteristics of the controlled laboratory mixtures of inert silt and montmorillonite, a group of five samples was prepared, with each group containing 4.75, 9.1, 13.0, 16.7, 20, 30, 35, 40, 45, and 50 per cent montmorillonite. The first sample of each group was admixed with 2 per cent of lime, the second sample of each group was admixed with 4 per cent lime, and so on to the fifth sample, which was admixed with 10 per cent of lime. The proportioning was on a dry weight basis. After the samples were properly prepared and thoroughly mixed, distilled water, as required for the Atterberg Limit tests, was added to each, and then the samples were thoroughly remixed. Twenty-four hours was allowed to elapse after the water was added before the tests were performed.

Table 7

AFFECT OF LIME ON PLASTICITY PROPERTIES
NAVASOTA SILT MONTMORILLONITE MIXTURES

Concentrations of Montmorillonite in Mixture Per Cent (1)	Atterberg Limit Tests (2)	Values of Limits, No Admix (3)	Values of Atterberg Limits For Indicated Percentage Of Lime Admix 2% (4)	4% (5)	6% (6)	8% (7)	10% (8)
	LL	56	46	41	42	42	45
4.75	PL	23	28	30	30	30	32
	PI	33	18	11	12	12	13
	LL	82	72	70	67	65	62
9.1	PL	27	26	27	32	35	35
	PI	55	46	43	35	30	27
	LL	105	84	70	59	55	55
13.0	PL	25	25	29	34	39	40
	PI	80	59	41	25	16	15
	LL	114	82	66	62	61	61
16.7	PL	25	26	34	40	43	43
	PI	89	57	34	22	18	17
	LL	134	80	68	64	62	62
20.0	PL	25	32	38	40	40	40
	PI	109	48	30	24	22	22
	LL	185	143	92	74	67	74
30	PL	26	25	41	46	39	46
	PI	159	118	51	28	28	28
	LL	210	148	90	85	94	84
35	PL	25	22	39	33	33	38
	PI	185	126	51	52	?	46
	LL	236	155	77	80	74	91
40	PL	25	23	36	40	39	41
	PI	211	132	41	40	35	50

The procedure, equipment, and technique for the tests were the same as has been described previously.

The results of the Atterberg Plasticity tests on the series of samples containing the previously indicated percentages of montmorillonite and to which 2, 4, 6, 8, and 10 per cent lime was added are summarized in Table 7. This information is best understood and visualized from a graphic presentation as shown by Figure 8. The deviation of some of the observed points from the average straight lines representing the influence of 2 and 8 per cent lime admixes is attributed to normal experimental error and to the variations from the 24-hour period established for the Base Exchange process to have been accomplished. The erratic variations which may be noted for the instances of the 4 and 6 per cent lime admixes is attributed to the deviations from the timing designed for the tests. The testing was accomplished by student assistants who may have been taking examinations concurrently with this work. The trend shown by the results demonstrates the tremendous beneficial changes in the plasticity of clay-like soils which can be accomplished by admixes of lime. The beneficial results, in this instance, vary directly as the concentration of the lime admix, with the maximum corresponding to 10 per cent.

In dealing with natural soils, it is not likely that PI's in excess of 150 would be experienced. In addition, it is not likely that soils would be found which contain relatively pure montmorillonite; however, by use of lime or similar admixtures, a comparable beneficial influence on the plasticity characteristics should be expected.

Influence of Lime on Plasticity Characteristics of Some Surface and Subsurface Natural Texas Soils

The objective of this part of the research was to ascertain the response of some representative surface and subsurface Texas natural soils to lime treatment, to explore the use of Total Base Exchange or its equivalent PI as a measure of susceptibility to treatment, and to determine the influence of various concentrations of lime admix on these clays.

The surface soils examined were for the most part the same ones as previously described and reported in Table 3; namely, the first eight and the last one as shown. The supply of subsurface soil samples previously examined had become exhausted; consequently, a new supply had to be secured from the alternate samples obtained from the same strata of soils and at approximately the same elevations as the original samples. These are designated by the letter "B" at the end of the sample numbers.

It may be noted that the subsurface samples in the Taylor Marl, TNS-21-4A, and the Beaumont Clay, TNS-31-4A, were both used again for this part of the program. These clays are both common to large areas of Texas and represent some of the natural soils that it may be desirable to improve by chemical means.

Total Base Exchange characteristics of the new samples were all obtained in the manner previously described. Five specimens of each of the soil samples were prepared to receive the lime admix by being air dried and pulverized by passage through a corn mill. A commercial grade of slaked lime was added on a weight basis in such proportions, as to give 2 per cent in the first specimen, 4 per cent in the second, 6 per cent in the third, 8 per cent in the fourth, and 10 per cent in the fifth specimen of each sample. A sufficient quantity of distilled water was added to each specimen so as to permit performing the Atterberg Limits. Each specimen containing lime and water was thoroughly mixed and allowed to remain in this condition for approximately 24 hours for the chemical reaction to occur. The Limit tests were repeated for each specimen to ascertain the influence of the chemical reaction with the lime. The results of the original and final tests are summarized in Table 8. Due to the variations of the plasticity characteristics of the natural soils, which is to be expected, it was not practicable to present the information contained in Table 8 as a single family of curves, such as Figure 8.

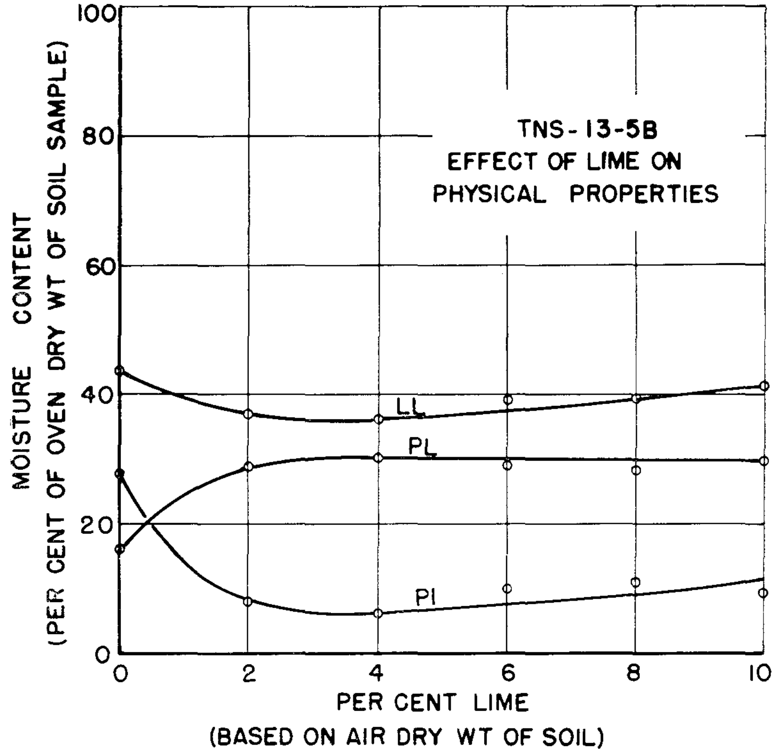


Figure 9.

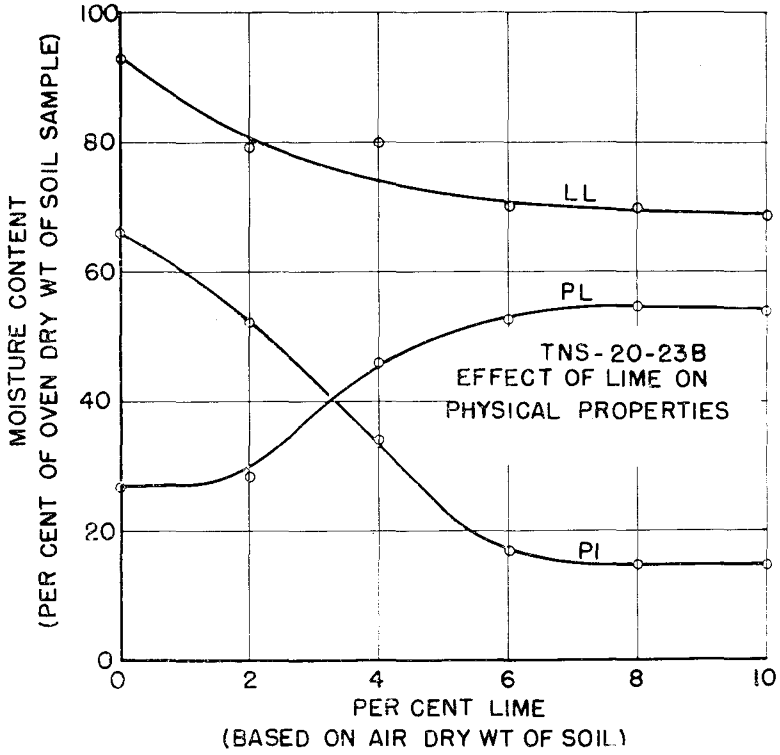


Figure 10.

However, the influence of the lime on each soil sample has been presented graphically by Figures 9 to 15.

Study of the information contained in Table 8 indicates that clay-like soils having a PI or Base Exchange capacity of less than 20 experienced negative to slight or insignificant reaction; soils possessing a value of these factors in the range from 20 to 40 experienced a moderate reaction, with exceptions discussed subsequently; and soils possessing values of 40+, without exception, experienced a significant improvement of their plasticity characteristics. Refinements of the foregoing subdivisions, according to PI's, appear possible from correlation of a larger number of soils. The slight influence of lime on the soils having PI's of less than 20 is to be expected, for such soils normally contain low proportion of clay sized grains which would be influenced by the exchange of the base caused by lime admix. For the clay-like soils within the range of PI's of 20 to 40, the moderate reaction is likewise expected, for only a moderate proportion of these soils is of clay-sized grains. It may be noted for Samples TNS-6-T and TNS-7-T, Table 8, having PI's of 31 and 29 respectively, for which similar reaction would be expected, that the first one experienced an increase of PI with the 2 per cent lime admix and then a progressive reduction accompanying the increase of the concentration of the lime; whereas, for the second one, the reduction was progressive for the complete range of lime admix. This contrast is considered normal for soils possessing this mid range characteristic and may be attributed to several factors; namely, the minerals and their ionic charge intensity comprising the first sample, the initial low concentration of lime causing an unknown reaction other than the exchange of base, or to other unknown factors. For the clay soils within the PI range of 40+, the pronounced reaction was in accordance with the previously explained process. It is for this latter range that the maximum beneficial influence of the lime admix occurs.

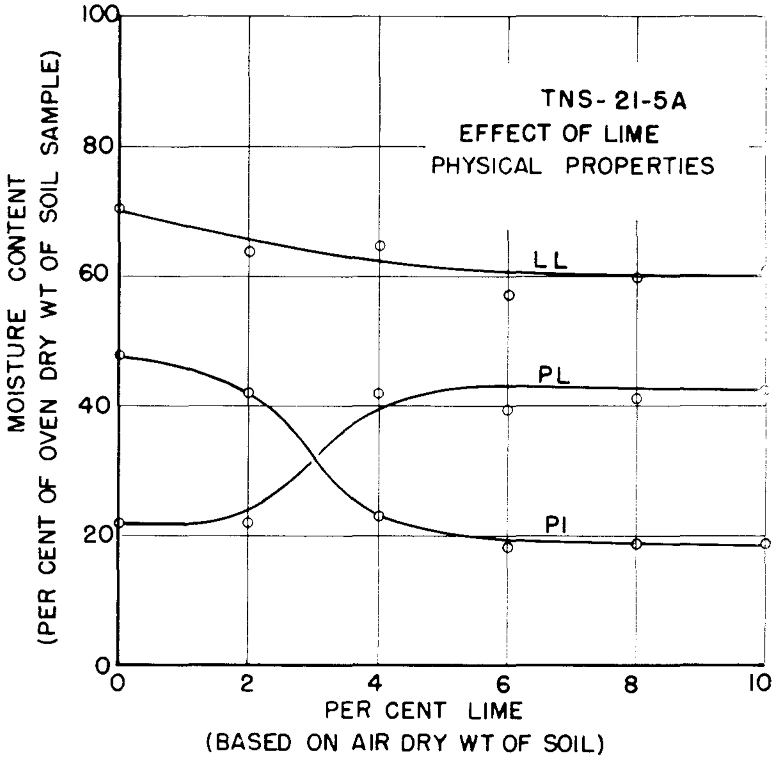


Figure 11.

Table 8

EFFECT OF LIME ON PLASTICITY CHARACTERISTICS OF TEXAS NATURAL SOILS, BOTH SURFACE AND SUBSURFACE

Sample Number (1)	Natural Plasticity Index (2)	Original Base Exchange Base (3)	Reaction Anticipated* (4)	Values of Plasticity Index for Indicated Percentages of Lime 2% (5)	4% (6)	6% (7)	8% (8)	10% (9)
			Surface Soils					
TNS-1-T	N.P.	0.7	N	2	3	5	6	6
TNS-2-T	3	3.5	S	2	1	1	0.7	0.6
TNS-3-T	3	4.2	S	3	2	1	1—	1—
TNS-4-T	6	4.5	S	2	0	0	0.5	0.7
TNS-5-T	3	6.0	S	7—	7+	7	7—	7—
TNS-6-T	31	30.0	M	38	33	33	31	29
TNS-7-T	29	31.0	M	23	20	20—	19	19—
TNS-8-T	43	45.0	P	32	29	27	27	27
			Subsurface Soils					
TNS-30-TB	50	40	P	21	14	14	13	13
TNS-13-5B	28	26	M	8	6	8	9	11
TNS-20-23B	66	47	P	53	33	17	15	15
TNS-21-5A†	48	34	M	42	23	19	18	18
TNS-22-17B	49	40	P	37	25	16	11	10
TNS-26-26B	54	42	P	24	15	14	16	17
TNS-28-25B	55	42+	P	43	29	16	15	15
TNS-31-4A‡	66	47	P	50	24	20	17	15

* Degree of color reaction as follows: N, none; S, slight; M, moderate; P, positive.
† Sample of Taylor Marl from indicated depth as supplied by Texas Highway Department.
‡ Sample of Beaumont clay from indicated depth as supplied by Texas Highway Department.

Observation of Table 8 and other data presented to show the effect of lime admix on the plasticity properties of the clay soils

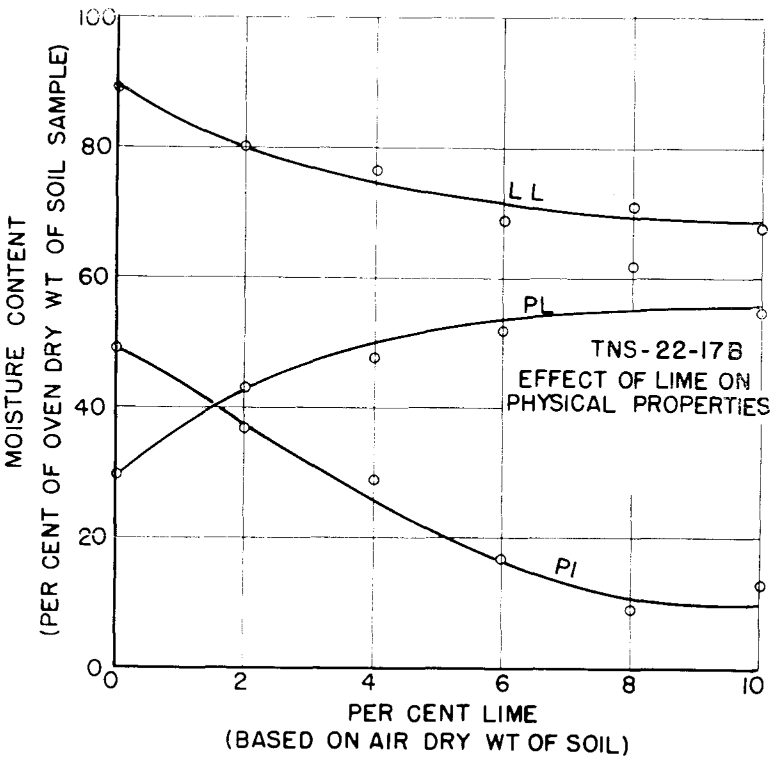


Figure 12.

might lead one to inquire concerning the effect of lime admix on the Total Base Exchange capacity of a particular clay specimen. How is the Total Base Exchange capacity affected by lime? This data is not presented because the method of performing the Base Exchange test does not permit accurate determination of this property after the use of lime. In adding lime to a clay the calcium takes the place of replaceable cations in the clay sample. The process of determining the Base Exchange capacity after lime admix involves the addition of ammonia which in turn replaces the calcium cations that had been added by liming. The net result is that the test gives the same Total Base Exchange capacity for "before" and "after" lime treatment.

Influence of Lime on Compaction Characteristics of Some Surface and Subsurface Natural Texas Soils

The objective of this part of the research was to determine the influence of the varying concentration of the lime admixes on the compaction characteristics of the soils reported in Table 8. The compaction characteristics of soils are significant in regard to the investigation, design, and control of construction of earth embankments and subgrades for highways and airfields.

The compaction characteristics of the raw surface soil, Samples TNS-1-T through TNS-8-T, were determined in accordance with the procedure set forth in Technical Bulletin No. 107, pages 65-71, 1948, of the American Road Builders Association. Special attention was given to the preparation of the test specimens in that they were prepared for testing by first being pulverized, thoroughly mixed with the compaction water, and then stored for sufficient time to allow the water to be dispersed in the soil before being subjected to the compaction test. Two duplicate specimens of each of the soils were prepared in the foregoing manner; however, to the first one lime was added in a concentration of 6 per cent, on a weight basis, and to the second one of each series lime was added in a concentration of 10 per cent.

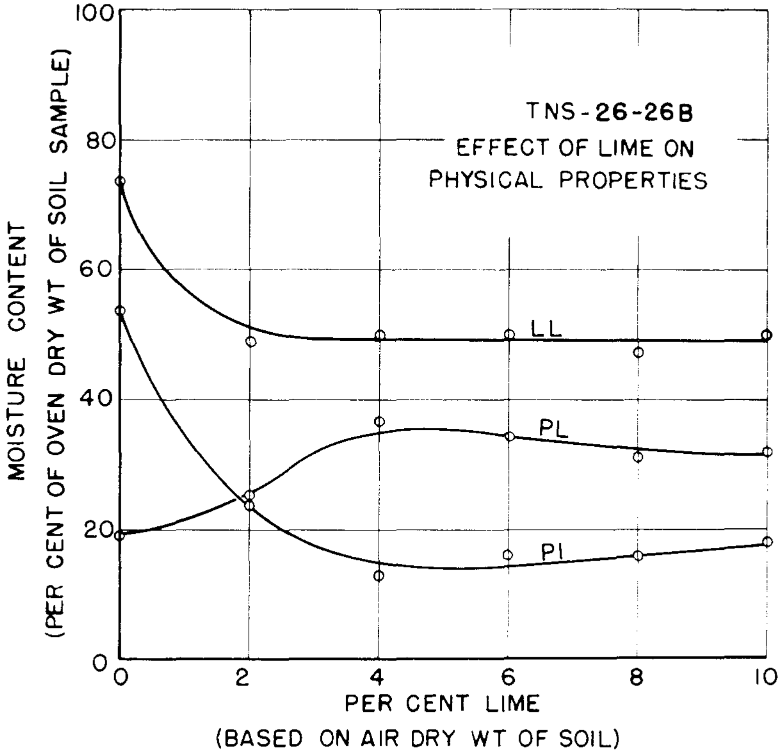


Figure 13.

These percentages were selected because they represented the approximate mid-range and highest range of the concentration of the effective lime admixes used. The lime was added in all instances to the pulverized soil specimen before the water was added and mixing undertaken, so that good dispersion in the soil would be achieved. The treated soil specimens were compacted in a manner like the raw soils.

The results of the compaction determinations of the raw and treated soils are presented graphically by Figures 16 through 23, which are self explanatory.

Study of the families of compaction curves for all of the soils shows that the compaction characteristics of the soils treated are influenced by the lime admixtures as follows:

a. The optimum unit dry weights of the compacted soils are decreased by the lime admixtures. The per cent reduction varies between the limits of 6.0 to 3.7 per cent (Table 9). It is indicated that the reduction of unit dry weight varies somewhat inversely as the PI of the virgin soil. This is considered to be a trend rather than a firm relationship. Study of the test results from many samples would be required to confirm this indicated trend. The indicated percentages of reduction of the unit dry weights of the soils tested are not considered to be significant.

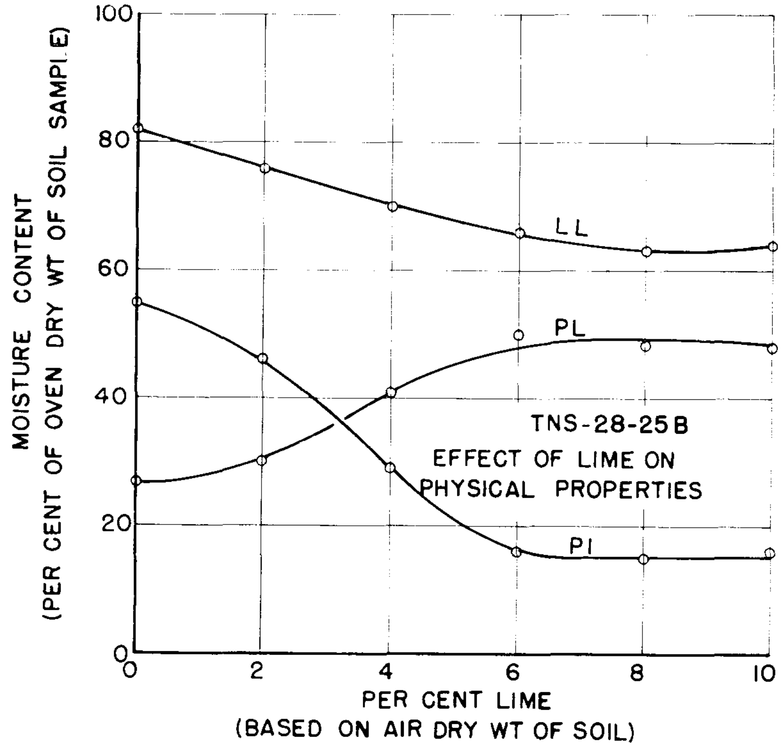


Figure 14.

Table 9

EFFECT OF LIME ON COMPACTION CHARACTERISTICS OF SOME SURFACE TEXAS NATURAL SOILS

Sample Number (1)	Natural Plasticity Index (2)	Original Base Exchange Value (3)	Decrease of Optimum Dry Unit Weight Due to 10% Lime Per Cent (4)	Increase of Optimum Moisture Content Due to 10% Lime Per Cent (5)
TNS-1-T	N.P.	0.7	6.0	2
TNS-2-T	3	3.5	4.8	2
TNS-3-T	3	4.2	6.7	2
TNS-4-T	6	4.5	4.8	3
TNS-5-T	3	6.0	4.3	2
TNS-6-T	31	30.0	4.7	2
TNS-7-T	29	31.0	3.7	2
TNS-8-T	43	45.0	4.4	3

b. The optimum moisture content of the compacted soils experienced an increase due to the lime admixture (Table 9). The increase varied between 2 and 3 per cent for a concentration of lime admixture of 10 per cent. Study of the data shows that there is apparently no relationship between the indicated increases and the other properties of the untreated or treated test specimens. Further consideration of the influence of lime admixes on the compaction characteristics of clay soils shows that for some conditions and localities the influences may be beneficial, and to the contrary for others. For example, in the Gulf Coastal Plain of Texas where the Beaumont Clay (TNS-31-4A) occurs as a surface soil, the influences may be very beneficial, because the soils are normally high in natural moisture content, and a slight increase in the optimum moisture would aid in the processing and field compaction operation. Further, the introduction of the dry lime as an admix would serve to blot excess moisture from the natural moist soils and tend to minimize the field compaction operation. On the other hand, in the central part of Texas, where the drier climate and dry Taylor Marl (TNS-21-5A) is common, the small increase of the optimum moisture content would require more compaction water to be used during the field construction, thus adding to the cost and time factors slightly.

Design Considerations of Economic Use of Lime Admixes for Clay Soils

Review of literature and discussion of the use of lime as a stabilizing agent for subgrade soils have indicated the normal planning has been to select for use the percentage of lime which would produce the maximum change of plasticity. This percentage of lime frequently has been specified for the top portion of the subgrade soils embracing thicknesses of 6, 10, 14, and 18 inches. Study of the problem has indicated that this procedure may be improved to result in the same advantages at lower costs, particularly for building up subgrades and bases for flexible pavements.

The practice of the Texas Highway Department for the de-

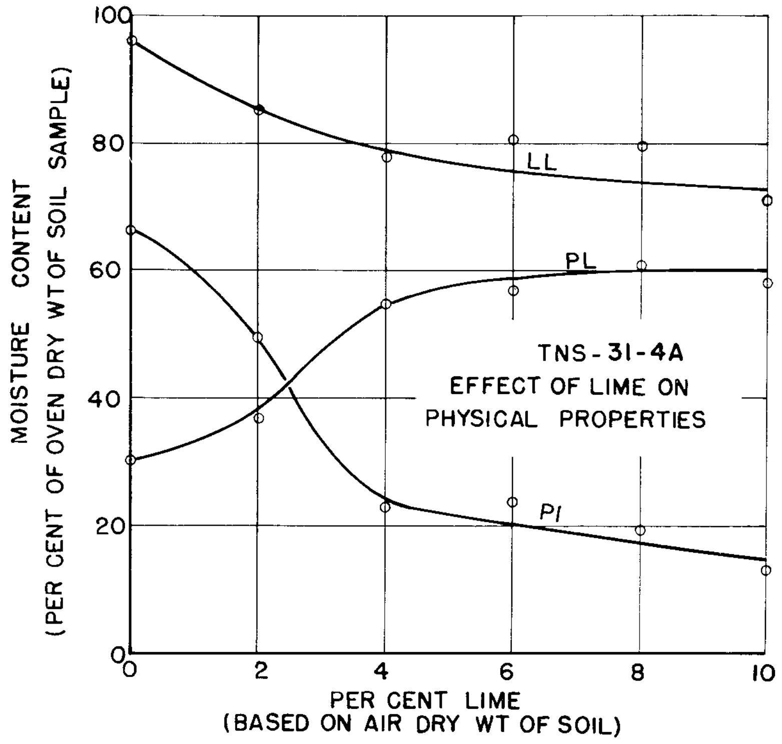


Figure 15.

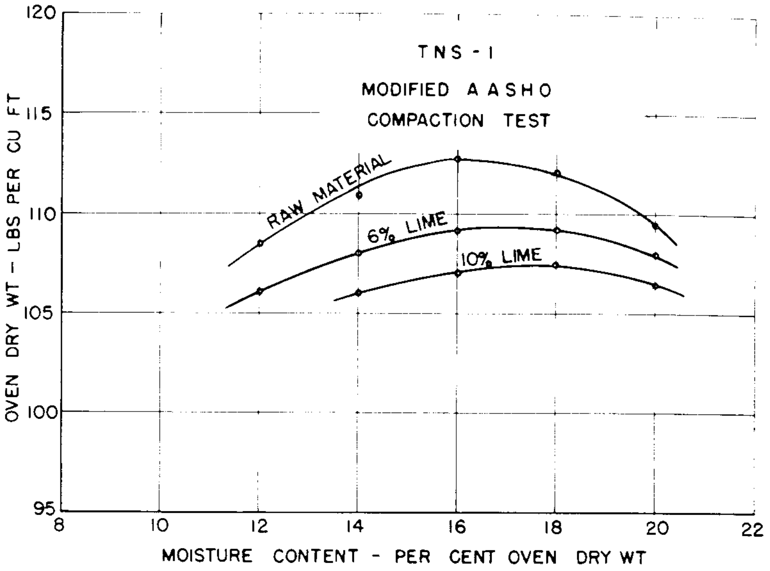


Figure 16.

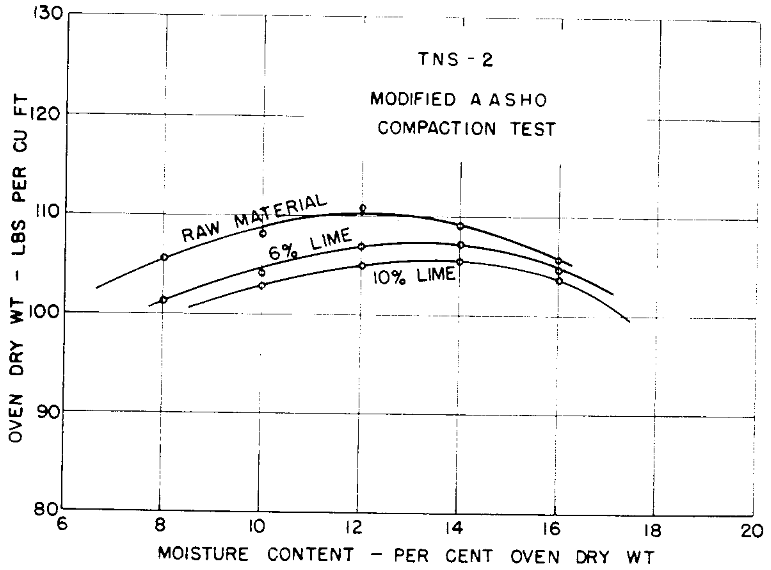


Figure 17.

sign of subgrades and bases for flexible pavements, as set forth in the Administrative Circular No. 43-50, Part II, provides for the classification of subgrade and base materials for flexible pavements on the basis of their shear strength. The design provides for the shear strength of the roadway materials to decrease with depth measured from the surface downward. For example, if a moderately low strength natural subgrade material were to support a pavement for a specified wheel-load and type of traffic, its strength might dictate reinforcement of 18 inches of progressively stronger overlying materials as the surface of the roadway is approached. The stronger materials required for use in the Gulf Coastal Plain may have to be imported from long distances, thus making them expensive, particularly in the indicated region. This same progressive increase in strength may be achieved through the increase of the concentration of the lime admix as the roadway surface is approached. To illustrate this line of thought further, consider the influence the various percentages of lime have on the PI of the Beaumont Clay (Sample TNS-31-4A) as shown in Table 8, wherein the value of PI is reduced from 66 to 15 by concentrations of lime varying from 2 to 10 per cent. It appears feasible in this instance to provide in the design for the use of low concentration of lime for depths considerably beneath the roadway surface, and progressively increase the concentration to a maximum at the surface. This practice appears contrary to the current procedure, wherein a single concentration is used throughout and is usually of the order of 8 to 10 per cent. However, through the modification outlined, considerable economy in the quantity of lime and processing could be effected. It is contemplated to study possible combinations of this nature in subsequent phases of this research, if arrangements for its continuation may be made.

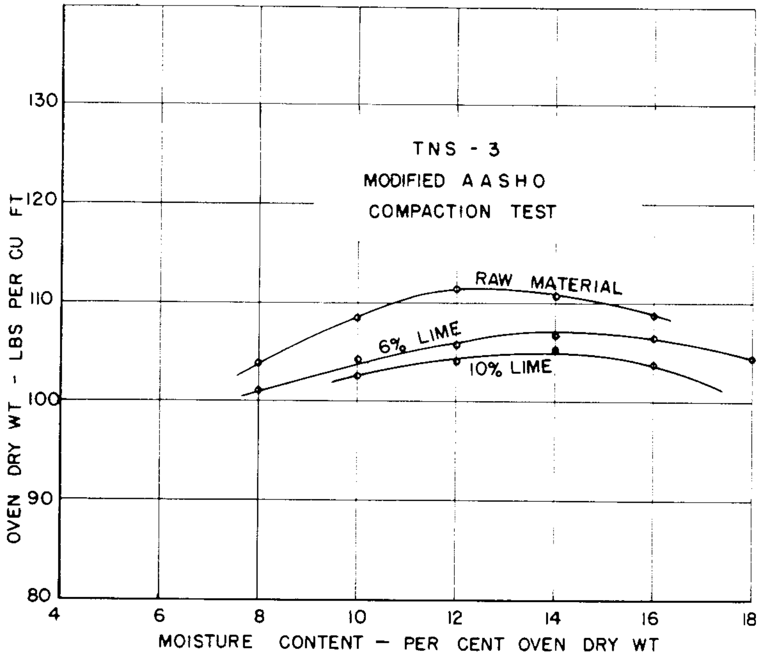


Figure 18.

Field Problems Anticipated in Use of Lime Admixes

Consideration of a method of soil stabilization would not be complete without some evaluation of how the method or process may be used for actual application. The following brief review of this matter is presented in order to show that some thought has been devoted to this aspect of the method.

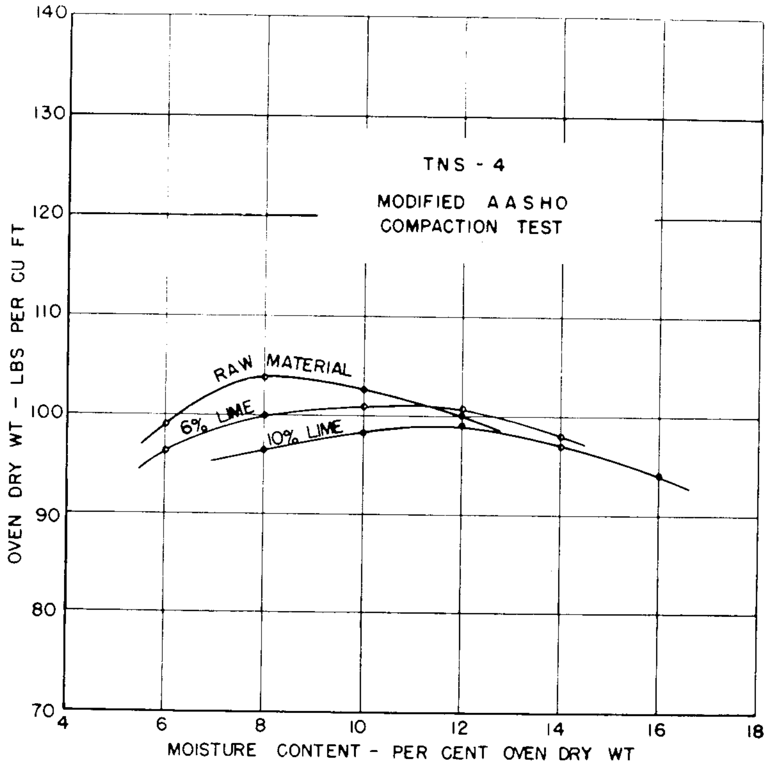


Figure 19.

In order for the lime to be effective, it must be dispersed in the soil which is to be stabilized. Due to the cohesive nature of clays, it is relatively impractical to pulverize such soils in the field, so that dispersion of lime admix is not easily accomplished. The actual dispersion is usually accomplished by discing and windrowing the soils to be treated back and forth across the roadway. Such processing is expensive.

The review of literature has not disclosed any information on efforts to simplify this process of dispersing the lime in the soils. It is thought that some attention should be given to the development of an easy means of accomplishing this dispersion, such as introducing the lime in suspension in the water sprinkled on the soil as a part of the normal compaction or construction operation. In addition, it is indicated that possibly water soluble liquid polymers, which are available commercially, may be used to advantage for this purpose in lieu of lime; however, time has not permitted experimentation with such substitutes.

Question arises concerning the permanence of the stabilizing effect of lime admixtures. Though tests have not confirmed the thought, it is felt that the stabilization will be reasonably perma-

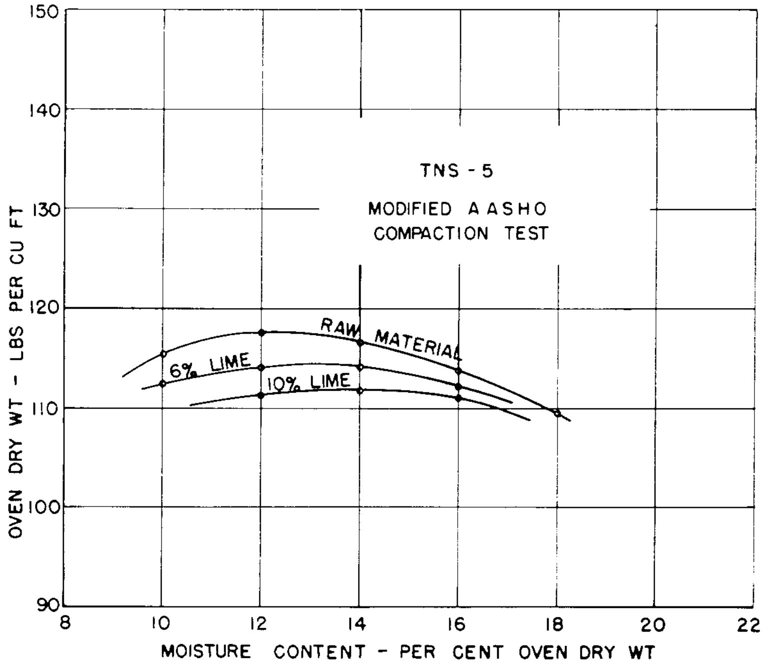


Figure 20.

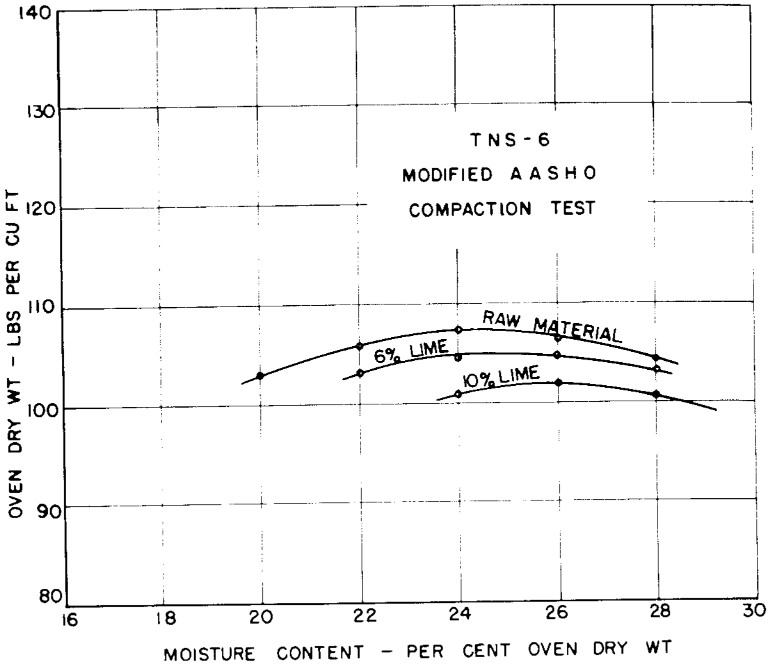


Figure 21.

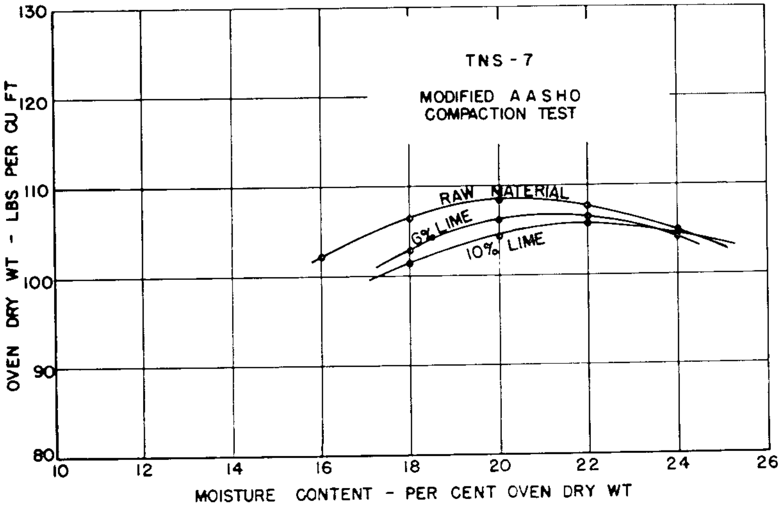


Figure 22.

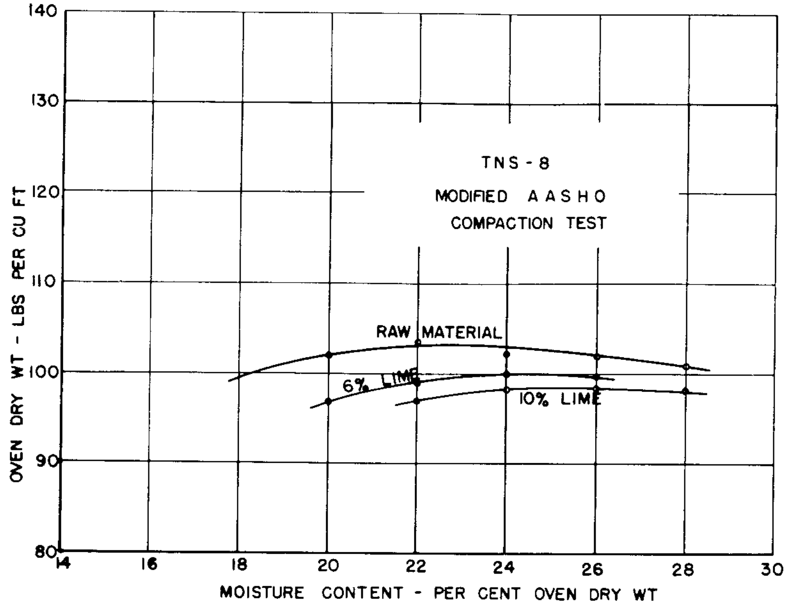


Figure 23.

nent. The relatively low replaceability of calcium, which has been interjected to take the place of the replaceable cations in the raw soil, should not permit it to be replaced by other minerals contained in the soil. Though vegetation may absorb the calcium over a period of years, this phenomenon is highly unlikely in subgrades or base courses of pavements.

CONCLUSIONS

General and specific conclusions were formulated as a result of the study.

General Conclusions—The stabilizing reaction of lime with clay soils is chemical in nature. It is the result of the replacement of the weaker positively charged metallic elements by the stronger positively charged calcium cations of the lime which, in turn, influence the thickness of the adsorbed halo-like moisture films on the exterior of the clay grains. The plasticity of clay soils, which is in effect a rough measure of their stability, is considered to be a function of the thickness of the water films. The results of the study show that the chemical reaction caused by the lime is not restricted to a specific group of the clay family, but rather reacts with all of the Texas natural surface and subsurface soils used in this research; consequently, the range of application of this method of improvement of the engineering properties of clays appears to be very broad, even though the influence of coagulation or flocculation and cementation are not treated in this report.

Specific Conclusions—The specific conclusions are treated in the following paragraphs.

1. The identification of members of the clay family; namely, kaolinite, illite, and montmorillonite by the differential thermal analysis was indicated to be satisfactory; however, the results of such identification were indicated to be of only general rather than specific value as regards lime stabilization. It did not appear possible to identify the sodium cation from the calcium cation montmorillonite clays by this method.

2. The identification of members of the clay family by the X-ray method is possible, but does not appear to be feasible for engineering purposes at the current state of knowledge.

3. The unreliability of the benzidine color reaction test for identification of montmorillonite was confirmed.

4. The identification of clay soils, without regard to classification by groups, susceptible to favorable reaction with lime, on the basis of the Total Base Exchange capacity appears to be valid for the small number of soils examined. The classification of the groups of the clay family on the basis of the Base Exchange ranges, as set forth by Grim, does not appear to apply to Texas natural soils or to laboratory mixtures of inert silt with commercial grade of montmorillonite. In addition, the correlation of the Plasticity Index with this Base Exchange, as developed for both laboratory and natural soils, appears to be reasonable and permits ready identification of the clay soils which would react favorably with lime as a stabilizing admix, based on the limited use reported herein.

5. The significance of time effect to the reaction of lime and soil is clearly demonstrated by the research. A minimum reaction time of 24 hours is indicated.

6. The influence of lime on the engineering properties of clay soils, both laboratory prepared (Figure 8) and Texas natural soils (Table 8) is clearly demonstrated for ranges of PI's from 0 to 340 per cent and concentrations of lime from 2 to 10 per cent.

7. The merit of lime as a soil stabilizing agent for clays of PI's greater than 20 appears to be clearly demonstrated from a theoretical and a laboratory basis. Its use depends upon economic considerations.

RECOMMENDATIONS

The indicated correlation of Total Base Exchange and Plasticity Indices, as developed in this study, should be continued to the extent of at least 100 comparisons for Texas natural clay soils, both surface and subsurface, so as to validate this method of determining the susceptibility of clay soils to treatment with lime.

The influence on the shear strength of lime stabilization of clay soils should be explored so that the indication shown by the change of plasticity may be confirmed.

The possibility of introducing the lime into the clay soils to be treated, as a water suspension, should be explored because of the economic and time benefits.

The possibility of using water soluble liquid polymers in lieu of lime should be explored from a theoretical, laboratory, and field experiment basis with proper emphasis on the durability of the polymers.

APPENDIX

Total Base Exchange Method

The selection of the modified method of determining Total Base Exchange capacity, as given below, was made after extensive literature research and after consultation with experts in the agricultural soil science division of the College. The changes made in the size of sample and filtering device were evolved because of the montmorillonite content of the laboratory mixed samples. As the particle size of the clay fraction of a given sample decreases, the rate of leaching likewise decreases, other operations being held constant. Also, in general, as the particle size of the clay fraction decreases, the wet volume of the sample increases, resulting in a decrease of the filtering rate; a large buchner funnel and a small sample was dictated. It is not advisable to increase the funnel size beyond 7 cm. so as to increase the filtering rate, but rather it is desirable to reduce the size of the sample to approximately 10 or 15 grams and change the multiplying factor in the Base Exchange equation. In some instances where sample material is very limited, Base Exchange capacity might be determined on a gram or less of material, but the neces-

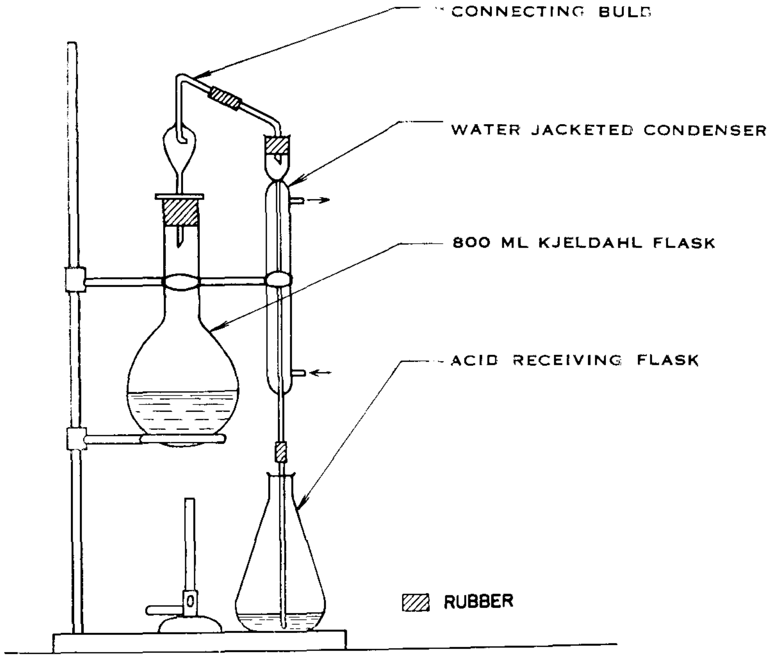


Figure 1a.

sary precision of determination would be increased greatly. The following modification was used.

Duplicate soil samples of 25 grams (air dry weight) were weighed out in a 250 ml. Ehrlenmeyer flask and 100 ml. of normal neutral (pH of 7.0 by glass electrode pH meter) ammonium acetate were added. The flasks were stoppered with rubber stoppers and shaken vigorously at 15-minute intervals for one hour and then allowed to set overnight. The samples were again shaken and poured into 7 cm. buchner funnels fitted with No. 42 Whatman filter paper which had been previously wet with distilled water. Side neck filtering flasks of 600 ml. capacity were used so that the rate of filteration could be controlled by applying a partial vacuum to the samples. The samples were kept covered with watch glasses in order to minimize contact with air. After the first 100 ml. of leachate had passed through the soil sample and before visible drying or cracking developed, 50 ml. of fresh leachate were added and filtering, continued as before, until four such 50 ml. batches had been used. The rate of leaching was regulated so that the leaching process required at least two hours. Following the leaching, the samples were washed with 80 per cent methyl alcohol adjusted to a pH of 7.0 (the pH adjustment of the alcohol-water mixture required one fourth drop of 99.5 per cent acetic acid per liter of solution whose original pH was 8.26) by the addition of three 50 ml. batches of alcohol. The samples were drained well between each addition of methonal, but care was exercised to avoid drying out the soil. The samples were then transferred to 800 ml. Kjeldahl flasks which were prepared for distillation as shown in Figure 1a.

The soil samples were washed into the distillation flask with 375 ml. of distilled water along with the filter paper. To this was added ten grams of sodium chloride, five drops of antifoam mixture, several small pieces of porcelain, and 25 ml. of normal sodium hydroxide. The mixture was stoppered and agitated by a whirling motion while still connected as shown in Figure 1. Any ammonia displaced during agitation was neutralized by 50* ml. of .2N sulphuric acid in the 400 ml. flask beneath the condenser. The burners were lighted, and the flame was adjusted so that the mixture began to boil in about 15 minutes. Distillation was continued for 45 minutes. The sample of distillate was then titrated using .1 sodium hydroxide and four drops of methyl red as an indicator. The exchange capacity of the sample was calculated by the equation: milliequivalents per 100 grams soil = [(ml. acid) × (normality of acid) − (ml. base) × (normality of base)] × (4).

---

* In some cases more than 50 ml. of .2N sulfuric acid are required. Additional acid must be added, should the indicator show the acid is neutralized.

Surface Soils Supplied by Texas Highway Department

Table 1a

IDENTIFYING NUMBERS OF SURFACE SOILS SUPPLIED BY TEXAS HIGHWAY DEPARTMENT

Report Number	Identification	Report Number	Identification
TNS-1-T	47-86-E	TNS-17-19	AMC 19′ depth
TNS-2-T	46-144-E	TNS-18-21	AMC 21′ depth
TNS-3-T	47-136-E	TNS-19-15	AMC 15′ depth
TNS-4-T	46-149-E	TNS-20-23	AMC 23′ depth
TNS-5-T	46-134-E	TNS-21-5A	Taylor Marl 5′ depth
TNS-6-T	Acme Brick Clay	TNS-22-17	AMC 17′ depth
TNS-7-T	39-59-M R	TNS-23-13	AMC 13′ depth
TNS-8-T	29-11-M R	TNS-24-8A	Taylor Marl 8′ depth
TNS-9-T	47-85-E	TNS-25-2A	Beaumont Clay 2′ depth
TNS-10-T	Limestone Sand	TNS-26-26	AMC 26′ depth
TNS-11-T	Navasota Silt	TNS-27-2A	Taylor Marl 1½′ depth
TNS-12-T	Franklin Brick Clay	TNS-28-25	AMC 25′ depth
TNS-13-5	AMC* 5′ depth	TNS-29-11	AMC 11′ depth
TNS-14-7	AMC 7′ depth	TNS-30-T	AMC 1′ depth
TNS-15-3	AMC 3′ depth	TNS-31-4A	Beaumont Clay 4′ depth
TNS-16-9	AMC 9′ depth	TNS-32-8A	Beaumont Clay 8′ depth

* A. and M. College grounds.

Mechanical Analysis Diagrams

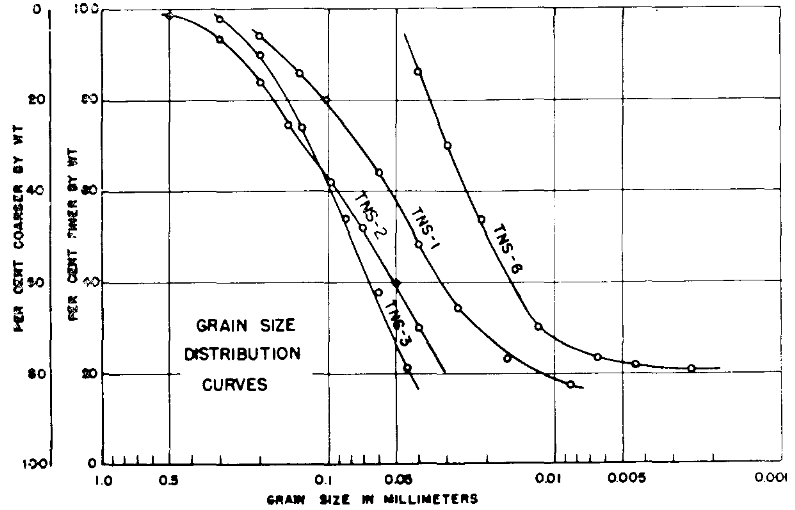


Figure 2a.

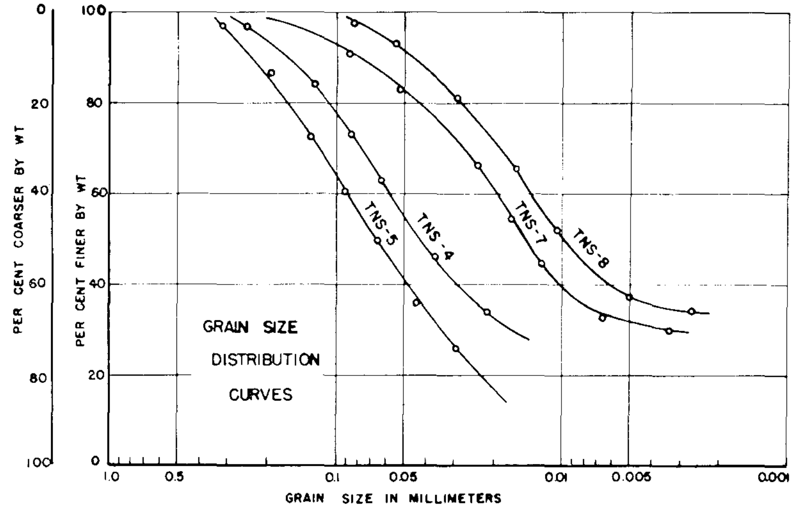


Figure 3a.

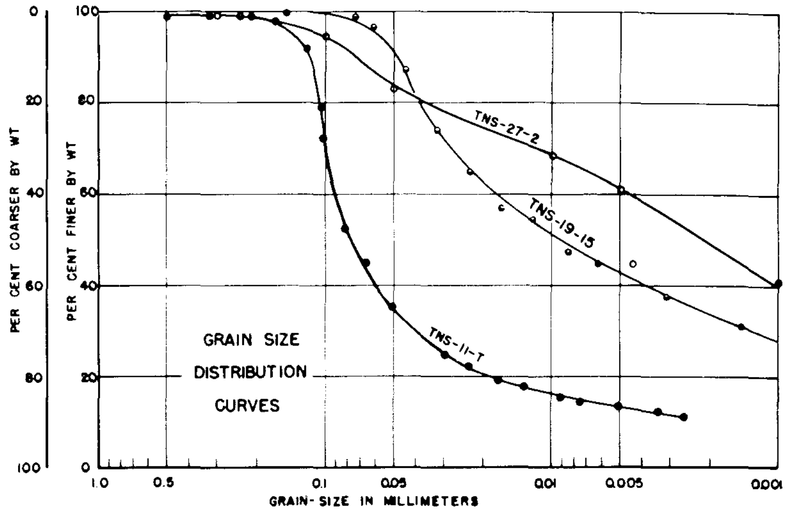


Figure 4a.

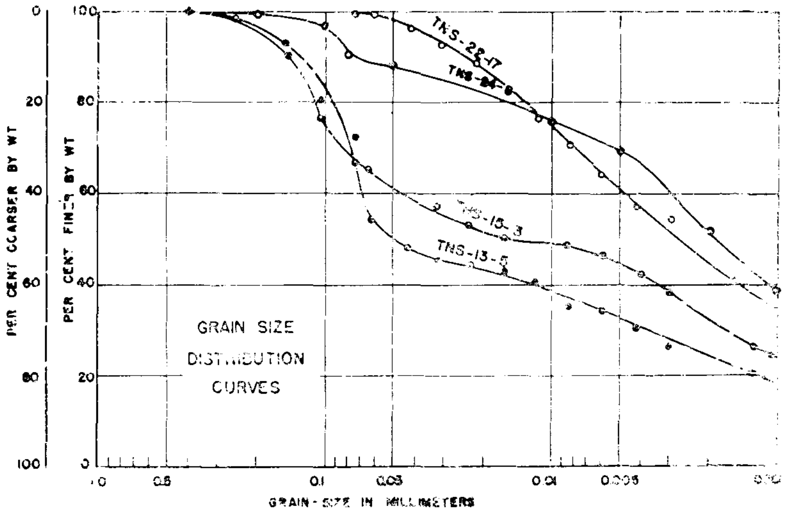


Figure 5a.

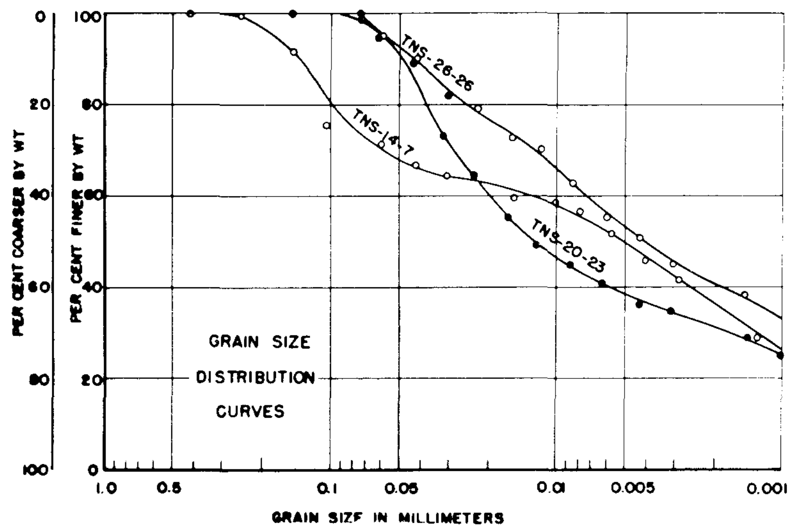


Figure 6a.

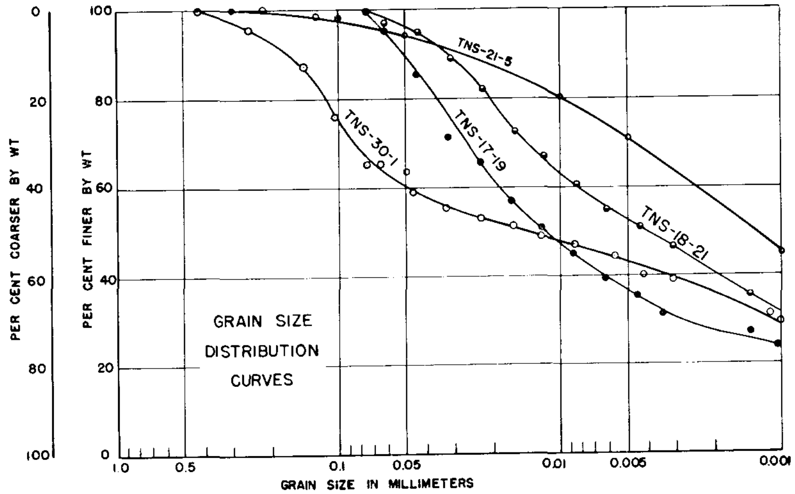


Figure 7a.

BIBLIOGRAPHY

1. Alexander, Jerome. "Bentonite," INDUSTRIAL ENGINEERING CHEMISTRY, Vol. 16 (1924), pp. 1140-42.

2. Casagrande, Arthur. "Research on the Atterberg Limits of Soils; Public Roads," Vol. 13, No. 8 (1932), pp. 121-30 and 136.

3. Davis, F. L. "Retention of Phosphates by Soils; II Effect of Drying and of Certain Cations and Anions on the Cation-Exchange Capacity of Soils," SOIL SCIENCE, Vol. 59 (1945), pp. 175-90.

4. Dolch, W. L. "The Lime Stabilization of Soil," unpublished summary, Purdue University, Lafayette, Indiana, March 1951.

5. Gieseking, J. E. "The Mechanism of Cation Exchange in the Montmorillonite-Beidellite-Nontronite Type of Clay Minerals," SOIL SCIENCE, Vol. 47 (1939), pp. 1-11.

6. Gieseking, J. E. and Jenny, Hans. "Behavior of Polyvalent Cations in Base Exchange," SOIL SCIENCE, Vol. 42 (1936), pp. 273-80.

7. Grim, R. E. "The Clay Minerals In Soils and Their Significance," PROCEEDINGS PURDUE CONFERENCE ON SOIL MECHANICS AND ITS APPLICATIONS, July 1940.

8. Grim, R. E. "Modern Concepts of Clay Minerals," THE JOURNAL OF GEOLOGY, Vol. 50 (1942), pp. 225-75.

9. Grim, R. E. "Geotechnique," Vol. 2, No. 3 (June, 1940), pp. 139-47.

10. Hanna, W. J. and Reed, J. F. "A Comparison of Ammonium Acetate and Buffered Barium Chloride Methods for Determining Cation-Exchange Properties of Limed Soils," SOIL SCIENCE, Vol. 66 (1948), p. 447.

11. Heatman, J. H. GEOLOGICAL SURVEY OF WYOMING, Bulletin No. 28, 1939.

12. Hendricks, S. B. "Base Exchange of the Clay Mineral Montmorillonite for Organic Cations and Its Dependence Upon Absorption Due to Van der Waals Forces," JOURNAL OF PHYSICAL CHEMISTRY, Vol. 45 (1941), pp. 65-81.

13. Hendricks, S. B., Nelson, R. A., and Alexander, T. L. "Hydration Mechanism of the Clay Mineral Montmorillonite Saturated by Various Cations," JOURNAL OF AMERICAN CHEMICAL SOCIETY, Vol. 62, Part 1 (1940), pp. 1457-64.

14. Hendricks, S. B. and Alexander, T. L. "A Qualitative Color Test for the Montmorillonite Type of Clay Minerals," JOURNAL

AMERICAN SOCIETY OF AGRONOMY, Vol. 32 (1940), pp. 455-58.

15. Jackson, M. L. and Hellman, N. N. "X-Ray Diffraction Procedure for Positive Identification of Montmorillonite from Hydrous Mica," SOIL SCIENCE SOCIETY OF AMERICA, Vol. 6 (1941), pp. 133-45.

16. Jennings, J. E. "Foundations for Buildings in the Orange Free State Goldfields," JOURNAL SOUTH AFRICAN INSTITUTION OF ENGINEERS, Vol. 9, Nos. 4 and 8 (November 1950).

17. Kelley, W. P. "The Agronomic Significance of Base Exchange," JOURNAL OF AMERICAN SOCIETY OF AGRONOMY, Vol. 22 (1930), pp. 977-85.

18. Kopeloff, Nicholas. "The Influence of Fineness of Division of Pulverized Limestone on Crop Yield as Well as the Chemical and Bacteriological Factors in Soil Fertility," SOIL SCIENCE, Vol. 4 (1917), pp. 19-67.

19. Lesesne, S. D. "Stabilization of Clay Roadbeds with Lime," Bulletin 325, National Lime Association.

20. Mattson, Sante. "The Laws of Soil Colloid Behavior: IV Isolectric Precipitates," SOIL SCIENCE, Vol. 31 (1931), pp. 57-77.

21. Mayestad, O. C., Fireman, M., and others. SOIL SCIENCE, Vol. 57 (1944), pp. 371-79.

22. McDowell, Chester and Moore, W. H. "Improvement of Highway Subgrades and Flexible Bases by the Use of Hydrated Lime," PROCEEDINGS OF THE SECOND INTERNATIONAL CONFERENCE ON SOIL MECHANICS AND FOUNDATION ENGINEERING, (1948).

23. Midgley, A. R. "Lime — Its Importance and Efficient Use of Soils," SOILS SCIENCE SOCIETY PROCEEDINGS, Vol. 8 (1943), pp. 324-33.

24. Page, J. B. "Unreliability of the Benzidine Color Reaction as a Test for Montmorillonite," SOIL SCIENCE, Vol. 51 (1941), pp. 133-40.

25. Peech, M. "Determination of Exchangeable Cations and Exchange Capacity of Soils," SOIL SCIENCE, Vol. 59 (1945), pp. 25-38.

26. Ross, C. S. and Hendricks, S. B. "Clay Minerals of the Montmorillonite Group; Their Mineral and Chemical Relationship and the Factors Controlling Base Exchange," SOIL SCIENCE SOCIETY OF AMERICA, Vol. 6 (1941), pp. 58-62.

27. Schollenberger, C. J. and Simon, R. H. "Determination of

Exchange Capacity and Exchangeable Bases in Soil: Ammonium Acetate Method," SOIL SCIENCE, Vol. 59 (1945), pp. 13-24.

28. Shaw, B. T. and Humbert, R. P. "Electron Micrographs of Clay Minerals," SOIL SCIENCE SOCIETY OF AMERICA, Vol. 6 (1941), pp. 146-49.

29. Simon, L. H. "X-Ray Analysis of Soils for Montmorillonite," unpublished M.S. thesis (Graduate School, Agricultural and Mechanical College of Texas, College Station, Texas, 1949).

30. Wear, J. I., Steckel, J. E., and others. "Clay Mineral Models: Construction and Implications," SOIL SCIENCE, Vol. 66 (1948), pp. 111-17.

31. Winterkorn, Hans F. "Application of Modern Clay Researches in Construction Engineering," THE JOURNAL OF GEOLOGY, Vol. 50 (1942), pp. 291-306.

PREVIOUS BULLETINS
OF THE
TEXAS ENGINEERING EXPERIMENT STATION

†No. 1. Earth Roads. R. L. Morrison. 1915.

No. 2. The Relation and Value of Chemistry to Industry. H. B. Gordon. 1915.

†No. 3. The Comparative Value of Fuels. M. K. Thornton. 1915.

No. 4. Highway Bridges and Culverts. B. K. Coghlan. 1915.

†No. 5. Highway Engineering at the Agricultural and Mechanical College of Texas. R. L. Morrison, (Superseded by No. 14.) 1915.

†No. 6. Household Conveniences and How to Make Them. C. E. Hanson. 1915.

No. 7. Gravel Roads. B. K. Coghlan. 1915.

No. 8. Electricity in the Country Home. F. C. Bolton. 1915.

No. 9. Cotton Classing and Marketing. J. B. Bagley. 1915.

No. 10. Sewage Disposal for Country Homes. D. C. Miller. (Superseded by No. 46.) 1915.

†No. 11. Purchasing by Specifications. W. P. Nelson, Jr. 1915.

†No. 12. Demonstration Roads at the Agricultural and Mechanical College of Texas, 1916-17. R. L. Morrison. 1916.

†No. 13. The Financial Side of Road Improvement. B. K. Coghlan. 1916.

No. 14. Highway Engineering at the Agricultural and Mechanical College of Texas. R. L. Morrison. 1916.

†No. 15. The Organization of a State Highway Department for the State of Texas. B. K. Coghlan. 1916.

†No. 16. Maintenance of Earth, Sand-Clay, and Gravel Roads. R. L. Morrison. 1917.

†No. 17. The Physical Testing of Non-Bituminous Road Materials. Roy M. Green. 1917.

No. 18. The Benefits of Good Roads. Robert J. Potts. 1917.

No. 19. Sand-Clay Roads. B. K. Coghlan. 1917.

No. 20. The Value of Applied Geology. D. R. Semmes. 1918.

No. 21. The Administration of Highway Improvements. R. L. Morrison. 1919.

No. 22. Bituminous Pavement Investigations in Certain Texas Cities. Part I, Bitulithic. Roy M. Green. 1919.

No. 23. Principles of Pavement Selection, with Statistics of Pavements in Texas Cities and Towns Prior to January 1, 1920. Roy M. Green and L. W. Kemp. 1920.

No. 24. Bituminous Pavement Investigations in Certain Texas Cities. Part II. Asphaltic Concrete (Topeka and Modified Topeka), Sheet Asphalt, Uvalde Rock Asphalt and Oklahoma Rock Asphalt. Roy M. Green. 1921.

No. 25. Proceedings of a Regional Conference for the Study of Highway Engineering and Highway Transport. Edited by J. C. Nagle. 1922.

No. 26. Preliminary Report of Power Producing Qualities of Certain Gasolines. Hugh M. Milton, Jr. 1922.

No. 27. Cotton Mill Development in Texas. J. B. Bagley. 1922.

No. 28. Asphaltic Paving Mixtures, Their Materials and Proportioning with Details of Plant Inspection. W. J. Emmons. 1922.

No. 29. A Study of Thermal Radiation. J. R. D. Eddy and J. H. Nelson. 1937.

No. 30. The Resistance of Electrical Ground Connections. O. B. Wooten. 1924.

†No. 31. A Study of the Fluxing of the Bitumen Contained in Texas Limestone Rock Asphalt. J. T. L. McNew. 1926.

†No. 32. Railway Grade Reduction Problems. B. D. Marburger. 1926.

No. 33. Paint Investigations—1922 Paint Fence. M. K. Thornton, Jr. 1926.

No. 34. Characteristics of Some Anti-Knock Fuels in Internal Combustion Engines. M. K. Thornton, Jr. and Ray Flagg. 1927.

No. 35. Electricity on Texas Farms. J. E. Waggoner. 1928.

No. 36. Proceedings, Fourth Annual Short Course in Highway Engineering. J. T. L. McNew. 1928.

No. 37. The Dunbar Sewage Filter. E. W. Steel and P. J. A. Zeller. 1928.

†No. 38. The Treatment of Dairy Wastes. E. W. Steel and P. J. A. Zeller. 1930.

No. 39. Design of the Reinforced Concrete Road Slab. L. E. Grinter. 1931.

No. 40. Sludge Temperatures and Capacities of Digestive Tanks, and Gravel as a Trickling Filter Medium. E. W. Steel and P. J. A. Zeller. 1930.

No. 41. The Loss of Head in Cast-Iron Tees. F. E. Giesecke, W. H. Badgett, and J. R. D. Eddy. 1932.

†No. 42. The Treatment of Laundry Wastes. J. A. Boyer. 1933.

†No. 43. The Distribution of Soil Pressure Beneath a Footing. F. E. Giesecke, W. H. Badgett, and J. R. D. Eddy. 1933.

No. 44. Laboratory Studies of Chemical Precipitation of Sewage. E. Whedbee and P. J. A. Zeller. 1936.

No. 45. Semi-Plant Scale Studies of Chemical Precipitation of Sewage. E. Whedbee and P. J. A. Zeller. 1938.

No. 46. Rural Water Supply and Sewerage. Part I, Excreta Disposal and Sewerage. E. W. Steel and P. J. A. Zeller. 1939.

No. 47. Treatment of Settled Sewage in Lakes. F. E. Giesecke and P. J. A. Zeller. 1939.

†No. 48. Lecture Notes on Practical Petroleum Geophysics. Garrett Kemp. 1940.

†No. 49. Papers Presented at the First Annual Air Conditioning Short Course. 1939.

No. 50. A Rational Method of Analyzing Water Rate Structures. S. R. Wright. 1940.

No. 51. Rural Water Supply and Sewerage. Part II, Rural Water Supply. E. W. Steel and P. J. A. Zeller. 1940.

No. 52. The Installation and Use of Attic Fans. W. H. Badgett. 1940.

No. 53. Proceedings of the Sixteenth Annual Short Course in Highway Engineering. 1941.

No. 54. The Willard Chevalier Lectures. 1940.

No. 55. The Effect of Voltage Variations on the Domestic Consumer. L. M. Haupt, Jr. 1940.

No. 56. Proceedings of the First Annual Conference on Surveying and Mapping, May 1940. 1941.

No. 57. A History of Suspension Bridges in Bibliographical Form. A. A. Jakkula. 1941.

No. 58. Two-Span Continuous Beams with Dead Loads. A. A. Jakkula. 1941.

No. 59. Space for Teaching. An Approach to the Design of Elementary Schools for Texas. W. W. Caudill. 1941.

No. 60. Proceedings of the First and Second Annual Conferences of Municipal Engineers. 1941.

No. 61. Proceedings of the Conference on Highway Economics. 1941.

No. 62. Heat Requirements of Intermittently Heated Buildings. Elmer G. Smith. 1941.

No. 63. Solvent Extraction of Cottonseed Oil. W. D. Harris. 1941.

No. 64. Solution of Two-Span Continuous Beams Under Live Loads by Use of Nomographs. A. A. Jakkula. 1941.

No. 65. Water Treatment with Limestone. C. H. Connell, P. J. A. Zeller, and J. H. Sorrels. 1941.

†No. 66. Some Fundamentals of Timber Design. Howard J. Hansen. 1942

No. 67-71A. ROADWAY AND RUNWAY SOIL MECHANICS DATA. Henry C. Porter. 1942.

No. 67. Part I—Permanency of Clay Soil Densification.

No. 68. Part II—Density and Total Moisture Content of Clay Soil.

No. 69. Part III—Density and Total Density Change of Clay Soils.
Part IV—Density and Total Volumetric Change of Clay Soils.

No. 70. Part V—Density and Intermediate Moisture Contents of Consolidated Clay Soils.

Part VI—Density and Intermediate Volumetric Changes of Consolidated Clay Soils.

Part VII—Intermediate Moisture Contents and Volumetric Changes of Consolidated Clay Soils.

No. 71. Part VIII—Method of Preparing Clay Soil Specimens for Physical Tests.

Part IX—Density and Strength of Clay Soils when Consolidated and Saturated.

No. 71A. Part X—Density, Moisture Content, and Strength of Consolidated Clay Soils.

Part XI—Moistures in Clay Soils Beneath Pavements. General Summary—Parts I Through XI.

No. 72. A Study of the Freight Rates Affecting Texas Agriculture. Tom D. Cherry. 1943.

No. 73. X-Ray Studies of Paving Asphalts. C. L. Williford. 1943.

No. 74. Design Loads for Wooden Roof Trusses. Howard J. Hansen. 1942.

No. 75. Rural Water Supply and Sewerage. Part III, The Specific Treatment of "Red Water" for the Removal of Iron and Carbon Dioxide. P. J. A. Zeller and J. H. Sorrels. 1942.

†No. 76. A Low Cost Home for Texas. C. J. Finney. 1943.

No. 77. Friction Heads of Water Flowing in Six-Inch Pipe and the Effects of Pipe Surface Roughness and Water Temperatures on Friction Heads. F. E. Giesecke and J. S. Hopper. 1943.

†No. 78. Reprint of Original Reports on the Failure of the Tacoma Narrows Bridge. Edited by A. A. Jakkula. 1944.

No. 79. A New Approach to Axonometric Projection and Its Application to Shop Drawings. J. G. McGuire. 1944.

No. 80. Proceedings of the Third Wartime Aviation Planning Conference. 1944.

No. 81. Proceedings of the First Annual Short Course and Conference—Airport Management and Planning. 1944.

†No. 82. The Effect of the Present Freight Rate Structure on Five Industries in Texas. Tom D. Cherry. 1944.

†No. 83. Bibliography on the Petroleum Industry. E. DeGolyer and Harold Vance. 1944.

No. 84. A Study of Rose Oil Production in Texas. J. H. Sorrels and J. C. Ratsek. 1944.

No. 85. The Texas School of the Air—Jobs Ahead in Engineering. Sponsored by the School of Engineering. 1944.

†No. 86. Postwar Planning Conference for Controlled Surveying and Mapping. 1945.

No. 87. Disinfection of Mattresses. E. H. Gibbons, W. D. Harris, and P. J. A. Zeller. 1945.

No. 88. Dimensioning and Shop Processes. J. G. McGuire. 1945.

No. 89. A Surface Water Treatment System for the Rural Home. Joe B. Winston. 1945.

†No. 90. Adobe as a Construction Material in Texas. Edwin Lincoln Harrington. 1945.

No. 91. Steel Columns. A Survey and Appraisal of Past Works. A. A. Jakkula and H. K. Stephenson. 1949.

No. 92. Analyses in High Frequency Fields. Fred W. Jensen and A. J. Parrack. 1945.

†No. 93. Well Logging Methods Conference. 1945.

No. 94. The Competitive Problems of Commodity Freight Rates. W. B. Langford. 1945.

No. 95. The Effective Use of Portable Fans. E. G. Smith. 1945.

†No. 96. Drilling Fluids Conference. 1945.

No. 97. Geographical Distribution of Some Basic Texas Industries. J. G. McGuire. 1945.

No. 98. Sewerage Service Charges. Samuel Robert Wright. 1945.

No. 99. The Willard Chevalier Lectures. Willard Chevalier. 1945.

No. 100. First Annual Short Course on Instrumentation for the Process Industries. 1946. (Not available for free distribution.)

No. 101. Development of a Cold Cathode Ion Source for a Mass Spectrometer Type Vacuum Leak Detector. Harold A. Thomas. 1947.

†No. 102. Preview of Engineering. J. G. McGuire. 1947.

No. 103. Second Annual Short Course on Instrumentation for the Process Industries. 1947. (Not available for free distribution.)

No. 104. Proceedings of the Second Short Course and Conference, Airport Management and Planning. 1947.

No. 105. Proceedings of the Twenty-Second Annual Short Course in Highway Engineering. 1948.

No. 106. Proceedings of the First Annual Management Engineering Conference. 1948.

No. 107. Essential Oil Production in Texas. II. Sweet Goldenrod. Bryant R. Holland, P. R. Johnson, and J. H. Sorrels. 1948.

No. 108. A Comparison of Freight Rates and Estimated Weights on Carrots, Carload. Jean D. Neal and W. B. Langford. 1948.

No. 109. Proceedings of the Third Short Course and Conference, Airport Management and Planning. 1948.

No. 110. Proceedings of the Fourth Annual Air Conditioning Conference. 1948.

No. 111. Third Annual Short Course on Instrumentation for the Process Industries. 1948. (Not available for free distribution.)

No. 112. Proceedings of the Twenty-Third Annual Short Course in Highway Engineering. 1949.

No. 113. Flow Characteristics of Gas Lift in Oil Production. S. F. Shaw. 1949.

No. 114. Phase Relationships in Oil and Gas Reservoirs. Donald M. Katz. 1949.

No. 115. Basic Models for Technical Drawing. J. G. McGuire, R. L. Barton, and P. M. Mason. 1949.

No. 116. Highway Loads and Their Effects on Highway Structures Based on Traffic Data of 1942. Henson K. Stephenson and A. A. Jakkula. 1950.

No. 117. Annotated Bibliography on Channelization and Related Problems of Highway Traffic Engineering. B. F. K. Mullins. 1950.

No. 118. Some Aspects of the Problem of Transporting Fresh Vegetables from Texas. W. B. Langford and Jean D. Neal. 1950.

No. 119. Significance of Tests for Asphaltic Materials. Marshall Brown and Fred J. Benson. 1950.

†No. 120. Fourth Annual Short Course on Instrumentation for the Process Industries. 1949. (Not available for free distribution.)

No. 121. Solvent Extraction of Cottonseed Oil With Isopropanol. W. D. Harris and J. W. Hayward. 1950.

No. 122. Research Activities for the Sessions 1948-49 and 1949-50. Texas Engineering Experiment Station and School of Engineering, A. and M. College of Texas. 1950.

No. 123. Sewage Purification by Rock Filters. The Performance of Standard-Rate Trickling Filters. J. H. Sorrels and P. J. A. Zeller. 1950.

No. 124. Lime Stabilization of Clay Soil. Bob M. Gallaway and Spencer J. Buchanan. 1951.

The Texas Engineering Experiment Station was established in 1914 to aid the industrial development of Texas by investigating engineering and industrial problems, independently and in cooperation with others, and to disseminate information relating to such problems.

Individuals and corporations who have problems in which the station might be of assistance are invited to communicate with the director.

Address inquiries and requests for publications to the
TEXAS ENGINEERING EXPERIMENT STATION
The Texas A. and M. College System
College Station, Texas

---

† Supply Exhausted