UNIVERSITY OF ILLINOIS

COLLEGE OF ENGINEERING

ENGINEERING EXPERIMENT STATION

BULLETIN 492

FACTORS INFLUENCING THE PLASTICITY AND STRENGTH OF LIME-SOIL MIXTURES

by

Marshall R. Thompson

ENGINEERING EXPERIMENT STATION

BULLETIN 492

FACTORS INFLUENCING THE PLASTICITY AND STRENGTH OF LIME-SOIL MIXTURES

by

Marshall R. Thompson

Assistant Professor of Civil Engineering
University of Illinois

Price: $3.00

Prepared as part of an investigation
conducted by
The Engineering Experiment Station
University of Illinois
in cooperation with

The State of Illinois
Division of Highways
and
The U. S. Department of Commerce
Bureau of Public Roads

Project IHR-76
Lime Stabilization of Soils for
Highway Purposes

Illinois Cooperative Highway Research Program
Series No. 73

Edited by
Ann C. Riggins

The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the State of Illinois, Division of Highways, or the Bureau of Public Roads.

REQUESTS FOR THIS PUBLICATION should be addressed to Engineering Publications Office, 112 Engineering Hall, University of Illinois, Urbana 61801. On your order refer to the Bulletin number on the front cover.

UNIVERSITY OF ILLINOIS BULLETIN

Volume 64, Number 100; April 10, 1967. Published twelve times each month by the University of Illinois. Entered as second-class matter December 11, 1912, at the post office at Urbana, Illinois, under the Act of August 24, 1912. Office of Publication, 114 Altgeld Hall, Urbana, Illinois 61801.

ABSTRACT

THE INFLUENCE OF LIME TYPE, LIME PERCENTAGE, AND CURING PERIOD ON THE PROPERTIES OF LIME-SOIL MIXTURES WAS INVESTIGATED. THIRTY-NINE REPRESENTATIVE ILLINOIS SOILS WERE INCLUDED IN THE EXTENSIVE LABORATORY TESTING PROGRAM.

PLASTICITY PROPERTIES OF ALL THE SOILS WERE REDUCED BY ALL COMBINATIONS OF LIME TYPE AND PERCENTAGE. LIME PERCENTAGE DID NOT GREATLY INFLUENCE THE PLASTICITY REDUCTIONS ACHIEVED, BUT THE FIRST INCREMENTS OF LIME ADDED WERE MOST BENEFICIAL. LIME TYPE PRODUCED SMALL BUT SIGNIFICANT EFFECTS.

THE STRENGTHS OF THE CURED MIXTURES WERE INFLUENCED BY MANY FACTORS. SOIL TYPE WAS THE MOST IMPORTANT. FOR REACTIVE SOILS, GOOD STRENGTH INCREASES WERE OBTAINED WITH ALL LIME TYPES. ONLY IF IT IS ESSENTIAL TO MAXIMIZE STRENGTH DO SUCH FACTORS AS LIME TYPE AND LIME PERCENTAGE BECOME HIGHLY SIGNIFICANT. HIGHER STRENGTHS WERE OBTAINED BY INCREASING THE CURING PERIOD LENGTH.

OPTIMUM LIME CONTENTS (PER CENT LIME FOR MAXIMUM STRENGTH) WERE AFFECTED BY CURING PERIOD, LIME TYPE, AND SOIL PROPERTIES.

THE STUDY INDICATED THAT THE PLASTICITY, SHRINKAGE, AND WORKABILITY PROPERTIES OF ANY FINE-GRAINED SOIL ARE SUBSTANTIALLY IMPROVED BY LIME TREATMENT, AND HIGH STRENGTH LIME-SOIL MIXTURES CAN READILY BE OBTAINED WHEN REACTIVE SOILS ARE STABILIZED WITH QUALITY LIME.

ACKNOWLEDGMENTS

This report was prepared as a part of the research under the Illinois Cooperative Highway Research Program Project IHR-76, "Lime Stabilization of Soils for Highway Purposes." The research was conducted by the Department of Civil Engineering of the University of Illinois in cooperation with the State of Illinois, Division of Highways and the U.S. Department of Commerce, Bureau of Public Roads.

On the part of the University of Illinois, the work covered by this report was carried out under the general administrative supervision of W. L. Everitt, Dean of the College of Engineering; Ross J. Martin, Director of the Engineering Experiment Station; N. M. Newmark, Head of the Department of Civil Engineering; and Ellis Danner, Director of the Illinois Cooperative Highway Research Program.

On the part of the Division of Highways of the State of Illinois, the work was under the administrative direction of Virden E. Staff, Chief Highway Engineer; Theodore F. Morf, Deputy Chief Highway Engineer; and John E. Burke, Engineer of Research and Development.

Assistance in the planning and conduct of the research was provided by a Project Advisory Committee consisting of the following:

Representing the Illinois Division of Highways:

John E. Burke, Engineer of Research and Development
W. J. Mackay, Engineer of Research Coordination, Bureau of Research and Development
Frank Brock, Materials Engineer, District 9, Carbondale
Robert H. Smith, Field Engineer, Bureau of Local Roads and Streets

Representing the Bureau of Public Roads:

H. J. Stahl, District Engineer
P. C. Smith, Principal Research Engineer (Soils), Materials Division; Physical Research (Consulting Member)

Representing the University of Illinois:

James L. Eades, Research Assistant Professor of Geology and of Civil Engineering
Edward C. A. Runge, Assistant Professor of Soil Classification Extension, Department of Agronomy

Special acknowledgment is also extended to the reviewers of this Bulletin: R. S. Boynton, Executive Director, National Lime Association; O. L. Lund, Assistant Engineer of Materials and Tests, Nebraska Department of Roads; and J. L. Eades, Research Assistant Professor of Geology and of Civil Engineering, University of Illinois.

CONTENTS

FIGURES

TABLES

This page is intentionally blank.

I. INTRODUCTION

A. GENERAL

Lime has been widely and successfully used as a soil stabilizing agent. Typical applications include subgrade stabilization, base course and subbase stabilization, plasticity and workability modification, use as a drying agent, etc.

Other than a few experimental test sections [1, 2]* throughout the state and some small projects, lime has not been extensively used in Illinois as a soil stabilizer. Consequently, little specific information is available concerning lime treatment of representative Illinois soils.

In order to effectively and economically utilize lime as a stabilizer for Illinois soils, certain essential information is required relative to the following items:

(1) Effect of lime on soil strength, plasticity, and workability properties.

(2) Influence of soil properties on lime-soil reactions.

(3) Significance of lime type and treatment percentage.

(4) Effect of curing period on lime-soil reactions.

The Department of Civil Engineering with the sponsorship of the Illinois Division of Highways and the Bureau of Public Roads has been conducting lime-soil research since 1960 for the purpose of investigating the problem areas described above. The early phases of the work were directed to determining the influence of natural soil properties on lime-soil reactions and evaluating the effect of lime on strength and plasticity. Selected Illinois soils and one lime, a commercially produced high calcium hydrated product, were used in the early work. These early investigations are described in detail in References 3 and 4.

B. STUDY OBJECTIVES

The investigation described in this report was developed to study the influence of lime type, lime percentage, and curing period on lime-soil reactions. The study consisted of a literature survey and a comprehensive laboratory testing program.

C. STUDY SCOPE

The thirty-nine representative Illinois soil samples utilized in the study were from throughout Illinois and included loess, Wisconsinan Till, and Illinoian Till-derived soils.

Three lime types commercially available in Illinois were used at different percentage treatment levels with the soils. Curing periods for the lime-soil mixtures were 28 and 56 days at 73°F.

Plasticity and strength properties of the natural and lime-treated soils were determined for evaluating the effectiveness of the lime treatments. • • •

*Superscript numbers in parentheses refer to entries in Chapter VIII, References.

II. LITERATURE REVIEW

A. GENERAL

Lime-soil literature through 1960 was reviewed, annotated, and summarized by Herrin and Mitchell [5]. The review indicated the beneficial effects of lime stabilization on the plasticity, shrinkage, workability, and strength properties of a soil. In general, the plasticity index was greatly reduced, the shrinkage limit markedly increased, workability characteristics were improved, and in many cases, strength was increased. According to Herrin and Mitchell, the published work (at that time) was primarily concerned with the effects of different types and quantities of lime on various physical properties, primarily strength and plasticity, of the soils studied. Subsequent work since 1960 has dealt with the nature of the lime-soil reaction products and the influence of natural soil properties on lime-soil reactions.

B. LIME-SOIL REACTIONS

Although little fundamental lime-soil research was completed at the time of Herrin and Mitchell's review (1960), the improvements in engineering characteristics of lime-soil mixtures were attributed to four basic reactions: cation exchange, flocculation and agglomeration, carbonation, and a pozzolanic reaction. Significant research advances have been made since 1960 concerning these basic reactions and their influence on the properties of lime-soil mixtures. A discussion of these basic reactions, based on currently available literature, is presented below.

C. CATION EXCHANGE

The general order of replaceability of the common cations associated with soils is given by the lyotropic series [6] $Na^+ < K^+ < Ca^{++} < Mg^{++}$. Any cation will tend to replace the cations to the left of it, and monovalent cations are usually replaceable by multivalent cations. The addition of lime to a soil supplies an excess of Ca^{++} and cation exchange will occur, with Ca^{++} replacing dissimilar cations from the exchange complex of the soil. In some cases the exchange complex is practically Ca^{++} saturated before the lime addition and cation exchange does not take place, or is minimized.

D. FLOCCULATION AND AGGLOMERATION

The addition of lime to a fine-grained soil causes flocculation and agglomeration of the clay fraction. These reactions result in an apparent change in texture, the clay particles "clumping" together into larger sized "aggregates." According to Herzog and Mitchell [7] the flocculation and agglomeration is effected by the increased electrolyte content of the pore water and also as a result of ion exchange by the clay to the calcium form. Kinter and Diamond [8] have postulated that the flocculated structure is stabilized through the rapid formation of tetracalcium aluminate hydrate cemeting agents that bond the flocculated particles.

The influence of cation exchange, flocculation, and agglomeration on the plasticity and shrinkage properties of lime-soil mixtures were studied by Thompson (3). The study indicated that these reactions are primarily responsible for the changes in plasticity, shrinkage, and workability characteristics of lime-soil mixtures. These beneficial changes were noted for all soils studied and relatively small percentages of lime were required to achieve the changes. Thompson (3) reported that cation exchange, flocculation, and agglomeration are not the basic lime-soil reactions which are responsible for the marked strength increases noted for many lime-soil mixtures.

E. LIME CARBONATION

Lime reacts with carbon dioxide to form the relatively weak cementing agents calcium and magnesium carbonate, depending on the type of lime used (9). Goldberg and Klein (10) and Eades and Grim (11) detected the formation of calcium carbonate when lime treated soils were laboratory cured in the open air, a condition conducive to promoting carbonation. Eades, Nichols, and Grim (12) reported field conditions where 2.5 per cent of $CaCO_3$ (by weight) formed due to the carbonation reaction.

Although carbonation does produce weak cementing agents, it is an undesirable reaction and steps should be taken to minimize carbonation during construction operations and also following construction.

F. POZZOLANIC REACTION

The pozzolanic reaction referenced in lime-soil stabilization literature is a reaction between soil silica and/or alumina and lime to form various types of cementing agents. These cementing agents are generally regarded as the major source of the strength increases noted in lime-soil mixtures (3, 13). Possible sources of silica and alumina in typical soils include clay minerals, quartz, feldspars, micas, and other similar silicate or aluminosilicate minerals.

When a substantial quantity (greater than approximately 1 per cent) of lime is added to a soil the pH of the lime-soil mixture is elevated to approximately 12.3, the pH of a saturated lime solution. This is a substantial pH increase compared to the pH of natural soils. Several investigators (14, 15, 16, 17, 18) reported the experimental work was conducted with forms of silica other than silicate minerals, the work of Correns (17) and Krauskopf (14) indicated that the principle of increased solubility at high pH was also applicable to them. According to Krauskopf (14),

> "The weathering of the silicate minerals is known to contribute large amounts of silica to solution, but the mechanism of the process is uncertain; in the absence of contrary data, there seems to be no reason to postulate any limit to the amount that could be dissolved short of the equilibrium solubility of amorphous silica."

The relation between solubility and pH as presented by Krauskopf is shown in Figure 1.

Eades (13) hypothesized that,

> "The high pH causes silica to be dissolved out of the structure of the clay minerals and it combines with the Ca^{++} to form calcium silicates. This reaction will continue as long as $Ca(OH)_2$ exists in the soil, and there is available silica."

In later work, Diamond, et al. (19) postulated that the reaction processes in the highly alkaline lime-soil system involved a dissolution at the edges of the silicate particles followed by the precipitation of the reaction products.

The products of lime-soil reactions were studied by several investigators. The earliest studies, those of Eades and Grim [11] established that the reaction products were crystalline calcium silicate hydrates. Subsequent work by Eades [13] and Eades, et al. [12] substantiated the earlier work. Glenn and Handy [20], and more recently, Diamond, et al. [19] also indicated that various forms of calcium silicate hydrates were formed as a consequence of lime-soil reactions.

The work of Hilt and Davidson [21], Glenn and Handy [20], and Diamond, et al. [19] established that various calcium aluminate hydrates are also formed in lime-soil reactions. This seems quite feasible, as the severe attack and at least partial decomposition and destruction of the clay minerals and other soil minerals by the highly alkaline environment would liberate not only silica but also some alumina for reaction with the lime. In addition, alumina, like silica, is more soluble at high pH levels [16]. Basic reactions in lime-soil mixtures have not been well established, and Diamond and Kinter [8] have prepared an interpretive review of the somewhat conflicting data that has been reported in the literature.

Many factors influence the lime-soil pozzolanic reaction. Important factors include natural soil properties, lime type, lime percentage, curing conditions, and density.

1. Natural Soil Properties

In an extensive study of typical Illinois soils, Thompson [4] found that the ability of a soil to participate in the lime-soil pozzolanic reaction was determined primarily by natural soil properties. Thompson measured the degree to which the lime-soil pozzolanic reaction proceeded in terms of lime-reactivity which was defined as the difference in the unconfined compressive strengths of the natural soil and the maximum strength developed by a 3, 5, or 7 per cent lime-soil mixture after a 28-day curing period at 73°F. Some soils did not display significant reactivity and others reacted to produce strength increases ranging up to several hundred per cent. Pertinent findings of Thompson's work are summarized below:

(1) Soil organic matter retarded the pozzolanic reaction if it was present in large quantities. None of the A horizon soils reacted with lime and some of the B horizons, particularly Brunizems with organic carbon contents greater than approximately 1 per cent, also did not react. The retardation of the reaction was attributed to a "masking effect" of the organic matter on the clay surfaces and/or an organic matter chelation reaction. Figure 2 shows the relation established for lime-reactivity and organic carbon content.

(2) Although $< 2\mu$ clay contents ranged from 7 to 65 per cent, it did not significantly influence lime-reactivity. However, some minimum quantity of clay is required to provide adequate silica and/or alumina sources for the pozzolanic reaction.

(3) Clay mineralogy also effected lime-reactivity; mixed layer and montmorillonitic clays were most reactive.

(4) Soil chemical properties greatly influenced lime-reactivity. Highly significant correlations were obtained between natural soil pH and lime-reactivity. As illustrated in Figure 3, higher pH values indicated a larger lime-reactivity. Soils with pH below approximately 7 had lime-reactivities less than 100 psi. Cation exchange capacity, exchangeable bases, per cent

base saturation, and Ca/Mg ratios were not significantly correlated with lime-reactivity. The better reactivities of the higher pH soils were attributed to reduced weathering status of the soil minerals.

(5) Natural soil drainage was a good indicator of lime-reactivity. B horizon soils with poor natural drainage displayed higher levels of lime-reactivity than better drained soils. All of the Humic-Gley soils, which are poorly drained, included in the investigation reacted very well. The increased reactivity of the poorly drained soils was attributed to minimal weathering of the soil minerals, thus the soil was a ready source of reactive silica and/or alumina. It was established that increased weathering and ferric oxide coatings on the soil mineral surfaces were responsible for the low reactivity of the better drained soils.

(6) There was a significant influence of horizon (A, B, C) on lime-reactivity. A horizons did not react to any extent; B horizons displayed variable lime-reactivities depending on organic carbon content, natural drainage, and pH and C horizon soils generally reacted satisfactorily with lime-reactivities greater than 50 psi.

(7) All calcareous soils, loess, and tills, included in the investigation reacted very well and exhibited an average lime-reactivity of approximately 100 psi.

(8) It was demonstrated that for the many soils included in the investigation, it was possible to quantitatively estimate soil lime reactivity based on natural soil properties.

The results of Thompson's study clearly indicate that the lime-soil pozzolanic reaction is very complex and is influenced by many properties and characteristics of the soil. It is probable that in many soils the influence of several soil properties may be operating simultaneously. Because of this possibility, it is difficult to differentiate or quantitatively evaluate the importance of any one of the properties.

2. Lime Type

Many investigators [22, 23, 24, 25] have indicated that lime type significantly influences the lime-soil pozzolanic reaction. Monohydrated dolomitic limes generally produced greater strengths than hydrated calcitic limes. Remus and Davidson [25] concluded from their study of nine soils that dolomitic limes produced higher strengths for montmorillonitic and illitic soils, but kaolinitic soils neither dolomitic nor calcitic limes consistently produced higher strengths. Wang, et al. [24] showed that the use of different brands of monohydrated dolomitic lime produced substantial variation in strength, but fairly consistent strengths were obtained with all brands of calcitic lime used.

Although the literature generally indicated that dolomitic limes were superior to calcitic limes, in some instances calcitic limes produced higher strengths. Other than the work of Remus and Davidson [25] satisfactory criteria have not been developed for determining whether a soil would react better with dolomitic or calcitic limes.

3. Lime Percentage

In most cases, for given curing conditions, a soil will achieve a maximum strength at some optimum lime content or will reach a lime content beyond which further increases of treatment level will not produce a significant strength increase. Remus and Davidson [25] found that optimum lime contents are generally higher for dolomitic than for calcitic limes.

The soil characteristics that significantly influence optimum lime contents have not been established, but they probably encompass such factors as chemical, physical, and mineralogical properties. The literature indicated that optimum lime contents will vary depending on soil type, lime type, curing period, curing temperature, and possibly other factors.

4. Curing Conditions

Herrin and Mitchell (5) indicated in their literature survey that increased curing time and elevated temperatures produced substantial strength increases in lime-soil mixtures. Reports of other investigators published subsequent to their work further substantiates this fact. Thompson (26) has presented data, see Figure 4, showing the influence of time and temperature on the strength of a typical Illinois soil.

5. Density

Density of the compacted material also influences the cured strength of a lime-soil mixture. As stated by Herrin and Mitchell (5),

> "The strength of a lime-soil mixture is increased materially when the mixture is compacted to a higher unit weight by a greater compactive effort."

With some mixtures, increasing the compactive effort from standard to modified AASHO elevated the strength more than 100 psi (25).

G. SUMMARY

The literature indicated that four basic reactions (cation exchange, flocculation and agglomeration, lime carbonation, pozzolanic reactions) effected substantial changes in the engineering properties of lime-soil mixtures. Cation exchange, flocculation, and agglomeration are primarily responsible for the alterations of plasticity, shrinkage, and workability characteristics. Although lime carbonation may contribute slightly to strength increases of the lime-soil mixtures, the pozzolanic reaction mechanism is regarded as the prime contributor.

Lime-soil pozzolanic reactions are influenced by many factors and a given lime-soil mixture can display wide strength variation depending upon prevailing conditions. There are soils that do not display substantial lime-reactivity regardless of lime type, curing period, compaction effort, etc. ●

III. MATERIALS

A. SOILS

In order to obtain samples representative of a substantial percentage of Illinois soils, it was necessary to sample the more extensive and prevalent soil types. The major parent materials of Illinois surficial soils are loess and Wisconsinan Till. In those areas of the state where the loess cover is thin, as in southern Illinois, the underlaying Illinoian Till is frequently encountered in highway construction operations.

The sampling program was planned to provide coverage of all these major parent materials and profiles developed in them. Since lime is used primarily with fine-grained soils, coarse-grained materials were not included in the investigation. Surficial soils derived from loess and Wisconsinan Till were samples based on pedologic soil types and in many cases A, B, and C horizons were obtained for a given soil type. Illinoian Till samples and weathering profiles developed in the till were selected and sampled on the basis of previous work by the Illinois State Geological Survey [27]. A concise summary of the properties of the major Illinois soils has been presented by Thompson [28].

Sampling operations were carried out with the cooperation of the Soil Survey Section of the University of Illinois Agronomy Department. Special effort was taken to insure that representative samples were obtained. Table 1 lists the soils included in the sampling program and selected information concerning them.

Soil processing consisted of air-drying the samples and then pulverizing them in a Lancaster mixer equipped with a muller. The soil was screened over a #4 sieve and stored for subsequent use. In most cases, little material was retained on a #4 sieve.

The soils were extensively analyzed to determine selected physical, chemical, and mineralogical properties. Those properties determined and the test procedures utilized are presented in Table 2. A tabulation of the test results is given in Table 3.

B. LIMES

Three lime types commercially available in Illinois were selected for the investigation. They included a hydrated calcitic lime, a monohydrated dolomitic lime, and a by-product hydrated calcitic lime.

The dolomitic and hydrated calcitic limes were produced by conventional processes. The by-product calcitic lime was produced in the manufacture of acetylene gas from calcium carbide and had been spray-dried.

Upon receipt from the producer, the lime was stored in sealed one-gallon cans to prevent carbonation. The limes were all in a dry powdered form and were easily handled and mixed.

Pertinent properties of the lime as provided by the respective producers are shown in Table 4. ● ● ●

IV. LIME TREATMENT OF SOILS

Hydrated calcitic lime (lime A) was the primary lime used in the investigation. The monohydrated dolomitic (lime B) and the by-product calcitic (lime C) were used in the phase of the investigation concerning lime-type effect. All of the soils were treated with lime A, but only selected soils with limes B and C. Treatment levels were based on per cent of dry soil weight.

A. PLASTICITY TESTS

The liquid, plastic, and shrinkage limits were determined according to AASHO designations T89-60, T90-56, and T92-42, respectively. The lime-soil mixtures were prepared by thoroughly mixing the lime and soil in the dry state and then adding water under continuous mixing. The plasticity tests were conducted after the mixture had been allowed to stand in a covered container for approximately one hour.

All of the soils were treated with 3 per cent lime A and the Atterberg limits of the mixture determined. Treatment levels of 5 and 7 per cent lime were used only if the lime-soil mixture at the lower treatment level(s) were not nonplastic. Lime percentages did not exceed 7 per cent in any case. Selected representative soils were then subjected to similar treatment levels with limes B and C. Test results are presented in Table 5 and results for the natural soils are included for comparison.

Shrinkage limit tests were conducted on all soils treated with 3 and 5 per cent lime A. One per cent treatment levels of lime A were used with soils that were noncohesive at the 3 per cent level, and in some cases 7 per cent treatment levels were used to examine the influence of higher treatment levels. Three, 5 and in some instances 7 per cent additions of limes B and C were used with selected soils to evaluate the effect of lime type on the shrinkage limits of lime-soil mixtures. The test results are summarized in Table 6.

B. STRENGTH TESTS

Unconfined compressive strength was used as a measure of the pozzolanic reaction that occurs to varying degrees with different lime-soil mixtures. The compressive strength of a lime-soil mixture is commonly used as an indication of its quality, and Thompson[29, 30] has shown that many significant engineering properties of lime-soil mixtures readily correlate with unconfined compressive strength.

The specimens were compacted at their optimum moisture contents as determined by moisture-density tests. The moisture-density relations of the natural soils were determined according to AASHO designation T99-57, Method A. The moisture-density relations for the lime treated soils were determined in a manner similar to those described in AASHO T99-57 except that 4-inch molds 2 inches in diameter were used and the compactive effort was 20 blows of a 4-pound hammer having a 12-inch drop. This compactive effort produced maximum dry densities and optimum moisture contents similar to those obtained from AASHO T99-57, Method A.

Specimens of the natural soils and lime-modified soils were prepared using 4-inch molds 2 inches in diameter. Natural soils were thoroughly mixed with the required amount of water and then molded. The lime and soil were thoroughly mixed in the dry state, and mixing continued while the proper amount of water was added. The lime-soil mixture was then covered and allowed to stand for approximately one hour before specimens were compacted.

Specimens were molded in three equal layers with each layer receiving a compactive effort of 20 blow of a 4-pound hammer dropping 12 inches. Each layer was scarified to provide bond between the adjacent layers. After proper trimming, the specimens were extruded. Specimens were made in series, each series consisting of eight specimens molded from the same mixture. Previous experience with lime-soil mixtures at the University of Illinois indicated that a series of eight specimens provided an average with confidence limits of $\pm$ 7 per cent (95 per cent probability level).

The series of specimens were placed in one-gallon cans and the lids sealed with Permatex to prevent the loss of moisture from the specimens. The specimens were cured in a constant temperature room at 73°F. Natural soil specimens were cured for 7 days to allow for thixotropic effects, and the lime-soil specimens for 28 and 56 days. Moisture content at the end of the curing period was approximately the same as compaction moisture content.

At the end of the curing period the specimens were tested in unconfined compression using a Riehle hydraulic testing machine with a constant rate of deformation of .05 inches per minute. The maximum load was recorded and moisture samples were taken from the specimens after testing. The average of the eight specimens was recorded as the unconfined compressive strength.

Three factors in addition to soil type were varied in the strength studies. The factors considered were lime type, lime percentage, and curing period.

All of the soils were treated with 3, 5 and 7 per cent lime A and cured for 28 days. Test results for the 28-day curing were evaluated and those lime contents that appeared to produce the maximum strength were determined. Additional series of specimens were molded at those lime contents and cured for 56 days. Since the A horizon soils did not display a significant reaction during the 28-day curing period, additional specimens were not prepared for 56-day curing.

Selected soils, those that displayed a substantial level of lime-reactivity with lime A, were treated with 3, 5 and 7 per cent limes B and C and were cured for 28 and 56 days.

A complete summary of compressive strength test results for the natural and lime-treated soils is presented in Tables 7 and 8. ● ● ●

V. DATA ANALYSIS

A. PLASTICITY

1. General

Plasticity properties of the natural soils included in the study displayed a wide range. Liquid limits varied from 62.2 to 24.5; plasticity indices from 35.7 to non-plastic; and shrinkage limits from 33.5 to 10.7. Lime treatment markedly decreased the plasticity indices, and in many cases, 3 per cent treatment produced a nonplastic mixture. Shrinkage limits were increased by lime treatment and some soils became noncohesive.

Workability was not directly measured, but the reduced plasticity indices, increased shrinkage limits, and the silty and friable texture of the mixtures indicated beneficial changes in workability.

2. Plasticity Index

The effect of lime type was evaluated in a randomized complete block statistical analysis of the plasticity indices for 3 per cent lime treatment levels. Nonplastic conditions were assigned a value of 0 in the analysis. Statistical results are presented in Table 9. Although the average values indicate the superiority of lime A there is not a statistically significant difference among the different lime types.

It was not possible to make lime type comparisons at higher treatment levels since many of the lime-soil mixtures were nonplastic after a 3 per cent treatment, but increased lime percentages generally produced further plasticity index reductions. Table 10 shows the amount of lime required to render the various soils nonplastic, or if the soil retained a degree of plasticity at the 7 per cent treatment level, the plasticity index of the 7 per cent lime-soil mixture. Since treatment levels were varied in 2 per cent increments, it was felt that the data presented in Table 10 was not particularly amenable to statistical analysis. However, the results indicate that higher average percentages of limes B and C are required to produce a nonplastic condition and that more lime-soil mixtures with limes B and C are still plastic at the 7 per cent treatment level. Based on Table 10, the limes would rank A, B, C in decreasing order of effectiveness for reducing soil plasticity. Other investigations [31] have indicated similar results.

3. Shrinkage Limits

Randomized complete block analyses of the data, see Tables 11 and 12, were utilized to evaluate the influence of lime type and percentage on the shrinkage limits of lime-soil mixtures. The results show that increased lime treatments, from 3 to 5 per cent, produced small but statistically significantly differences. Different lime types, used at the same treatment levels did not produce statistically significant test result variations.

B. COMPRESSIVE STRENGTH

1. General

The unconfined compressive strengths of the natural soils included in the investigation varied from 22 to 105 psi. Lime-soil mixture strengths varied widely, depending on the soil, lime type, lime percentage, and curing period. The strength of a lime-soil mixture is not a constant value, but varies in response to changes in the above factors.

As indicated in the literature survey, not all soils react with lime to produce significant strength increases. Soil type is the most important factor influencing lime-soil reactions and if a soil is nonreactive, substantial strength cannot be developed.

If lime-soil mixtures are to be effectively utilized as a pavement material, it is essential to understand the relative importance and effects of such factors as lime type, lime percentage, and curing period.

2. Lime Type, Lime Percentage, and Curing Period

The effects of the above factors on lime-soil mixture compressive strengths were evaluated in a randomized complete block factorial design. Three lime types (A, B, C), three lime percentages (3, 5, 7), and two curing periods (28 and 56 days at 73°F) were utilized. Seventeen lime-reactive soils, representing typical Illinois materials, provided experimental replication. The factorial design was chosen not only to explore the influence of the major factors (lime type, lime percentage, and curing period) but also to evaluate the interaction between factors, i.e., do all lime types show the same response to change in lime content, etc. Only lime-reactive soils were included in the analysis since strength is not a major consideration in determining the appropriate lime treatment for nonreactive soils.

Average strengths for different treatment combinations and the results of the factorial analysis are presented in Table 13. Lime type, lime percentage, and curing period were significant factors ($\alpha = .05$). Interaction between lime type and lime percentage was also significant, indicating that all lime types did not show the same response to lime percentage changes.

Duncan's Multiple Range test was used to determine which averages were significantly different. The results showed:

(1) significant differences between the average strengths of all three lime types.

(2) significant differences between 3 and 5 per cent, but no significant differences between 5 and 7 per cent treatment levels.

(3) significant differences between 28 and 56 days curing periods.

In summary, the analysis indicated that the lime types ranked in the descending order of B, C, A; 5 and 7 per cent treatments produced greater strengths than 3 per cent, but there was no significant strength difference between 5 and 7 per cent; and 56 day strengths were larger than 28 day strengths.

It is emphasized that the analysis is based on the average response of the seventeen soils and data for any one particular soil may deviate from the average.

3. Optimum Lime Content

It has been noted by many investigators that the lime percentage-strength curves for a given soil and curing conditions (time, temperature) peak out at some optimum lime content, i.e., increased lime percentages do not necessarily produce increased strength. Although Jambors work [32] has indicated that excessive lime may increase the porosity and reduce the strength of lime-pozzolan reaction products, little is currently known about the factors influencing optimum lime content.

Optimum lime content is primarily a question relevant to those soils that display good reactions with lime. Only with these soils is an attempt normally made to develop maximum strength response.

Two factors are of major concern with regard to the optimum lime content question. First, is optimum lime content different for various lime types, and secondly, does optimum lime content change if the curing period (for a given temperature) is increased?

Twenty-one lime-reactive soils were included in the optimum lime content study. All soils were treated with 3, 5, and 7 per cent lime, three lime types (A, B, C), and 28 and 56 day curing periods at 73°F were utilized.

For each soil, the optimum lime percentage was determined for each combination of lime type and curing period. "t" test (α = .05) comparisons of the 3, 5, and 7 per cent strengths indicated the optimum lime percentage above which further lime content increases did not produce statistically different strengths. Test results are summarized in Table 14.

In the analysis of the optimum lime content data, it was difficult to employ statistical procedures since the incremental increases of 2 per cent (3 to 5 to 7) did not permit a precise determination of the true optimum lime content.

For most of the soils, the optimum lime content remained the same or increased when the curing period was changed from 28 to 56 days. The average values, see Table 14, show a slight increase in optimum lime content for limes A and C when the curing is lengthened, but the 28 day and 56 day averages are the same for lime B. For a given curing period, the average values are approximately the same for the high calcium limes (A and C), but the dolomitic lime average, lime B, is slightly higher.

For a given lime type and curing period it was possible to group the soils according to their optimum lime percentage. Using analysis of variance techniques, statistical comparisons were made to determine if there were significant differences (α = .05) in the natural soil properties for those soils with different optimum lime contents. Of the soil properties considered (< 2 micron clay content, liquid limit, plasticity-index, group index, organic carbon, pH, cation exchange capacity, exchangeable cations, total exchangeable bases, Ca/Mg ratio, base saturation, and clay mineralogy) the only consistent trend appeared to be correlated with natural soil pH and per cent base saturation. High pH and base saturation soils displayed lower optimum lime contents.

4. Strength Increases with Curing

When a lime-reactive soil is treated, increased curing generally produces a stronger mixture. However, the magnitudes of the strength increases obtained are quite variable. Some soils show a large strength gain, 100 psi or so, while others do not respond to any extent when subjected to extended curing.

Data from this investigation were analyzed to determine the influence of lime type and percentage on the 28 to 56 day strength increase and a correlation analysis was made to determine what soil properties effect the magnitude of this strength increase.

Table 15 summarizes strength increase data for seventeen lime-reactive soils treated with various percentages of different lime types. Randomized complete block factorial analysis of the data is presented in Table 16. The analysis indicates that lime percentage, but not lime type is a significant factor influencing strength increase. Duncan's multiple range tests show that the average strength increase for 5 and 7 per cent treatments are significantly larger than for 3 per cent.

The strength increases for the 5 and 7 per cent treatments of limes A, B, and C were, therefore, averaged for each soil to provide an average response to increased curing. Simple correlation coefficients between the average response and the properties of the natural soils were determined, see Table 17. The only soil properties significantly correlated (α = .05) were lime-reactivity and organic carbon content.

Lime-reactivity, as defined by Thompson [(4)], is a measure of the ability of a soil to react with lime to achieve a strength increase after a 28-day curing period at 73°F. Thus, if a soil provides a good initial reaction, substantial strength increases can be expected to develop during the 28- to 56-day curing interval. Increased organic carbon contents tend to retard the lime-soil reaction and, therefore, strength gain with increased curing is not pronounced. ●

VI. DISCUSSION

A. PLASTICITY

Although all lime types substantially reduced plasticity index, the test data indicated that high calcium, hydrated lime (lime A) was most effective. If a soil remained plastic after a 3 per cent lime treatment, further plasticity index reductions were achieved at higher treatment levels although as other studies [3] have shown, the first increments of lime were most effective.

Substantial shrinkage limit increases were obtained with all lime types at various treatment levels. Little additional benefit was obtained by increasing the treatment level from 3 to 5 per cent. For similar treatment levels, all of the lime types produced approximately the same shrinkage limit increases.

Although lime contents less than 3 per cent were not extensively used in this study, treatments as low as 1 per cent may be very effective with certain soils.

In summary, all of the treatment combinations (lime type and lime percentage) studied produced substantial improvement in soil plasticity and related workability properties although lime A was slightly more effective. Other investigations [31] have indicated similar results.

B. STRENGTH

1. General

Many factors (soil type, lime type, lime percentage, curing conditions) influence the strength of cured lime-soil mixtures. Consequently mixture strength is not a "static" value, but variable. If an adequate level of lime treatment is to be determined, an awareness of the major factors affecting mixture strength is essential.

If a reactive soil is to be stabilized, good results can be obtained with normal applications (3 to 7 per cent) of a quality lime. It is only in those circumstances when it is desirable to maximize strength that all of the factors assume significance.

It is generally accepted that the strength of cured lime-soil mixtures is dependent on the development of various hydrated calcium silicates and calcium aluminates. These cementitious reaction products bond the soil particles or "aggregates of particles" together into a strong compact mass. Eades et al. [12] have detected this bonding in microscopic studies of samples from field lime sections. Therefore, lime-soil mixture strength variations are partially attributable to the quantity and/or quality of the cementitious reaction products and the number of cemented contact points. As indicated by Diamond and Kinter [8], basic lime-soil reaction mechanisms have not been firmly established. Consequently, definite and satisfactory explanation of the experimental data from this study cannot be offered. However, this does not detract from the validity of the experimental observations previously presented regarding the factors influencing strength.

2. Optimum Lime Content

In contrast to some soil stabilization procedures, increased lime content does not always increase mixture strength. As indicated by the experimental data, a given soil has an optimum lime content for the development of maximum strength when cured under fixed conditions of time and temperature. For the representative Illinois soils utilized, the optimum lime contents (for the conditions studied) were normally between 3 and 7 per cent. The optimum values did not appear to be related to natural soil properties such as plasticity or clay content, but were influenced by soil pH and per cent base saturation. High pH and per cent base saturation, characteristic of relatively unweathered soils, generally indicated a lower optimum lime percentage. However, this trend was not evident for all combinations of lime types and curing periods. With the more weathered soils (low pH, low per cent base saturation) a larger quantity of lime would be required in the base exchange reaction initiated by the lime addition and, therefore, it may be hypothesized that additional lime (higher optimum lime percentage) would be required to promote the lime-soil pozzolanic reaction. The fact that the more readily reactive soil silica and/or alumina has been weathered from the low pH soils may also be significant. Because of the interaction among these factors (optimum lime content - curing temperature - curing time) the concept of an "optimum lime content" is somewhat nebulous.

Since curing conditions influence lime-soil mixture strength as well as "optimum lime content," it is obvious that careful consideration of the project's stabilization objectives is essential in the proper selection of laboratory curing conditions for mixture design operations.

3. Lime Type

Although lime type was a significant factor influencing strength, it is difficult to assess the importance of the strength differences observed. In conditions where the lime-soil mixture is used as a structural material, the differences may be of concern, but in those stabilization situations where the main objectives are plasticity reduction, drying action, and workability improvement, strength considerations may be secondary. It is emphasized that the influence of lime type detected in this study might be different for different soil types, parent materials, etc. Consequently, the results of this study cannot be applied indiscriminately.

The proper selection of a lime type is not a simple task, but should include an evaluation of economics and over-all stabilization objectives. It is stressed that improvements in soil plasticity and workability properties are always obtained when fine-grained soils are treated with lime, but marked strength increases are not always attained. It is important to note that these improvements are secured with all high quality limes; lime type only slightly affects the stabilization benefits.

4. Strength Increases with Curing

The concept of continuing strength increase with time is important in the evaluation of a lime-soil mixture. Strength increases help off-set repeated load effects (fatigue) and also may be salient with respect to "healing effects" that may occur in a mixture after cyclic wetting and drying or freeze-thaw action.

For the soils in this investigation, higher lime contents, 5 and 7 per cent, favored strength increases with curing but lime type did not prove to be a significant factor. Soils that reacted well during initial curing (28 days at 73°F) normally continued to gain strength as curing was extended. Eades (13) has emphasized that the strength producing pozzolanic reaction should continue as long as lime and available silica are present in the lime-soil system. Thompson (26) has presented data, see Figure 4, for the Ottawa AASHO Road Test subgrade soil (a calcareous, Wisconsinan Till, see Table 3, soil reference number 32) that shows a continuing strength gain for 3 per cent lime treatment even after 75 days curing at 120°F. The data did not reflect any leveling off trend which would indicate that the reaction was subsiding and the maximum compressive strength at 75 days curing was 1,033 psi.

Although Illinois does not have long time strength records on field lime projects, Dawson and McDowell (33) have reported instances where Texas lime projects continue to gain in strength after ten years in service. Other cases of field strength gain have been recorded by many investigators, so similar gains under field conditions would be expected for representative Illinois soils.

VII. SUMMARY AND CONCLUSIONS

Lime-soil mixture properties (plasticity and strength) are influenced by many conditions: soil type, lime type, lime percentage, curing period, etc.

(1) For all of the fine-grained soils studied, workability increased and plasticity properties were substantially reduced by lime treatment. Lime type did not greatly influence the results, but lime A (high calcium hydrated) was somewhat more effective. Increased lime percentages generally caused further reductions in plasticity index and small shrinkage limit increases. The experimental results definitely show that all fine-grained soils can be successfully treated with lime to achieve plasticity reductions, irrespective of the chemical and mineralogical properties of the soil.

(2) Many factors influence the magnitude of the strength increases obtained with lime treatment of soils. Soil type as related to chemical, mineralogical, and physical properties is the most important factor. If a soil is reactive, the lime-soil reaction (as evidenced by a strength increase) is readily achieved with normal quantities (3 - 7 per cent) of any high quality lime. Only if it is desirable to maximize strength do such factors as lime type, lime percentage, etc., become highly significant. Based on this study, the following factors are important in lime-soil reaction strength development:

(a) There was a significant influence of lime type. The limes ranked B, C, A, in descending order.

(b) Lime percentage produced significant effects. Treatments of 5 and 7 per cent were superior to 3 per cent.

(c) Curing time (days at 73°F) was a significant factor. Fifty-six-day strengths were larger than 28-day strengths.

(d) Optimum lime content (per cent lime for maximum strength) was influenced by curing period, lime type, and soil properties. Longer curing, 28 to 56 days at 73°F, increased optimum lime content. Optimum lime contents for lime B, a dolomitic lime, were higher than for the calcitic limes, A and C. Soils with low pH and low per cent base saturation appeared to require higher optimum lime contents, but the trend was not evident for all lime types and curing periods.

(e) Strength increase with curing (from 28 to 56 days at 73°F) was influenced by lime percentage but not lime type. Strength increases obtained with 5 and 7 per cent treatments were significantly greater than those obtained with 3 per cent treatment. Lime type did not influence the magnitude of the strength increases achieved.

(f) If a soil displayed a good

initial reaction with lime (28-day strength) subsequent strength increases generally were attained with extended curing. Organic carbon in the soil tended to retard strength development with time.

PRACTICAL SIGNIFICANCE OF STUDY RESULTS

It is apparent that lime-soil reactions are complex and are influenced by many factors as discussed throughout this report. The complexity of the reactions should not, however, limit the practical field applications of lime stabilization. Plasticity, shrinkage, and workability properties of any fine-grained soil are substantially improved by lime treatment and lime-soil mixtures of high strength can readily be attained when reactive soils are stabilized with quality lime.

VIII. REFERENCES

1. McAllister, R. W., "Report to the Mississippi Lime Company on Lime Stabilized Highway Construction," Arthur D. Little, Inc., 1957.

2. Thompson, M. R., and Hollon, G. W. A Lime Stabilized Test Road in Randolph County, Illinois. (Civil Engineering Studies, Highway Engineering Series No. 10, Illinois Cooperative Highway Research Program Series No. 10). Urbana, Ill.: Department of Civil Engineering, University of Illinois, 1962.

3. Thompson, M. R. The Significance of Soil Properties in Lime-Soil Stabilization. (Civil Engineering Studies, Highway Engineering Series No. 13, Illinois Cooperative Highway Research Program Series No. 23). Urbana, Ill.: Department of Civil Engineering, University of Illinois, 1964.

4. Thompson, M. R., "Lime-Reactivity of Illinois Soils," Journal of the Soil Mechanics and Foundations Division, ASCE, Vol. 92, No. SM5, September, 1966.

5. Herrin, M., and Mitchell H. Lime-Soil Mixtures. (Highway Research Board Bulletin No. 304). Washington, D. C.: National Academy of Sciences/National Research Council, 1961.

6. Grim, R. E. Clay Mineralogy. New York: The McGraw-Hill Book Company, 1953.

7. Herzog, A., and Mitchell, J. K. Reactions Accompanying the Stabilization of Clay with Cement. (Highway Research Record No. 36). Washington, D. C.: National Academy of Sciences/National Research Council, 1963.

8. Diamond, S., and Kinter, E. F. Mechanisms of Soil-Lime Stabilization, An Interpretive Review. (Highway Research Record No. 92). Washington, D. C.: National Academy of Sciences/National Research Council, 1965.

9. Davidson, D. T., and Handy, R. L., "Lime and Lime-Pozzolan Stabilization," Highway Engineering Handbook. New York: The McGraw-Hill Book Company, 1960, pp. 21-98.

10. Goldberg, I., and Klein, A., "Some Effects of Treating Expansive Clays with Calcium Hydroxide," Special Technical Publication No. 142, Symposium on Exchange Phenomena in Soils. Philadelphia: ASTM, 1952.

11. Eades, J. L., and Grim, R. E. Reactions of Hydrated Lime with Pure Clay Minerals in Soil Stabilization. (Highway Research Board Bulletin No. 262). Washington, D. C.: National Academy of Sciences/National Research Council, 1962.

12. Eades, J. L., Nichols, F. P., Jr., and Grim, R. E. Formation of New Minerals with Lime Stabilization as Proven by Field Experiments in Virginia. (Highway Research Board Bulletin No. 335). Washington, D. C.: National Academy of Sciences/National Research Council, 1962.

13. Eades, J. L. Reactions of $Ca(OH)_2$ with Clay Minerals in Soil Stabilization. Unpublished Ph.D. dissertation, University of Illinois, 1962.

14. Krauskopf, Konrad B., "The Geochemistry of Silica in Sedimentary Environments," Special Publication No. 7, Society of Economic Paleontologists and Mineralogists, 1959.

15. Rankama, D., and Sahama, G. Geochemistry. Chicago: The University of Chicago Press, 1949.

16. Keller, W. D. The Principles of Chemical Weathering. Columbia, Mo.: Lucas Brothers Publishers, 1957.

17. Correns, C. W., "The Experimental Chemical Weathering of Silicates," Clay Minerals Bulletin, Vol. 4, No. 26 (1961).

18. Iler, R. K. The Colloid Chemistry of Silica and Silicates. Ithaca, N. Y.: Cornell University Press, 1955.

19. Diamond, S., White, J. L., and Dolch, W. L., "Transformation of Clay Minerals by Calcium Hydroxide Attack," Proceedings, 12th National Conference on Clays and Clay Minerals. New York: Pergamon Press, 1964.

20. Glenn, G. R., and Handy, R. L. Lime-Clay Mineral Reaction Products. (Highway Research Record No. 29). Washington, D. C.: National Academy of Sciences/National Research Council, 1963.

21. Hilt, G. H., and Davidson, D. T. Isolation and Investigation of a Lime-Montmorillonite Crystalline Reaction Product. (Highway Research Board Bulletin No. 304). Washington, D. C.: National Academy of Sciences/National Research Council, 1961.

22. Laguros, J. G., et al., "Evaluation of Lime for Stabilization of Loess," Proceedings of ASTM, Vol. 56, 1956.

23. Lu, L. W., et al., "The Calcium-Magnesium Ratio in Soil-Lime Stabilization," Proceedings, Highway Research Board, Vol. 36. Washington, D. C.: National Academy of Sciences/National Research Council, 1957.

24. Wang, J. W., et al. Comparison of Various Commercial Limes for Soil Stabilization. (Highway Research Board Bulletin No. 335). Washington, D. C.: National Academy of Sciences/National Research Council, 1962.

25. Remus, M. D., and Davidson, D. T. Relation of Strength to Compaction and Density of Lime-Treated Soils. (Highway Research Board Bulletin No. 304). Washington, D. C.: National Academy of Sciences/National Research Council, 1961.

26. Thompson, M. R., "Influence of Soil Properties on Lime-Soil Reactions," Public Works, Vol. 96, No. 8 (August, 1965), pp. 120-123.

27. Frye, J. C., Willman, H. B., and Glass, H. D. Gumbotil, Accretion-Gley, and the Weathering Profile. (Illinois State Geological Survey, Circular 295). 1960.

28. Thompson, M. R. Lime-Reactivity of Illinois Soils as it Relates to Compressive Strength. (Civil Engineering Studies, Illinois Cooperative Highway Research Program, Series No. NP-4). Urbana, Illinois: Department of Civil Engineering, University of Illinois, 1964.

29. ——— Split-Tensile Strength of Lime-Stabilized Soils. (Highway Research Record No. 92). Washington, D. C.: National Academy of Sciences/National Research Council, 1965.

30. ——— Shear Strength and Elastic Properties of Lime-Soil Mixtures. (Highway Research Record No. 139). Washington, D. C.: National Academy of Sciences/National Research Council, 1966.

31. Mateos, M., "Soil Lime Research at Iowa State University," Journal of the Soil Mechanics and Foundation Division, Proceedings of ASCE, Vol. 90, No. SM2 (1964), pp. 127-153.

32. Jambor, I. J., "Relation Between Phase Composition, Over-all Porosity and Strength of Hardened Lime-Pozzolana Pastes," Magazine of Concrete Research, Vol. 15, No. 45 (November, 1963).

33. Dawson, R. F., and McDowell, C. A Study of an Old Lime-Stabilized Gravel Base. (Highway Research Board Bulletin No. 304). Washington, D. C.: National Academy of Sciences/National Research Council, 1961.

• • •

This page is intentionally blank.

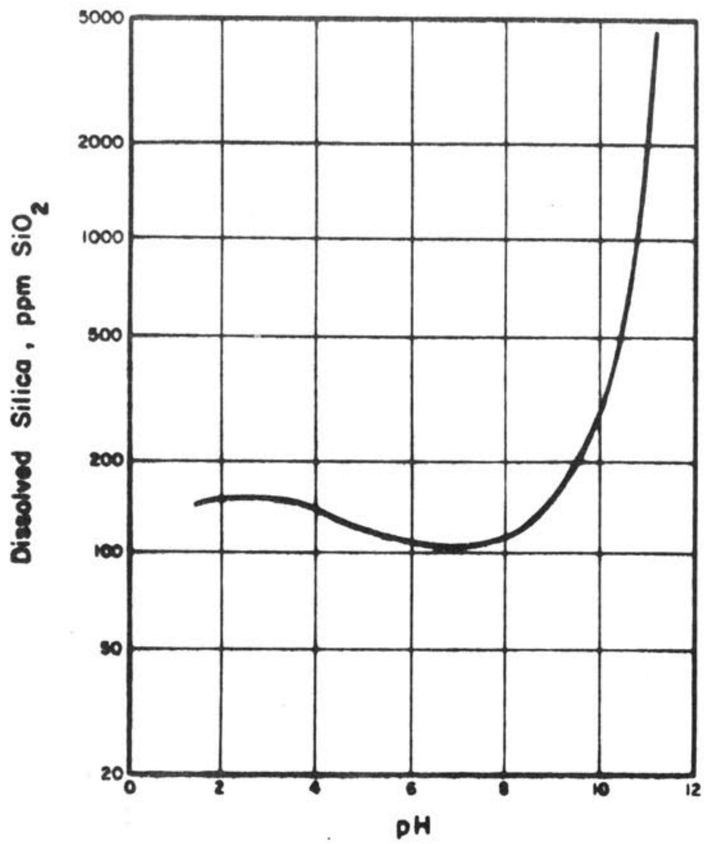

FIGURE 1. EFFECT OF pH ON SILICA SOLUBILITY

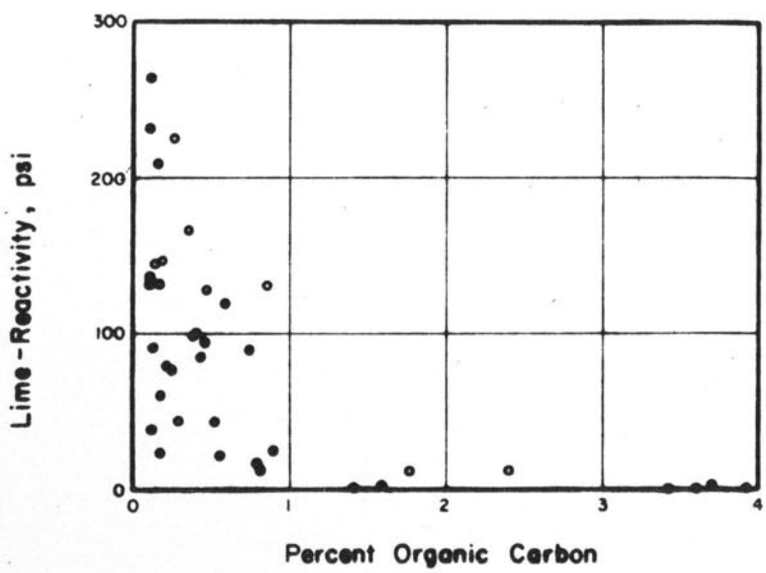

FIGURE 2. INFLUENCE OF ORGANIC CARBON ON LIME-REACTIVITY

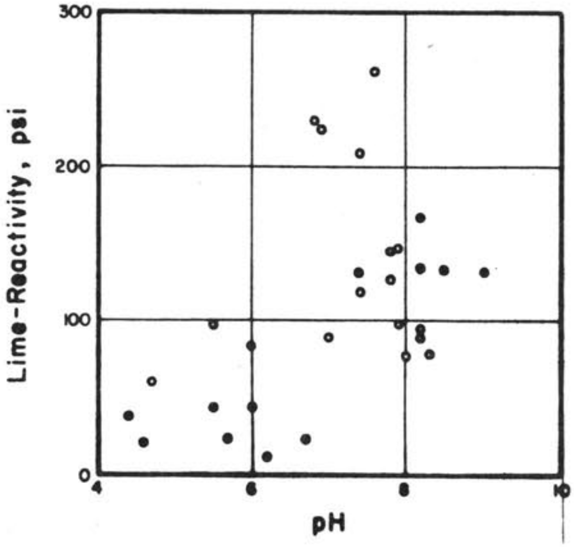

FIGURE 3. INFLUENCE OF pH ON LIME-REACTIVITY

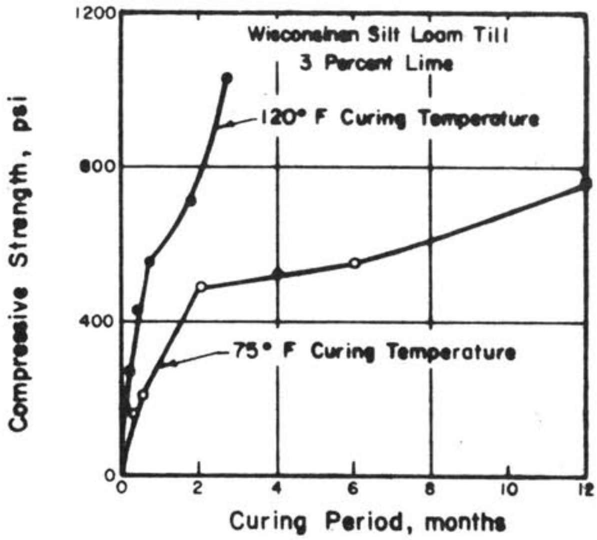

FIGURE 4. INFLUENCE OF CURING TEMPERATURE ON STRENGTH

TABLE 1.

SOILS INCLUDED IN THE SAMPLING PROGRAM

Soil Series	Parent Material	Horizons	Great Soil Group	Sample Site Location
Bryce	Wisconsinan Till	A, B	Humic-Gley	Iroquois Co.
Cisne	Loess	B	Planosol	Jasper Co.
Clarence	Wisconsinan Till	C	Brunizem	Livingston Co.
Cowden	Loess	A, B, C	Planosol	Randolph Co.
Cowden	Loess	B, C	Planosol	Montgomery Co.
Drummer	Wisconsinan Till	A, B	Humic-Gley	Iroquois Co.
Elliott	Wisconsinan Till	A, B	Brunizem	Iroquois Co.
Fayette	Loess	A, B, C	Gray-Brown Podzolic	Henry Co.
Accretion Gley 1	Illinoian Till-Loess	G Zone	--------	Sangamon Co.
Accretion Gley 2	Illinoian Till-Loess	G Zone	--------	Sangamon Co.
Hosmer	Loess	A, B_2, B_2'	Gray-Brown Podzolic	Randolph Co.
Huey	Loess	B, D	Solonetz	Jasper Co.
Accretion Gley 3	Illinoian Till-Loess	G Zone	--------	Effingham Co.
Illinoian Till	Illinoian Till	------	--------	Effingham Co.
Illinoian B	Illinoian Till	B	(In-Situ Weathering Profile)	Sangamon Co.
Illinoian Till	Illinoian Till	------	--------	Sangamon Co.
Loam Till	Wisconsinan Till	------	--------	Champaign Co.
Miami	Wisconsinan Till	A, B, C	Gray-Brown Podzolic	Iroquois Co.
Ottawa	Wisconsinan Till	------	--------	Lasalle Co. (AASHO Road Test Site)
Calcareous Peorian Loess	Loess	------	--------	Schuyler Co.
Leached Peorian Loess	Loess	------	--------	Schuyler Co.
Piasa	Loess	A, B	Solonetz	Jersey Co.
Sable	Loess	B	Humic-Gley	Marshall Co.
Tama	Loess	A, B	Brunizem	Henry Co.

TABLE 2.

DETERMINATION OF NATURAL SOIL PROPERTIES

Soil Property	Test Method
Engineering Properties	
Grain size distribution	AASHO T88-57[1]
Liquid limit	AASHO T89-60[1]
Plastic limit	AASHO T90-56[1]
Mineralogical Properties	
Clay mineral determination (< 2μ)	X-ray diffraction
Calcium carbonate equivalent (only for calcareous soils)	Sulfuric acid-gasometric procedure
Chemical Properties	
pH	Coleman pH meter; 1:1 soil-water mixture
Organic carbon	Wet combustion method
Cation exchange capacity	Ammonium acetate method
Total exchangeable bases	Titration procedure
Exchangeable bases	
Ca	Titration procedure
Mg	Titration procedure
Na	Flame photometer procedure
K	Flame photometer procedure

(1) Refers to American Association of State Highway Officials recommended test procedure.

TABLE 3.

NATURAL SOIL PROPERTIES

Soil Reference Number	Soil Type	Horizon	Drainage Class	AASHO Class	< 2μ Clay, %	Liquid Limit, %	Plasticity Index, %	pH	Organic Carbon, %	Base Saturation, %	Ca/Mg Ratio	Carbonates	Cation-Exchange Capacity, meq/100 gms	Exchangeable Cations (meq/100 gms)				Clay Mineralogy (< 2μ)					
														Ca	Mg	Na	K	Quartz, %	Illite, %	Chlorite, %	Kaolinite, %	Montmorillonite, %	Mixed Layer, %
1	Bryce Silty Clay	A	Poor	A-7-5 (17)	40	57.9	24.2	6.9	3.69	100	2.9	NC*	35.1	26.18	9.13	0.54	0.49	20	40	20	Trace	Trace	20
2	Bryce Silty Clay	B	Poor	A-7-6 (18)	52	53.1	28.8	7.4	0.86	98	1.8	NC	29.15	18.08	10.23	0.44	0.37	5	45	25	Trace	Trace	25
3	Cisne Silt Loam	B	Poor	A-7-6 (20)	39	58.6	38.8	5.5	0.38	32	1.3	NC	21.43	3.63	2.70	0.85	0.30	35	15	0	15	0	35
4	Wisconsinan Clay Till	-	--	A-7-6 (17)	65	49.3	26.9	8.2	0.74	100	3.1	C**(8.6%)	16.88	41.37	13.48	0.66	0.43	8	60	32	0	0	0
5	Cowden Silt Loam	A	Poor	A-4 (8)	19	33.4	7.7	6.3	1.42	83	1.1	NC	15.3	11.25	1.01	0.27	0.19	30	10	Trace	10	Trace	50
6	Cowden Silt Loam	B	Poor	A-7-6 (19)	38	54.0	32.5	6.0	0.43	92	1.6	NC	24.3	12.7	7.7	1.99	0.31	5	20	10	Trace	65	Trace
7	Cowden Silt Loam	C_1	Poor	A-6 (10)	30	34.2	15.2	7.9	0.19	100	1.7	NC	15.8	8.05	4.8	3.33	0.24	20	20	10	5	0	45
8	Cowden Silt Loam	B	Poor	A-7-6 (19)	34	53.4	31.4	5.5	0.43	94	1.1	NC	25.08	11.91	11.32	1.03	0.38	13	0	31	0	56	0
9	Cowden Silt Loam	C	Poor	A-6 (9)	20	32.4	12.6	7.0	0.13	100	1.3	NC	14.78	8.57	6.82	1.19	0.29	16	13	0	0	71	0
10	Drummer Silty Clay Loam	A	Poor	A-7-6 (14)	30	49.6	20.6	7.0	3.93	100	2.9	NC	34.0	26.18	9.0	0.23	0.48	15	25	10	0	Trace	50
11	Drummer Silty Clay Loam	B	Poor	A-7-6 (19)	34	54.4	30.8	7.4	0.57	100	1.9	NC	21.6	17.77	9.44	0.44	0.35	15	20	10	0	55	Trace
12	Elliott Silt Loam	A	Moderately well to imperfect	A-7-5 (12)	29	45.6	17.5	6.3	3.43	91	3.7	NC	23.25	15.9	4.25	0.28	0.67	25	30	10	5	Trace	30
13	Elliott Silt Loam	B	Moderately well to imperfect	A-7-6 (18)	52	52.6	28.4	6.2	0.82	85	1.3	NC	22.15	10.61	8.29	0.32	0.50	10	40	Trace	15	35	Trace
14	Fayette Silt Loam	A	Well	A-7-5 (9)	19	41.4	11.2	6.7	2.40	100	3.4	NC	18.45	14.2	4.23	0.14	0.36	5	25	10	Trace	60	Trace
15	Fayette Silt Loam	B	Well	A-7-5 (17)	32	49.9	28.6	6.0	0.29	89	1.2	NC	19.28	9.33	7.98	0.23	0.24	5	10	5	Trace	80	Trace
16	Fayette Silt Loam	C	Well	A-6 (8)	21	31.9	10.1	7.8	0.14	100	5.3	C (20%)	11.53	22.2	4.2	0.33	0.24	Trace	30	10	Trace	60	Trace
17	Accretion Gley #1	-	--	A-6 (12)	26	35.9	21.9	7.4	0.15	100	.9	NC	14.01	6.64	7.65	0.56	0.33	Trace	0	5	Trace	0	95
18	Accretion Gley #2	-	--	A-6 (10)	25	32.5	14.2	6.9	0.26	100	1.0	NC	15.11	7.59	7.47	0.54	0.23	5	0	10	Trace	0	85
19	Hosmer Silt Loam	A	Well to Moderately Well	A-4 (8)	16	26.1	1.9	5.2	0.80	50	3.5	NC	8.20	2.76	0.78	0.33	0.20	30	15	15	Trace	0	50

*Noncalcareous
**Calcareous

TABLE 3. CONTINUED

Soil Reference Number	Soil Type	Horizon	Drainage Class	AASHO Class	< 2μ Clay, %	Liquid Limit, %	Plasticity Index, %	pH	Organic Carbon, %	Base Saturation, %	Ca/Mg Ratio	Carbonates	Cation-Exchange Capacity, meq/100 gms	Exchangeable Cations (meq/100 gms)				Clay Mineralogy (< 2μ)					
														Ca	Mg	Na	K	Quartz, %	Illite, %	Chlorite, %	Kaolinite, %	Montmorillonite, %	Mixed Layer, %
20	Hosmer Silt Loam	B_2	Well to Moderately Well	A-7-6 (11)	25	41.4	17.4	4.7	0.17	62	1.2	NC	17.65	5.93	4.87	0.23	0.37	Trace	25	10	Trace	0	65
21	Hosmer Silt Loam	B_2'	Well to Moderately Well	A-7-6 (13)	29	44.5	20.4	4.4	0.12	58	1.0	NC	21.15	5.98	5.87	0.55	0.47	Trace	25	10	Trace	65	Trace
22	Huey Silt Loam	B	Imperfect	A-7-6 (17)	31	46.3	28.9	9.0	0.17	100	2.3	NC	16.40	10.55	4.62	4.63	0.32	35	0	0	10	55	0
23	Huey Silt Loam	D	Imperfect	A-6 (15)	27	38.6	26.4	8.5	0.10	100	2.1	NC	13.84	8.92	4.32	3.45	0.28	35	0	0	10	55	0
24	Accretion Gley #3	-	--	A-6 (7)	18	33.7	18.4	7.6	0.11	100	1.6	NC	15.23	9.66	5.89	0.78	0.16	5	0	10	Trace	85	Trace
25	Illinoian Till	-	--	A-6 (6)	17	24.6	11.7	8.2	0.46	100	12.7	C (13.5%)	5.56	37.96	2.98	0.20	0.28	Trace	45	15	10	0	30
26	Illinoian B Horizon	-	--	A-6 (11)	29	37.2	19.2	6.8	0.11	100	1.4	NC	16.17	9.78	7.25	0.27	0.28	5	20	5	Trace	0	70
27	Illinoian Till	-	--	A-6 (6)	14	25.5	11.0	8.2	0.10	100	5.4	C (18.6%)	6.21	17.54	3.22	0.14	0.20	Trace	80	10	Trace	0	10
28	Wisconsinan Loam Till	-	--	A-4	18	24.5	7.8	8.3	0.21	100	6.0	C (13.8%)	5.90	26.69	4.43	0.33	0.19	19	59	22	0	0	0
29	Miami Silt Loam	A	Well	A-4 (8)	11	26.0	NP*	6.8	1.77	100	3.2	NC	11.5	9.22	2.92	0.18	0.26	30	25	15	10	Trace	20
30	Miami Silt Loam	B	Well	A-6 (9)	26	27.7	11.3	4.6	0.56	46	1.2	NC	12.58	3.19	2.74	0.17	0.23	10	30	0	5	Trace	55
31	Miami Silt Loam	C	Well	A-6 (9)	23	28.7	14.3	7.9	0.38	100	10.2	C (14.1%)	11.35	25.25	2.48	0.40	0.30	10	50	15	5	Trace	20
32	Ottawa A-6	-	--	A-6 (8)	25	25.2	10.8	8.3	0.53	100	1.2	C (27.4%)	13.19	7.77	6.38	0.80	0.22	5	80	15	0	0	0
33	Calcareous Peorian Loess	-	--	A-4 (8)	7	28.5	3.0	8.0	0.25	100	2.0	C (15.0%)	6.48	11.99	5.88	0.60	0.22	Trace	15	10	Trace	75	Trace
34	Leached Peorian Loess	-	--	A-4 (8)	11	29.5	3.9	6.7	0.17	100	1.6	NC	9.34	5.87	3.76	0.24	0.18	Trace	15	10	Trace	75	Trace
35	Piasa Silt Loam	A	Poor	A-6 (10)	29	36.1	14.8	7.4	1.57	100	8.3	NC	19.03	21.45	2.6	0.66	0.25	15	25	10	5	Trace	45
36	Piasa Silt Loam	B	Poor	A-7-6 (19)	40	54.5	35.7	8.2	0.36	100	2.0	NC	25.73	16.4	8.25	3.85	0.38	10	20	10	5	55	Trace
37	Sable Silty Clay Loam	B	Poor	A-7-6 (16)	36	50.7	23.5	7.8	.47	100	1.8	NC	24.19	16.88	9.24	0.33	0.36	35	10	0	10	0	45
38	Tama Silt Loam	A	Well to Moderately Well	A-7-5 (20)	31	62.6	33.7	5.9	3.60	79	4.5	NC	32.7	20.2	4.53	0.29	0.67	15	25	5	5	Trace	50
39	Tama Silt Loam	B	Well to Moderately Well	A-7-6 (20)	39	62.6	33.7	5.7	0.90	82	2.1	NC	27.18	14.98	7.1	0.18	0.46	5	10	10	Trace	75	Trace

*Non-plastic

TABLE 4.

PROPERTIES OF LIMES

Lime Designation	Type	Per Cent $Ca(OH)_2$	Per Cent MgO	Per Cent $Mg(OH)_2$	Per Cent Passing No. 325 Sieve
A	High-calcium hydrated	96	----	---	95
B	Monohydrated dolomitic	58.8	33.3	1.7	85
C	By-product high-calcium hydrated	96	----	---	76

TABLE 5.

PLASTICITY TEST RESULTS

Soil Number	Soil	Natural Soil LL	Natural Soil PI	Lime A 3 LL	Lime A 3 PI	Lime A 5 LL	Lime A 5 PI	Lime A 7 LL	Lime A 7 PI	Lime B 3 LL	Lime B 3 PI	Lime B 5 LL	Lime B 5 PI	Lime B 7 LL	Lime B 7 PI	Lime C 3 LL	Lime C 3 PI	Lime C 5 LL	Lime C 5 PI	Lime C 7 LL	Lime C 7 PI
1	Bryce A	57.9	24.2	NP[1]		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2	Bryce B	53.1	28.8	47.9	21.4	NP		-	-	47.9	12.7	46.3	8.0	45.7	8.3	48.0	10.1	47.9	9.0	48.8	9.6
3	Cisne B	58.6	38.8	NP		-	-	-	-	43.2	7.6	-	-	-	-	-	-	-	-	-	-
4	Clay Till, Livingston, Co.	49.3	26.9	51.1	13.7	58.5	11.0	52.3	14.8	58.5	11.9	53.9	12.7	53.7	13.8	52.5	14.8	55.9	18.2	51.7	17.1
5	Cowden A	33.4	7.7	NP		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
6	Cowden B	54.2	32.5	46.7	7.4	NP		-	-	44.1	10.0	45.7	9.6	44.0	6.1	45.5	8.7	46.8	9.0	45.2	7.1
7	Cowden C_1	34.2	15.2	NP		-	-	-	-	NP		-	-	-	-	NP		-	-	-	-
8	Cowden B, Montgomery Co.	53.9	31.4	47.4	13.7	NP		-	-	49.4	16.8	NP		-	-	47.4	12.7	48.0	7.0	46.2	5.7
9	Cowden C, Montgomery Co.	32.4	12.6	NP		-	-	-	-	NP		-	-	-	-	31.9	6.8	NP		-	-
10	Drummer A	49.6	20.6	NP		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
11	Drummer B	54.4	30.8	44.1	10.4	NP		-	-	45.8	13.9	NP		-	-	44.1	9.5	47.6	11.3	NP	
12	Elliott A	45.6	17.5	NP		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
13	Elliott B	52.6	28.4	41.9	19.1	NP		-	-	-	-	-	-	-	-	-	-	-	-	-	-
14	Fayette A	41.4	11.2	NP		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
15	Fayette B	49.9	28.6	NP		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
16	Fayette C	31.9	10.1	NP		-	-	-	-	NP		-	-	-	-	NP		-	-	-	-
17	Accretion-Gley 1	35.9	21.9	44.6	8.2	NP		-	-	34.3	15.0	NP		-	-	32.6	7.7	33.7	9.0	33.1	9.6
18	Accretion-Gley 2	32.5	14.2	NP		-	-	-	-	32.7	5.0	NP		-	-	33.0	9.2	32.4	7.5	33.6	5.9
19	Hosmer A	26.1	1.9	NP		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
20	Hosmer B^2	41.4	17.4	NP		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
21	Hosmer B$_2$	44.5	20.4	NP		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Liquid Limit (LL) or Plasticity Index (PI), Per Cent

[1] NP: Nonplastic

[2] Wisconsinan calcareous silt loam till; used as embankment soil at the Ottawa AASHO Road Test.

TABLE 5. CONTINUED

Soil Number	Soil	Natural Soil		Per Cent Lime A						Per Cent Lime B						Per Cent Lime C					
				3		5		7		3		5		7		3		5		7	
		LL	PI	LL	PI	LL	PI	LL	PI	LL	PI	LL	PI	LL	PI	LL	PI	LL	PI	LL	PI
22	Huey B	46.3	28.9	39.5	8.9	NP		-	-	38.4	11.2	40.2	11.7	38.5	8.2	40.5	14.1	38.8	12.0	37.6	10.6
23	Huey D	38.6	26.4	36.3	9.2	NP		-	-	34.7	10.5	35.1	6.7	NP		36.2	7.5	35.1	10.0	NP	
24	Accretion-Gley 3	33.7	18.4	NP		-	-	-	-	NP		-	-	-	-	27.9	2.3	NP		-	-
25	Illinoian Till, Effingham Co.	24.6	11.7	26.3	4.8	NP		-	-	26.0	6.4	NP		-	-	25.3	8.5	24.9	7.3	25.7	5.3
26	Illinoian B, Sangamon Co.	37.2	19.2	NP		-	-	-	-	38.9	10.0	NP		-	-	50.3	8.2	NP		-	-
27	Illinoian Till, Sangamon Co.	25.5	11.0	27.1	5.9	NP		-	-	NP		-	-	-	-	26.7	6.0	27.6	7.8	27.6	5.7
28	Loam Till, Champaign Co.	24.5	7.8	NP		-	-	-	-	38.9	7.6	NP		-	-	27.9	5.4	NP		-	-
29	Miami A	NP		NP		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
30	Miami B	27.7	11.3	NP		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
31	Miami C	28.7	14.3	NP		-	-	-	-	28.7	6.6	NP		-	-	30.4	7.8	28.8	6.8	31.6	8.9
32	Ottawa A-6 (2)	25.2	10.8	27.0	5.6	26.6	4.6	-	-	-	-	-	-	-	-	-	-	-	-	-	-
33	Calcareous Peorian loess	28.4	3.0	NP		-	-	-	-	NP		-	-	-	-	NP		-	-	-	-
34	Leached Peorian loess	29.5	3.9	NP		-	-	-	-	NP		-	-	-	-	NP		-	-	-	-
35	Piasa A	36.1	14.8	NP		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
36	Piasa B	54.5	35.7	48.3	11.4	NP		-	-	-	-	-	-	-	-	-	-	-	-	-	-
37	Sable B	50.7	23.5	NP		-	-	-	-	47.1	6.6	NP		-	-	NP		-	-	-	-
38	Tama A	60.2	26.9	NP		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
39	Tama B	62.6	33.7	NP		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

1 NP: Nonplastic

2 Wisconsinan calcareous silt loam till; used as embankment soil at the Ottawa AASHO Road Test.

TABLE 6.

SHRINKAGE LIMIT TEST RESULTS

	Soil Reference Number	Natural Soil	Per Cent Lime A				Per Cent Lime B			Per Cent Lime C		
			1	3	5	7	3	5	7	3	5	7
1	Bryce A	23.1	23.9	NC [1]	NC	----	----	----	----	----	----	----
2	Bryce B	12.5	----	41.9	43.8	----	38.5	39.6	39.8	44.6	47.5	43.8
3	Cisne B	17.4	----	33.6	33.6	36.1	31.3	38.0	37.9	33.3	40.0	41.2
4	Clay Till, Livingston Co.	17.5	----	31.2	35.3	----	34.7	37.5	----	35.0	37.2	----
5	Cowden A	28.1	----	36.4	43.6	----	----	----	----	----	----	----
6	Cowden B	12.9	----	30.6	55.0	----	36.1	42.8	49.7	38.2	37.5	44.7
7	Cowden C_1	18.2	----	31.0	35.1	----	40.6	43.8	41.9	35.5	33.4	36.0
8	Cowden B, Montgomery Co.	19.9	----	34.9	37.5	----	30.8	36.6	----	32.9	36.5	----
9	Cowden C, Montgomery Co.	16.9	----	27.9	26.2	----	25.5	28.3	----	26.8	28.2	----
10	Drummer A	25.4	NC	NC	NC	----	----	----	----	----	----	----
11	Drummer B	17.1	----	36.3	40.8	----	33.8	38.5	----	38.4	35.9	----
12	Elliott A	33.5	35.6	NC	NC	----	----	----	----	----	----	----
13	Elliott B	20.0	----	39.2	39.0	----	----	----	----	----	----	----
14	Fayette A	28.7	36.7	41.5	44.3	----	----	----	----	----	----	----
15	Fayette B	23.2	----	36.1	43.5	----	----	----	----	----	----	----
16	Fayette C	28.9	----	35.7	55.2	----	34.5	34.2	35.7	32.5	34.5	33.1
17	Accretion-Gley 1	13.3	----	31.8	29.8	----	29.2	27.2	----	26.6	26.9	----
18	Accretion-Gley 2	16.5	----	28.7	28.7	----	30.7	26.5	----	28.2	28.0	----
19	Hosmer A	27.4	----	31.4	37.8	----	---	----	----	----	----	----
20	Hosmer B_2	20.7	----	40.2	42.2	----	----	----	----	----	----	----
21	Hosmer B_2^2	16.9	----	39.1	40.1	----	----	----	----	----	----	----
22	Huey B	11.7	----	31.4	35.4	33.6	28.6	30.7	35.0	27.2	33.0	36.3
23	Huey D	10.7	----	29.6	31.4	32.2	32.4	34.8	31.4	34.9	35.6	36.0
24	Accretion-Gley 3	15.4	----	23.9	25.1	----	22.9	24.7	----	27.6	26.6	----
25	Illinoian Till, Effingham Co.	14.8	----	18.6	19.2	----	18.6	18.4	----	22.1	22.8	----
26	Illinoian B, Sangamon Co.	15.0	----	29.2	30.2	----	31.5	32.7	----	35.6	33.8	----
27	Illinoian Till, Sangamon Co.	13.9	----	25.1	21.4	----	20.4	21.0	----	23.8	26.5	----
28	Loam Till, Champaign Co.	13.8	----	22.5	26.5	24.5	27.4	27.7	27.6	23.6	25.8	28.3
29	Miami A	23.4	----	30.7	30.1	----	----	----	----	----	----	----
30	Miami B	21.4	----	34.3	31.6	----	----	----	----	----	----	----
31	Miami C	15.8	----	27.4	34.4	----	31.0	29.4	30.6	28.6	29.4	29.4
33	Calcareous Peorian loess	30.5	----	37.1	31.8	----	29.4	29.5	31.5	27.5	30.1	27.3
34	Leached Peorian loess	29.0	----	34.9	31.8	----	35.8	36.7	35.8	33.3	33.2	38.1
35	Piasa A	22.4	30.9	NC	NC	----	----	----	----	----	----	----
36	Piasa B	26.2	----	47.8	49.5	----	----	----	----	----	----	----
37	Sable B	19.5	----	29.9	38.6	41.5	48.0	46.8	44.6	41.7	43.0	41.9
38	Tama A	32.1	34.5	NC	NC	----	----	----	----	----	----	----
39	Tama B	22.6	30.5	41.7	NC	----	----	----	----	----	----	----

1 - Non-cohesive

TABLE 7.

COMPRESSIVE STRENGTH RESULTS -- TWENTY-EIGHT-DAY CURING PERIOD

Soil Reference Number		Natural Soil	Compressive Strength, psi								
			Per Cent Lime A			Per Cent Lime B			Per Cent Lime C		
			3	5	7	3	5	7	3	5	7
1	Bryce A	57	43	58	53	---	---	---	---	---	---
2	Bryce B	81	201	212	193	142	162	153	127	143	131
3	Cisne B	93	107	190	189	94	197	281	107	153	164
4	Clay Till, Livingston Co.	78	167	148	139	205	238	232	160	180	178
5	Cowden A	48	42	47	45	---	---	---	---	---	---
6	Cowden B		142	137	112	73	147	153	93	90	103
7	Cowden C_1	51	198	171	122	121	154	166	132	125	125
8	Cowden B, Montgomery Co.	76	81	119	110	88	139	193	83	135	145
9	Cowden C, Montgomery Co.	67	156	140	157	240	298	299	208	199	210
10	Drummer A	53	29	49	32	---	---	---	---	---	---
11	Drummer B	68	186	152	146	187	337	330	240	218	216
12	Elliott A	53	21	38	33	---	---	---	---	---	---
13	Elliott B	98	89	110	110	---	---	---	---	---	---
14	Fayette A	38	37	46	49	---	---	---	---	---	---
15	Fayette B	70	109	114	113	---	---	---	---	---	---
16	Fayette C	40	137	185	125	190	168	169	122	121	125
17	Accretion-Gley 1	76	249	279	285	294	467	499	441	469	423
18	Accretion-Gley 2	58	263	247	283	---	---	---	---	---	---
19	Hosmer A	31	35	45	41	---	---	---	---	---	---
20	Hosmer B_2	63	101	123	95	---	---	---	---	---	---
21	Hosmer B_2	88	92	125	116	---	---	---	---	---	---
22	Huey B	102	223	216	233	265	306	273	242	234	210
23	Huey D	89	222	179	197	224	289	275	192	174	184
24	Accretion-Gley 3	79	277	343	306	426	513	554	464	476	493
25	Illinoian Till, Effingham Co.	43	126	126	136	261	219	283	179	254	181
26	Illinoian B, Sangamon Co.	52	255	282	254	234	402	389	319	336	313
27	Illinoian Till, Sangamon Co.	51	150	186	143	287	268	320	244	238	252
28	Loam Till, Champaign Co.	105	172	184	174	---	---	---	---	---	---
29	Miami A	41	39	53	45	---	---	---	---	---	---
30	Miami B	81	70	96	102	---	---	---	---	---	---
31	Miami C	73	153	171	116	---	---	---	---	---	---
32	Ottawa A-6 (1)	101	170	174	137	243	236	267	216	198	175
33	Calcareous Peorian Loess	22	98	94	96	84	112	123	51	79	71
34	Leached Peorian Loess	33	50	57	53	49	102	141	27	32	40
35	Piasa A	55	53	56	35	---	---	---	---	---	---
36	Piasa B	66	232	178	119	---	---	---	---	---	---
37	Sable B	98	225	184	185	238	330	208	305	182	174
38	Tama A	58	32	41	40	---	---	---	---	---	---
39	Tama B	74	71	98	85	---	---	---	---	---	---

1 - Wisconsinan calcareous silt loam till; used as embankment soil at the Ottawa AASHO Road Test.

TABLE 8.

COMPRESSIVE STRENGTH RESULTS -- FIFTY-SIX-DAY CURING PERIOD

Soil Reference Number		Compressive Strength, psi								
		Per Cent Lime A			Per Cent Lime B			Per Cent Lime C		
		3	5	7	3	5	7	3	5	7
2	Bryce B	162	231	202	116	255	229	142	136	123
3	Cisne B	142	238	198	105	239	348	103	188	228
4	Clay Till, Livingston Co.	214	187	176	231	298	289	174	244	203
6	Cowden B	119	131	---	115	171	155	81	136	111
7	Cowden C_1	261	187	---	246	253	265	212	227	187
8	Cowden B, Montgomery Co.	134	190	98	256	196	321	104	161	148
9	Cowden C, Montgomery Co.	392	313	340	364	433	441	320	400	424
11	Drummer B	247	238	246	203	364	420	273	271	246
13	Elliott B	---	109	99	---	---	---	---	---	---
15	Fayette B	97	92	91	---	---	---	---	---	---
16	Fayette C	156	228	238	179	199	223	159	202	199
17	Accretion-Gley 1	305	377	395	345	620	638	500	697	622
18	Accretion-Gley 2	255	318	384	---	---	---	---	---	---
20	Hosmer B_2	94	100	78	---	---	---	---	---	---
21	Hosmer B_2	84	117	124	---	---	---	---	---	---
22	Huey B	302	352	325	313	370	391	323	418	380
23	Huey D	277	280	282	341	358	378	271	266	243
24	Accretion-Gley 3	472	570	624	479	476	627	548	753	774
25	Illinoian Till, Effingham Co.	191	201	202	334	333	353	342	280	203
26	Illinoian B, Sangamon Co.	385	369	396	296	471	541	423	532	565
27	Illinoian Till, Sangamon Co.	311	277	270	332	355	358	394	368	331
28	Loam Till, Champaign Co.	229	214	223	---	---	---	---	---	---
30	Miami B	---	80	70	---	---	---	---	---	---
31	Miami C	---	153	131	258	236	200	244	217	164
32	Ottawa A-6 (1)	223	208	210	313	313	263	274	260	248
33	Calcareous Peorian Loess	100	134	143	142	153	178	---	107	103
34	Leached Peorian Loess	63	55	86	123	114	149	40	54	48
37	Sable B	247	226	226	231	356	328	213	239	209
39	Tama B	---	87	82	---	---	---	---	---	---

1 - Wisconsinan calcareous silt loam till; used as embankment soil at the Ottawa AASHO Road Test.

TABLE 9.

EFFECT OF LIME TYPE ON PLASTICITY INDEX OF LIME SOIL MIXTURES

Statistical Summary of Randomized Complete Block Analysis

Per Cent Lime	Lime Type	Replicates	Treatment Variance	Error Variance	Calculated F	Critical F	
						Degrees of freedom	Significance level, $\alpha = .05$
3	A, B, C	22	28.3	9.3	3.04	2, 42	3.22

Averages for Various Treatments

Lime Type	Lime Per Cent	Average Plasticity Index
A	3	4.7
B	3	6.9
C	3	6.3

TABLE 10.

LIME PERCENTAGE REQUIRED TO RENDER SOILS NONPLASTIC

Soil Number	Lime A	Lime B	Lime C
2	5%	8.3[a]	9.6[a]
3	3%	5%	3%
4	14.8[a]	13.8[a]	17.1[a]
6	5%	6.1[a]	7.0[a]
7	3%	3%	3%
8	5%	5%	5.7[a]
9	3%	3%	5%
11	5%	5%	7%
16	3%	3%	3%
17	5%	5%	9.6[a]
18	3%	5%	5.9[a]
22	5%	8.2[a]	10.6[a]
23	5%	7%	7%
24	3%	3%	5%
25	5%	5%	5.3[a]
26	3%	5%	5%
27	5%	3%	5.7[a]
28	3%	5%	5%
31	3%	5%	8.9[a]
33	3%	3%	3%
34	3%	3%	3%
37	3%	5%	3%
Average lime per cent	3.9	4.3	4.3
Number of mixes still plastic	1	4	10

[a] Plasticity index for 7 per cent lime treatment

TABLE 11.

INFLUENCE OF LIME TYPE ON SHRINKAGE LIMITS

Statistical Summary of Randomized Complete Block Analysis

Lime Per Cent	Lime Type	Replicates	Treatment Variance	Error Variance	Calculated F	Critical F	
						Degrees of freedom	Significance level, $\alpha = .05$
3	A, B, C	22	7.5	10.9	0.69	2, 42	3.22
5	A, B, C	22	7.6	16.6	0.46	2, 42	3.22

Averages for Various Treatments

Lime Per Cent	Lime Type	Average Shrinkage Limit
3	A	30.6
	B	31.4
	C	31.7
5	A	34.0
	B	33.0
	C	33.0

TABLE 12.

INFLUENCE OF LIME PERCENTAGE ON SHRINKAGE LIMITS OF LIME-SOIL MIXTURES

Statistical Summary of Randomized Complete Block Analysis

Lime Type	Per Cent Lime	Replicates	Treatment Variance	Error Variance	Calculated F	Critical F	
						Degrees of freedom	Significance level α = .05
A	3, 5	32	155	18.4	8.4*	1, 31	4.16
B	3, 5	22	25.8	3.9	6.6*	1, 21	4.32
C	3, 5	22	17.2	2.7	6.4*	1, 21	4.32

* F value is significant @ α = .05

Averages for Various Treatments

Lime Per Cent	Lime Type	Average Shrinkage Limit
3	A	32.8
	B	31.4
	C	31.7
5	A	35.9
	B	33.0
	C	33.0

TABLE 13.

COMPRESSIVE STRENGTH -- RANDOMIZED, COMPLETE, BLOCK FACTORIAL ANALYSIS

Analysis of Variance Summary

Source of Variation	Degrees of Freedom	Variance	Calculated F
Total	305		
Soil type (replicates)	16	212,055	70.1*
Lime type	2	137,979	45.6*
Lime percentage	2	44,695	14.5*
Curing period	1	467,690	154.6*
Interactions:			
Lime type-lime percentage	4	16,180	5.35*
Lime type-curing period	2	1,827	0.6
Lime percentage-curing period	2	6,519	2.16
Lime type-lime percentage-curing period	4	1,364	0.45
Error	272	3,025	

* Significant F, α = .05

Compressive Strength Averages for Various Treatments

Per cent Lime	Lime Type	Average q_u, psi	
		28-day cure	56-day cure
3	A	175	248
	B	216	268
	C	216	271
5	A	187	267
	B	275	344
	C	214	322
7	A	176	266
	B	286	371
	C	213	306

Soils Included in Analysis - Soil reference numbers, see Table

2, 3, 4, 8, 9, 11, 16, 17, 22, 23, 24, 25, 26, 27, 32, 34, 37

TABLE 14.

OPTIMUM LIME CONTENTS

Soil Reference Number	Lime A 28[a]	Lime A 56[a]	Lime B 28[a]	Lime B 56[a]	Lime C 28[a]	Lime C 56[a]
2	3	5	5	5	5	3
3	5	5	7	7	5	7
4	3	3	5	5	3	5
6	3	3	5	5	3	5
7	3	3	5	3	3	3
8	5	5	7	7	5	5
9	3	3	5	5	3	5
11	3	3	5	7	3	3
16	5	5	3	5	3	5
17	5	5	5	5	3	5
22	3	5	5	5	3	5
23	3	3	5	5	3	3
24	5	5	5	5	3	5
25	3	3	3	3	3	3
26	3	3	5	7	3	5
27	5	3	7	3	3	3
31	3	5	3	3	3	3
32	3	3	3	3	3	3
33	3	5	5	5	5	5
34	3	7	7	7	5	5
37	3	3	5	5	3	5
Average	3.6	4.0	5.0	5.0	3.5	4.3

[a] Days of curing @ 73F

TABLE 15.

STRENGTH INCREASE[a] FROM TWENTY-EIGHT TO FIFTY-SIX DAYS CURING

Soil Reference Number	Lime A			Lime B			Lime C		
	3 Per Cent	5 Per Cent	7 Per Cent	3 Per Cent	5 Per Cent	7 Per Cent	3 Per Cent	5 Per Cent	7 Per Cent
2	0	19	0	0	93	76	15	0	0
3	35	48	9	11	42	77	0	35	64
4	47	29	37	26	60	57	14	64	25
8	53	71	0	168	57	128	21	26	3
9	236	173	183	124	135	142	112	201	214
11	61	86	100	16	27	90	33	53	30
16	19	43	113	0	31	54	37	81	74
17	56	98	110	51	153	139	59	228	199
22	79	136	92	48	64	118	81	184	170
23	55	101	85	117	69	103	79	92	59
24	195	227	318	53	63	73	84	277	281
25	65	75	66	73	114	70	163	126	22
26	130	87	142	62	69	152	104	196	252
27	161	91	127	45	87	38	150	130	79
32	53	34	73	70	77	0	58	62	73
34	13	0	33	64	12	8	13	22	8
37	22	42	41	0	26	120	0	57	35

[a] Strength increases are in psi

[0] No strength increase or a decrease

TABLE 16.

COMPRESSIVE STRENGTH INCREASE -- RANDOMIZED, COMPLETE, BLOCK FACTORIAL ANALYSIS

Analysis of Variance Study

Source of Variation	Degrees of Freedom	Variance	Calculated F
Total	152		
Soil type (replicates)	16	21,089	10.3*
Lime type	2	4,099	2.01
Lime percentage	2	10,168	4.98*
Interaction (Lime type-Lime per cent)	4	2,443	1.20
Error	128	2,042	

* Significant F, α = .05

Compressive Strength Increase Averages for Various Treatments

Lime Per Cent	Lime Type	Average strength Increase, psi
3	A	75
	B	55
	C	60
5	A	80
	B	69
	C	108
7	A	90
	B	85
	C	93

TABLE 17.

SIMPLE CORRELATION COEFFICIENTS FOR AVERAGE STRENGTH INCREASES AND NATURAL SOIL PROPERTIES

Natural Soil Property[a]	Correlation Coefficient
Lime-reactivity	.72*
< 2 micron clay, per cent	-.36
Liquid limit	-.31
Plasticity index	-.13
AASHO group index	-.37
Organic carbon, per cent	-.61*
pH	.16
Cation exchange capacity	-.28
Total exchangeable bases	-.23
Exchangeable Cations:	
Ca	-.24
Mg	-.16
Na	.22
K	-.33
Ca/Mg	-.11
Base saturation, per cent	.21
Clay mineralogy ($< 2\mu$):	
Quartz, per cent	-.17
Illite, per cent	-.40
Chlorite, per cent	-.39
Kaolinite, per cent	-.16
Montmorillonite, per cent	.27
Mixed layer, per cent	.05

[a] See Tables 2 and 3 for test procedures and results

PUBLICATIONS OF THE COLLEGE OF ENGINEERING

Bulletins from the University of Illinois College of Engineering are detailed reports of research results, seminar proceedings, and literature searches. They are carefully reviewed before publication by authorities in the field to which the material pertains, and they are distributed to major engineering libraries throughout the world. They are available at a charge approximately equal to the cost of production.

The annual *Summary of Engineering Research* is available in the fall of each year. It contains a short report on every research project conducted in the College during the past fiscal year, including the names of the researchers and the publications that have resulted from their work. It is available free of charge.

Engineering Outlook, the College's monthly newsletter, contains short articles about current happenings, new research results, recent technical publications, and educational practices in the College of Engineering. Free subscriptions are available upon request.

The Seminar and Discussion Calendar, which is published and distributed weekly, lists current meetings, lectures, and other events on the engineering campus that are open to the public. Free subscriptions are available upon request.

Requests for a catalog of available technical bulletins or for any of the above publications should be addressed to the Engineering Publications Office, College of Engineering, University of Illinois, Urbana, Illinois 61801.

OTHER PUBLICATIONS IN RELATED FIELDS BY THE ENGINEERING EXPERIMENT STATION

Bulletin 473. *Possolanic Pavements*, by H. L. Ahlberg and E. J. Barenberg. 1965. *Three dollars.*

These publications are available from:
Engineering Publications Office
112 Engineering Hall
University of Illinois
Urbana, Illinois 61801