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Soil Taxonomy and Soil Properties

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Part 1
Soil Taxonomy

Soil Taxonomy: An Overview

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Soil Taxonomy is a comprehensive soil classification developed from 1951 to 1974. In synthesizing the system, all soil properties were considered but selection of differentiating criteria was guided by modern theories of soil genesis. To the degree permitted by present knowledge, the class limits are defined in quantitative terms. The system was designed to be uniformly usable and applicable by competent soil scientists regardless of their area of training and experience. In this system, classification is objective in that it proceeds from properties of the soils themselves and not from the beliefs of the pedologist about soils in general. The system was intended to embrace all known kinds of soils including cultivated and eroded soils. Definitions for a few classes are incomplete because of lack of sufficient data. Soil Taxonomy is a six-category system that permits aggregation of soil data and interpretations at various levels of generalization, whether they are displayed as maps or statistics. It is the only soil classification with a consistent, systematic nomenclature that indicates location in the system and something about the properties of the soils in each class. Soil properties that are important for plant growth also affect the performance of soils for engineering and other nonfarm uses. Soil Taxonomy is a tool for communicating about soils and for extending modern technology into newly developing areas. Interpretations can be made for almost all farm and nonfarm uses.

Although soil is traditionally considered to be a medium for plant growth, the word soil has several meanings. In the development of Soil Taxonomy (1), the following definition is used: Soil

> is the collection of natural bodies on the earth's surface, in places modified or even made by man of earthy materials, containing living matter and supporting or capable of supporting plants out-of-doors. Its upper limit is air or shallow water. At its margins it grades to deep water or to barren areas of rock or ice. Its lower limit to the not-soil beneath is perhaps the most difficult to define. Soil includes the horizons near the surface that differ from the underlying rock material as a result of interactions, through time, of climate, living organisms, parent materials, and relief. In the few places where it contains thin cemented horizons that are impermeable to roots, soil is as deep as the deepest horizon. More commonly soil grades at its lower margin to hard rock or to earthy materials virtually devoid of roots, animals, or marks of other biologic activity. The lower limit of soil, therefore, is normally the lower limit of biologic activity, which generally coincides with the common rooting depth of native perennial plants. Yet in defining mapping units for detailed soil surveys, lower layers that influence the movement and content of water and air in the soil of the root zone must also be considered.

The American Geological Institute (2) defines soil for engineering and geological uses as "all unconsolidated earthy material over bedrock. It is approximately equal to regolith." Many older geological surveys do not discuss the unconsolidated surficial deposits. But in recent years both geologists and engineers have recognized that soils have distinctive properties both horizontally and vertically. According to Lambe and Whitman (3), "The determination of the soil profile is an essential step in almost all soil mechanics problems" and "The properties of the soils in a profile depend on (a) the nature of the components, (b) the method of profile formation, and (c) the alternation of the profile after formation." Thus, there is an increasing awareness that a knowledge of the soil profile and its properties is important in soil engineering. Soil scientists in cooperation with engineers can ensure that suitable interpretations of soil information are available for engineering uses. In the past, for example, there has been close cooperation between highway engineers and soil scientists.

CLASSIFICATION OF SOILS

Interest in soil classification probably developed after man first started to till the soil. Soils vary in some or nearly all their properties within variable distances and are seldom uniform over large areas. Although the best management practices for each soil could be discovered by trial and error, this was an expensive and time-consuming process. The discovery that soils with similar properties and in a similar environment respond similarly to the same management practices was a practical reason to develop a system of soil classification for the transfer of experience.

The soil survey program in the United States started late in the nineteenth century. Soil Taxonomy was initiated about 1951, at a time when there were about 5500 soil series recognized in the United States, each with a defined range in properties. These series were being classified according to the U.S. system of 1938 (4) in which classes were only loosely defined. As a result, there were differences of opinion about the classification of many soil series. Some did not seem to have a place in the classification system whereas others seemed to fit into more than one class in a category. Because many soil scientists of differing experience were classifying soils, consistency in soil correlation and soil interpretations was difficult to maintain. The number of defined soils continued to increase. It was recognized that more precise definitions of soil classes were needed as well as a more logical system of classification.

DEVELOPMENT OF SOIL TAXONOMY

Soil Taxonomy was intended to accommodate all soils and as many of the existing classes as was reasonable. Large areas of the United States had soil surveys that were adequate for current needs. The mapping units were carefully defined and many of the classes were meaningful, particularly those in the intermediate category, the great soil groups, and the lower categories, series, and types. But many soils were classed in some of the great soil groups because the definitions for the next lower category, the family, had not been developed. This deficiency resulted in a wide range of properties in the soil series in different great soil groups. Some series were relatively narrowly defined and others were quite broadly defined.

After World War II there was considerable interest in the agricultural potential of the less developed nations. A better system of classifying soils and providing soil interpretations was needed so that knowledge about soils could be transferred between locations having similar soils and similar environments. The greatest stimulus to the development of an improved classification system resulted from a need to improve the organization of the increasing knowledge about soils and from the increased use of soil survey information. Although the agronomic applications of soil information have long been recognized, the use of soil as a construction material, as a base for low buildings and other structures, as a basis for tax assessment, and for planning purposes and other uses required that a comprehensive system of soil classification be developed to serve as many of these needs as was practical. To meet these needs more adequately, the range in soil properties of the more broadly defined soil series was appropriately reduced.

For most soil interpretations, the range in properties of a soil series is not small enough to provide the degree of refinement necessary for use and management decisions. Mapping units are designed that include only a portion of the range in characteristics of a soil series. These phases of soil series are the bases for soil interpretations. Soil slope characteristics, amount of soil removed by erosion, soil depth and texture, and content of coarse fragments are common phase criteria. The practical limit for restricting ranges in the properties of mapping units is the point beyond which errors of observation in making soil surveys become nearly as great as the range in characteristics of one or more properties.

Cline (5) applied Mill's logic of classification (6) to soil. Some important elements of that logic follow.

1. Classification is a creation of man for a specific purpose and should be designed to serve that purpose.
2. Classification consists of creating classes by grouping objects and ideas on the basis of their common properties.
3. Classification should deal with existing knowledge.
4. As knowledge grows, classification must change to make use of new knowledge.

Soil Taxonomy was designed to conform to these principles.

Soil Taxonomy was developed through many approximations. Seven approximations with extensive changes were tested in the field, as well as many less extensive modifications in the categories and classes. The sixth approximation was the first relatively complete classification that could be adequately tested in the field. It included family differentiae so that series could be classified into the five higher categories of the system. Testing consisted of classifying soil series in families of subgroups and examining the components of the families. For most uses the interpretations for the soil series in any one family should be more similar than for any other grouping. Many changes in definitions resulted from this testing. The 7th Approximation included these changes and, in turn, was tested and modified before its adoption for use in the United States in January 1965.

Certain characteristics of a soil classification system are needed specifically to serve the objectives of soil surveys. The classification must first consider all the soil properties that affect soil use. It must consider soil genesis because the pedologist uses a knowledge of the genetic factors to make maps and interpretations more accurate. Soil scientists of diverse education and experience, working independently, should be able to classify soils in the same classes. Such uniformity can be achieved only if the application is objective rather than subjective, that is, objective in the sense that classification proceeds from the properties of the soils themselves and not from the beliefs of the pedologist about soils in general.

To be useful the classification must embrace all known soils. In particular it must include cultivated soils and other disturbed soils as well as virgin ones.

The system should be multicategoric; there should be few taxa in the highest category and a large number in the lowest to permit the arrangement and comprehension of soil information by classes at different levels of generalization. A multicategoric system provides an orderly scheme for remembering what is known about soils and provides convenient bases for designing mapping units for soil surveys and soil maps of different scales and different degrees of detail.

SOIL TAXA, PEDONS, AND POLYPEDONS

Soil taxa are conceptual; they are not the real soils that are classified. The taxonomy should link the real soils being classified and the soil bodies delineated on maps to the conceptual taxa. The building blocks of soil taxonomic classes and soil mapping units are called pedons. Pedons are real, natural soil volumes just large enough to show all the soil layers present and their relationships (7). Soil individuals, called polypedons, are the real objects that are classified (8). They are collections of contiguous pedons, all of which have characteristics lying within the defined limits of a single soil series, and are comparable to individual pine trees, individual fish, and individual people.

CLASSES

There are six categoric levels in Soil Taxonomy: orders, suborders, great groups, subgroups, families, and series. The highest category, the order, has 10 classes, the suborder category has 47 classes, and each succeeding category has an increasing number of classes. In the United States, 10 orders, 44 suborders, 185 great groups, and about 1000 subgroups, 5000 families, and nearly 11 000 series are known. The system is capable of expanding to include any soils that may be observed. As knowledge and experience with soils in the United States and other parts of the world increase, some classes will have to be redefined, some definitions elaborated, and some new classes established.

NOMENCLATURE

Early in the development of Soil Taxonomy, the need for an entirely new nomenclature for soil classes was recognized. Most classes in the 1938 classification were loosely defined and inconsistently used, and many names had become meaningless. Accordingly, names were improvised from appropriate Greek and Latin roots in order to make the class names as connotative as possible. The new nomenclature was also designed so that class names were indicative of the category in the system. In many languages, the new terminology requires little translation.

Categories

The names of the classes in each category are distinctive. All order names have "sol" for a final syllable, from the Latin solum. The suborder names consist of two syllables, the first identifying a common characteristic of the suborder and the second distinguishing the order. Great group names are formed by prefixing another formative element to the suborder name. Subgroup names are formed from great group names with one or more modifiers that indicate properties intergrading to some other class or to some aberrant soil property. The fifth category, the family, has a polynomial name based on criteria used to differentiate families. The sixth category, the soil series, is usually named after a community or geographic feature located close to the place where the soils were originally defined.

The following table gives the categories and the classification in Soil Taxonomy for two different soil series. Note that all Alfisols and Mollisols between the order and series categories have a suffix—"alf" or "ol"—derived from the order name.

Category	Classification
Order	Alfisol
	Mollisol
Suborder	Udalf
	Ustoll
Great Group	Hapludalf
	Argiustoll
Subgroup	Typic Hapludalf
	Aridic Argiustoll
Family	Fine-loamy, mixed, mesic Typic Hapludalf
	Fine, montmorillonitic, mesic Aridic Argiustoll
Series	Miami
	Richfield

Names in other orders are similarly derived.

Intergrades

Subgroups with properties that intergrade to other classes are named according to the basis of the intergrade. For example, Richfield soils are drier than members of the subgroup Typic Argiustoll. Thus, these soils intergrade to Aridisols, dryness being a property of that order. But if Richfield soils also crack widely on drying and have some vertisolic properties, a torrertic subgroup name would be appropriate because the Torrerts are Vertisols that occur in arid climates. If a soil is similar to a Typic Hapludalf but has more wetness characteristics than is permitted in the typic subgroup, the soils would intergrade to the Aqualfs. The name, however, is contracted to Aquic (rather than Aqualfic) Hapludalf. The names of intergrades to another order are never contracted because the basis of the intergrade is changed. For example, a soil too wet and with too dark a surface horizon for a Typic Hapludalf is classified as an Aquollic Hapludalf because the Aquolls have dark surface horizons and wetness characteristics. The rule is that adjective modifiers are as short as possible to indicate the basis of the intergrade.

Extragrades

Soils of some great groups have the properties of the typic or another subgroup except for one property. If this property is not that of a known kind of soil in a class of a great group or higher category, an extragrade is provided. For example, no classes in Soil Taxonomy are differentiated solely on the basis of shallowness, for uneven distribution of organic matter with depth, or for an overthickened surface horizon. If a typic subgroup definition excludes soils as shallow as 50 cm (19.5 in), soils with irregular distribution of organic matter with depth, or soils with a surface horizon thicker than 50 cm, lithic, cumulic, or pachic subgroups respectively are appropriate. Twenty-two kinds of extragrades are defined.

Soil Moisture Regimes

Five principal moisture regimes are defined in Soil Taxonomy. They are used to differentiate all four higher categories and, to some extent, the lowest category. This is to be expected because of the close relationship between moisture and vegetation and many soil properties. Buol's paper in this Record discusses the moisture regimes in some detail.

SOIL ORDERS, SUBORDERS, AND GREAT GROUPS

A brief review of the major properties of the classes in the three higher categories of Soil Taxonomy follows. In general the soils are discussed in order of increasing degree of weathering.

1. Histosols are soils derived mainly from organic soil materials. Except for the Folists, the soils in all suborders were developed when some or all of the soils were saturated with water. The Folists have less than 1 m (3.3 ft) of organic material overlying bedrock and are rarely saturated with water. The Fibrists, Hemists, and Saprists are distinguished on the basis of the decomposition of the surface organic layers. Great groups are separated on the basis of soil temperature or kind of organic materials.
2. Entisols are recently deposited or recently exposed soils that have not been in place or exposed to weathering long enough for much to happen to them. These soils occur in all climatic regions. Suborders are established because of wetness, disturbance by man, sand content, stratification, and moisture regime.
3. Vertisols are clayey soils that occur in environments where the soils develop deep, wide cracks during periods of dryness. Because soil falls down the cracks and the soils tend to remoisten from the base of the cracks up, some churning of these soils results. This mixing of the soil is sufficient to prevent any appreciable horizon differentiation. Suborders are based on moisture regimes and great groups on the chroma of the upper 30 cm (12 in). The higher chroma Vertisols are better aerated than those having lower chroma.
4. Inceptisols are characterized for the most part by indistinct horizons. Most are believed to be young soils, but some that are composed of very stable minerals may be very old. They are found in most environments except those that are very dry. Vegetation is extremely variable between classes. Suborders are distinguished by wetness, presence of amorphous and vitreous material, manmade layers, high temperatures, light colors, high organic matter content, and low pH. Great groups are distinguished by their moisture and temperature regimes, presence or absence of distinctive horizons, and composition.
5. Aridisols are distinguished mainly by being usually dry or at least physiologically dry because of high salt content. Suborders are distinguished on the basis of the presence or absence of a horizon of clay accumulation. Great groups have different kinds of horizons, such as duripan (silica-cemented), petrocalcic (carbonate-cemented), and salic and gypsic horizons.
6. Mollisols have dark-colored surface horizons that are rich in bases. Most of them developed under grass, which returns a copious supply of plant residues to the upper soil. The soils are naturally fertile but, under continuous cultivation, respond well to suitable fertilizers. They occur most commonly in subhumid to semiarid areas of the midlatitudes of all continents. Of the seven suborders, four are separated on the basis of their moisture regimes, one because it is cold, one because of high $CaCO_3$ content, and one because of profile characteristics. Great group separations are based on the presence or absence of distinctive horizons.
7. Spodosols have either a horizon in which amorphous mixtures of organic matter and aluminum have accumulated or, less commonly, a thin, black or dark reddish pan cemented by iron or iron-manganese, or an iron-organic matter complex is present. At undisturbed sites, the upper mineral layer is usually gray or light gray. The soils occur in cool to hot, humid climates. Four suborders are recognized on the basis of wetness and the ratio of free iron to carbon. Great groups are separated on the basis of cold temperatures, the minimal difference between mean summer and winter temperatures, and cemented or compact pans.

8. Alfisols are intermediate in many properties between Mollisols and Ultisols. All Alfisols have a zone of clay accumulation and do not have the dark surface horizon that characterizes the Mollisols. Alfisols contain fewer bases than Mollisols but more than Ultisols. In general, they are more erodible than Mollisols when cultivated, have a higher fertilizer requirement, and are not in an environment favorable to the accumulation of organic matter. Some Alfisols have silica-cemented layers (duripans) and dense layers (fragipans), both of which are absent in Mollisols. Four suborders of Alfisols are distinguished on the basis of moisture regime and one on the basis of low temperature. Great groups are distinguished by the presence or absence of distinctive horizons. Alfisols are found in most environments except those that are usually dry.

9. Ultisols contain translocated clay but are relatively low in bases. Thus, the soils respond well to suitable applications of fertilizers. Ultisols are extensive in warm, humid climates. One suborder is distinguished on the basis of the organic matter content of the upper portion, but the other suborders are distinguished by moisture regime. Great groups are distinguished by the kind and distinctness of horizons.

10. Oxisols are old soils that have low cation exchange capacity of the fine-earth fraction, low cation retention, and no more than traces of primary aluminosilicates at depths above 2 m (6.5 ft), or they have an iron-rich mixture of clay, quartz, and other diluents with a mottled appearance (plinthite) that forms a continuous phase within 30 cm (12 in) of the soil surface. Plinthite changes irreversibly to an ironstone hardpan or to irregular aggregates on exposure to repeated wetting and drying. Without amendments the soils are unproductive. Most Oxisols are in tropical and subtropical, moist environments. Suborders are separated on the basis of kind of moisture regime and organic matter content of the upper part of the soil. The bases for separating great groups are surface and subsurface accumulation of humus, very low cation retention, presence of plinthite or gibbsite, and cation exchange capacity.

SUBGROUPS, FAMILIES, AND SERIES

The great groups of all orders are subdivided into subgroups on the basis of intergrades to other classes and extragrades, as previously described. The central concept of the great group defines the type subgroup and is divided by restricting the limits of the great group definition, just as great groups are defined by segmenting the suborder definition and suborders are segments of orders. For example, the Hapludalfs are those Udalfs that have no more than 15 percent tongues of albic material (uncoated mineral grains) in the argillic horizon; have 5°C (41°F) or more difference between mean summer and mean winter temperatures; lack a fragipan, a natric horizon, or an agric horizon; and have a specified kind of argillic horizon. With respect to tonguing, the Typic Hapludalfs are defined as having almost none. Those with as much as 15 percent tonguing are classified as Glossic Hapludalfs, whereas those with 15 percent or more would be classified in a subgroup of Glossudalfs, assuming that all other properties are the same. Differences between mean summer and mean winter temperatures separate the Tropudalfs and Hapludalfs. By placing additional restrictions on properties of the typic subgroup—for example, depth or base saturation—provision can be made for lithic or ultic subgroups. Whereas a great many subgroups are possible in each great group, differences must be great enough that the soils can be separated in the field and that differences in use and management are significant at the subgroup categoric level.

Differentiae for families are based on classes of particle size, mineralogy, calcareousness and reaction, temperature, depth, slope, consistency, coatings of silt and clay, and cracks. Two to four differentiae are commonly used to describe a family, but the number and differentiae used vary between classes. Control sections to which differentiae for the classes apply are defined. Series differentiae include all differentiae that apply to the classes in higher categories that are appropriate for the series as well as some pertinent subdivision(s) of any of these differentiae. More than 60 percent of the families are represented by 1 series, 10 percent by 5 or more series, and about 2 percent by 10 or more series. However, the range of characteristics of a single series in a family covers only part of the range that is possible for the whole family.

MAPPING UNITS AND CATEGORIC LEVEL

Each category in Soil Taxonomy is intended to include all existing soils. The soils in classes at each categoric level are more uniform in their properties than they are between that level and other classes. Thus, map units can be designed as phases of any categoric level suitable to meet the needs of the soil survey. Where detailed planning information about contrasting soils is needed for areas as small as 1 hm^2 (2.5 acres), a map scale of about 1:20 000 is necessary. Most map units are phases of soil series. For planning larger areas such as counties, states, or regions, broader soil relationships are more important. For county planning, a map scale of 1:100 000 is common. Associations of phases of soil series are the commonest map units at this scale. For national planning, a map scale of 1:7 500 000 may be desirable with map units that are phases or associations of phases of great groups. The scale of the base map for soil surveys and the kinds of mapping units used are designed to fit the objectives of the soil survey. In general, the smallest scale map that can show the smallest delineations necessary to meet the objectives of the soil survey is selected because of ease of preparation and cost.

When soil maps of any scale are used, limitations in map preparation must be recognized. For example, the most detailed published soil surveys usually have a map scale of 1:15 840 or smaller. The minimum size delineation is usually about 0.5 by 0.5 cm (0.19 by 0.19 in) on the map, which represents about 1 hm^2 (2.5 acres) on the ground. Thus, on-site investigations are always needed before any construction is undertaken or small areas are planned for intensive use.

CONCLUSIONS

Soil Taxonomy makes it possible to classify all soils. Its structure serves equally well for organizing existing knowledge about soils for project planning and for relating test results and research to specific soil properties. Knowledge about soils can thus be increased in a structured manner that permits application of new knowledge in planning future projects. This has not been possible with previous systems of soil classification. Now ways must be found to use this capability to the fullest extent so that all disciplines can make maximum use of soil information.

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Diagnostic Soil Horizons in Soil Taxonomy

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This paper discusses the major kinds of soil horizons, their use in Soil Taxonomy, and their significance in engineering soil behavior. The characteristics of the soil in any place are a result of the combined influence of climate and living organisms on a specific kind of parent soil material, conditioned by relief, over a period of time. The combined effect of these factors is reflected in most soils as soil horizons of unique kinds. The presence or absence of kinds of soil horizons is an important criterion in the definition of classes in Soil Taxonomy. Each key soil horizon has a unique morphology that reflects its genesis and composition and a unique behavior due to its properties. Some soil horizons have accumulated clays, organic matter, or iron and other minerals. Other soil horizons have lost such materials. In the classification and mapping of soils, the pedologist studies the properties of each soil horizon in situ and, on the basis of this study, selects sites for obtaining samples of soils for characterization in the laboratory.

The diagnostic soil horizons more commonly referred to as the A, B, or C horizons are used as the building blocks of the soil classification system. They reflect soil weathering processes and are the result of the combined influence of climate and animal and plant organisms on a specific kind of soil parent material. Soil Taxonomy includes those inherent soil characteristics that affect plant root-soil relations and soil-engineering relations. J. S. Mill (1) wrote that the useful classification is one that uses the properties of constituent objects chosen to identify groups that are causes of, or at least sure marks of, many other properties. Soil horizons are the marks of many other properties. They are the link between Soil Taxonomy and soil genesis.

A soil horizon is defined as a layer that is approximately parallel to the soil surface. It has some sets of properties that have been produced by soil-forming processes, and it has some properties that are not like those of the layer just above or beneath it (2). Soil horizons are the marks that now exist in the soil that indicate the genesis of the natural soil. For example, a soil with an argillic horizon indicates a soil formed under a climate that enhanced rock weathering, leaching of the base, and a downward movement of clays.

The objective of this paper is to define some of the key soil horizons, explain their role in Soil Taxonomy, and relate their significance to engineering soil behavior.

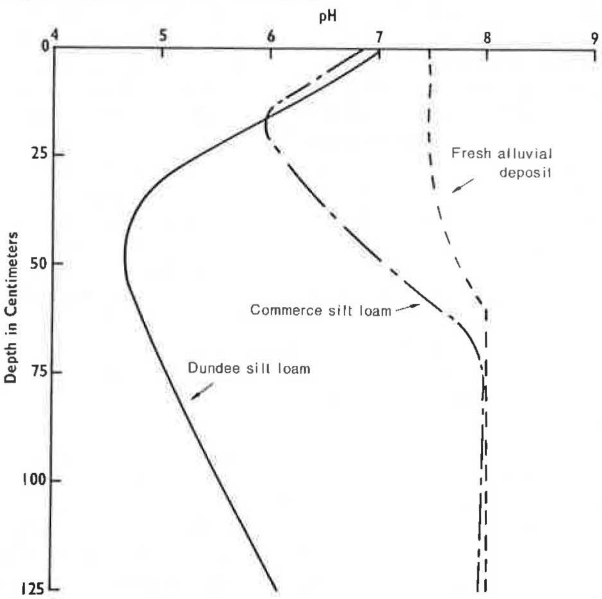
INTERPRETATIONS USING SOIL TAXONOMY

Soil Taxonomy has enhanced soil-use interpretations because of the many soil-engineering and soil-plant relations interwoven throughout the system. The diagnostic horizon encompasses both the effect of soil genesis and, indirectly, the impact on soil behavior. The most precise predictions are made at the phase level of the soil series. These units are more precise because they are based on additional criteria such as slope, surface texture, and soil temperature. The diagnostic horizons are used in the higher categories to define broad soil groups. The more exact quantitative definitions introduce a higher degree of standardization in the A, B, C horizon concept than that found in former systems. This avoids subjectivity in definition and allows for greater consistency and for easier comparison between soils of different areas. The system is also better equipped to facilitate the transfer of research information from one area to another. All of this leads to increased effectiveness in using soil surveys for planning and building better road systems and other engineering works.

SELECTION OF CRITERIA

Diagnostic horizons are used as criteria in Soil Taxonomy because they are the result of the soil weathering process. Soil weathering encompasses those processes that produce the natural soil in situ. The natural soil is born as soon as earthy material is exposed to the soil-forming elements. The effects vary. Water moving freely through calcareous soil material begins to move soluble calcium carbonates out of the soil system. Figure 1 shows how pH or soil acidity changes with depth in three soils in Tensas Parish, Louisiana (3). The oldest soil, Dundee silt loam, is estimated to be 3000 years old and has the lowest pH. It has a B horizon that meets the requirements of an argillic horizon. The fresh alluvial deposits have no reduction, and the Commerce silt loam is in between in age and has experienced some leaching. The B horizon in the Commerce soil classifies as a cambic horizon. No clay

Figure 1. pH of soils of differing ages.



translocation is noted in these soils.

The process of soil weathering becomes much more complex with time. Rocks weather to release minerals, organic matter is added, plant roots penetrate deeper, and minerals and salts are translocated from one part of the soil profile to another and sometimes moved completely out of the soil system. The processes that go on in soils can seldom be seen or measured (4), but the effects of at least some of the dominant processes can. Some processes produce horizons whereas others tend to prevent horizon formation. For example, downward-moving water carries suspended or dissolved materials and tends to produce B horizons; opposing processes of churning and "self-swallowing," prominent in the expansive Vertisols (4), tend to mix horizons (the absence of B horizons is definitive of Vertisols).

Simonson (5) has observed that a very important lesson in the development of soil classification in the United States is that soil characteristics exist in combinations. For example, strongly leached A-2 horizons occur with clayey B horizons. The diagnostic horizons are used to produce groupings in which the same present or past soil-forming processes have been dominant. Many of the diagnostic horizons take the form of A, B, and C horizons but with more precise definitions. For example, Spodosols are defined as having spodic horizons (horizons that have accumulated aluminum, iron, and organic matter), Alfisols have accumulations of clays and are named argillic horizons, and Mollisols have a mollic epipedon (surface horizon) that is dark-colored and high in organic matter. Calciustolls are recognized at the great group level by having calcic horizons. Although these classes of soils are too broad to correlate with American Association of State Highway Officials (AASHO) or Unified Soil Classification units, they do lead to groups of soils that can be correlated at the family and series levels.

The table below gives the syllables in great group names that indicate their respective diagnostic horizons.

Great Group	Syllable	Horizon
Argiabolls	arg	Argillic
Natralbolls	natr	Natric
Argiaquolls	arg	Argillic
Calciaquolls	calc	Calcic
Hapoloborolls	hapl	Minimum
Durixerolls	dur	Duripan
Fragiudalfs	frag	Fragipan

CHARACTERISTICS AND SIGNIFICANCE OF DIAGNOSTIC HORIZONS

Soil horizons have a unique relation to the engineering behavior of soils. The subsurface soil horizon is usually exposed by excavation during road construction. It may serve as the subbase or subgrade of the road, it has great influence on the design criteria and behavior of a road bank, and its nature is of value in estimating costs of excavations and cutting.

Most diagnostic horizons are subsurface horizons, but a few surface horizons, or epipedons, are used. The mollic epipedon is an important surface horizon because it is identified with some of the most productive soils in the world. It includes the A and B horizons of many of the prairie soils. The mollic epipedon is dark-colored, high in organic matter, and usually thicker than 18 cm (7 in) and friable. Other important surface horizons are the umbric epipedons, which are similar to mollic epipedons but have a lower base saturation and consist mostly of the A-1 horizons of timbered swamps in the southeastern United States, and the histic epipedons, which are thin surface horizons of peat or muck that occur in marshy and swampy areas.

These surface horizons are high in organic matter, which results in an engineering behavior in many that is equivalent to that of the A-7 or OH and OL soils of the AASHTO or Unified Soil Classification units. The mollic and umbric horizons are not always saturated with water but have received enough moisture to support luxuriant plant growth. The histic epipedon is saturated with water most of the time, has very high compressibility, subsides when drained, and classifies as OH or OL soil. The light-colored A horizons developed under forest vegetation are named ochric epipedons and are low in organic matter.

Most soil horizons that occur below the surface of the soil are considered B horizons and are closely related to the genesis of the soil. The B horizon is in part a layer of change from the overlying A to the underlying C horizon. The B horizon also has distinctive characteristics caused by soil-forming factors, such as an accumulation of clay, humus, sesquioxides, or some combination of these or a blocky structure, redder colors than the A horizon, or some combination of these.

An argillic horizon, which is an illuvial horizon in which clays have accumulated, is a very common soil horizon that occurs in many parts of the United States. The major soil orders Alfisols and Ultisols are characterized by argillic horizons. An argillic horizon is formed by clay moving from one horizon to another or from one point to another within a horizon. The clay is carried by water from the surface and near-surface horizons and is deposited on surfaces of soil aggregates or sand grains as the mixture dries. This means that a substantial amount of water has moved through the soil. Soils with argillic horizons occur in warm climates that have enough rainfall for effective leaching. The use of this horizon at a higher categorical level in the system has produced groupings of soils that have the largest number of common properties important to the use of the soil. These horizons are usually more clayey than any other part of the soil. Figure 2 shows the distribution of clay with depth in a typical Alfisol, and Figure 3 shows the clay distribution of an argillic horizon in a much older Ultisol. The clays in argillic horizons are also typically finer and more active than clays in other portions of a soil profile. Argillic horizons that contain high proportions of the more active 2:1 lattice clays make poor subbase or subgrade materials. In sandy soils, however, argillic horizons have enough clay for the binding necessary in good subbase materials.

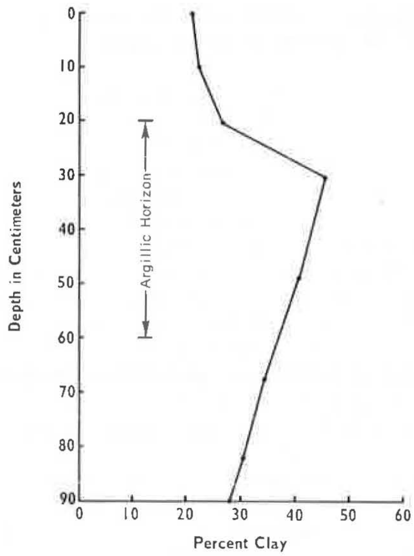


Figure 2. Distribution of clay with depth in typical Alfisol.

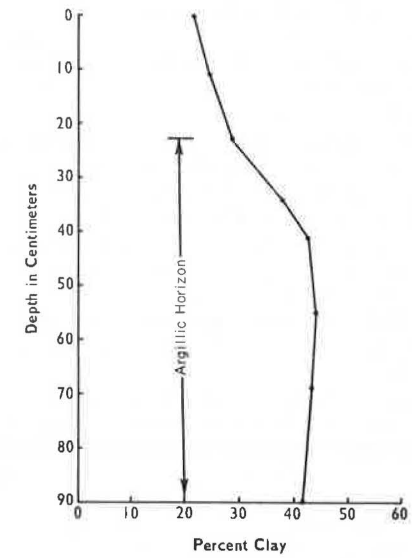


Figure 3. Distribution of clay with depth in typical Ultisol.

The natric horizon—a special kind of argillic horizon that is high in sodium—is another important B soil horizon, mainly because of its poor physical properties. Soils with natric horizons are more common in the more arid states of the Great Plains but also occur along the southern Mississippi River Valley. The material in these soil horizons is poorly suited for road base material. Soils with these horizons usually test A-7, have low traffic-supporting capacity, and are trouble spots in the location of road systems.

The spodic horizon is an accumulation of organic matter and aluminum with or without iron, formed by downward-moving water that carries the organic material. These B horizons, formed under pine forests, occur in both warm and cold climates. The material is usually precipitated at the upper limits of a fluctuating water table and is very active. It has high exchange capacity, large surface area, and high water retention when not cemented. The material in the less sandy spodic horizons behaves much like OM or OL soil material and makes very poor subgrade material.

Cambic horizons are also subsurface horizons that are altered through soil weathering. These too are identified as B horizons, but they have a sandy loam or finer texture and are less altered than the diagnostic horizons discussed above. There is no evidence of clay translocation in cambic horizons. The evidence of alteration includes the soil structure; chemical changes caused by wetness, such as dull grey colors and mottling; movement of carbonates; and browner or redder colors than those found in the parent material. The pH curve of Commerce silt loam in Figure 1 is an example of a slightly weathered cambic horizon. The cambic horizon is indicative of a soil that exhibits very little alteration. Such a horizon may occur in a young soil that has not been in place very long or in a soil on a steep slope or in any other location where the natural process of clay translocation is preempted by other forces such as soil erosion and soil creep. The engineering behavior of the soil material in cambic horizons is very similar to that of the parent materials. These horizons may range in the AASHO classification from A-2 to A-6.

The oxic horizons, which are the B horizons of soils common in tropical regions, are mineral subsurface horizons in an advanced stage of weathering. They are a mixture of hydrated oxides of iron or aluminum or both and variable amounts of 1:1 lattice clays. Oxic horizons generally are found in soils of very old, stable, geomorphic surfaces. Whatever the materials, the great age of the oxic horizon has allowed time for so much soil weathering that the horizon retains almost no vestige of the original rock structure. Analyzing the particle-size distribution in an oxic horizon is difficult: Some oxic horizons have silt- and sand-size aggregates of clay that are not easily dispersed but that contribute to the cation exchange capacity and other aspects of behavior common to the clays. The materials in oxic horizons are stable and very porous in place and have high bearing capacity. Once disturbed, however, they behave much differently: They are difficult to compact, unstable, and highly susceptible to slippage and other movement. The normal engineering tests on these soils can be misleading. The tests may indicate sands and silts with little clay, but the behavior may be like that of fat clays. It is not possible to indicate the engineering properties accurately from the engineering classification. Many of the tests show a CH classification in the laboratory, but in situ behavior of the soils is more like that in an SM classification.

The duripan is a subsurface horizon cemented by silica. Duripans may also be cemented by iron oxides and calcium carbonates. These horizons are always brittle, even after wetting, and they are common in the arid and semiarid climates of the western United States. They are difficult to sample and to test in the laboratory. When in place and not disturbed, they behave like rock, but they are rippable and, when properly crushed, make good road base material.

A fragipan is another kind of brittle subsurface horizon. Fragipans, identified as B and C horizons, have high bulk density and loamy texture and are seemingly cemented when dry. They are very difficult to excavate. When they are moist, the material is softer and easier to crush. Soils with these horizons occur in the more humid sections of the United States. The significance of these soil horizons is that they are nearly impervious and, because they create excessive wetness during rainy periods, they can cause problems in highway performance. Water stands above the pan in a level soil and moves laterally along the top of the pan if the soil is sloping, creating seep lines in road cuts. In the colder regions soils with these horizons are very susceptible to frost heaving.

The calcic horizon, another form of B horizon, is an accumulation of calcium carbonate or of calcium and magnesium carbonate. This accumulation may occur in the mollic epipedon, an argillic or natric horizon, or a duripan. These horizons occur mostly in soils of arid and semiarid regions and indicate the depth of water movement. In soils rich in carbonates, the calcic horizon tends in time to become plugged with carbonates and cemented into a hard, massive, continuous horizon that is called petrocalcic. In engineering behavior this horizon simulates hard country rock.

The diagnostic horizons may not have a direct bearing on soil behavior, but they are important building blocks of the system. They are used to group together soils that have something in common that is eventually expressed in the unique behavior of the soil. For example, argillic horizons indicate an accumulation of transported clay; they do not reflect kind and amount of clay, which strongly influence engineering behavior. Kind and amount of clay are reflected in the lower categories of the system, namely, family and series. Thus, there are many kinds of soils that have different engineering properties but that all have argillic horizons.

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Soil Moisture and Temperature Regimes in Soil Taxonomy

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Soil moisture and temperature regimes have been used as criteria for the classification of soils in the United States since the National Cooperative Soil Survey adopted Soil Taxonomy in 1965. The quantitative criteria used to define soil moisture regimes are based on the depth, probable duration, and seasonality of soil saturation and vegetation-restricting soil dryness. Soils with morphological evidence of frequent surface flooding are identified. Soils with extremely low bearing strength because of the interaction of their mineral and organic components with ambient high moisture contents are also taxonomically identified. Criteria for soil temperature regimes encompass the mean annual soil temperature and the amplitude of the change in soil temperature from summer to winter. Permafrost conditions are identified. Limited ranges for each of these soil temperature and moisture properties are defined and readily identified by connotative formative elements in the formal taxonomic name of each soil classified in modern soil surveys.

Historically, the study of temperature and moisture conditions affecting plant growth has been ascribed to the science of climatology or meteorology. Earlier, and some current, attempts to classify soils did not deal directly with soil temperature or moisture content except as they related to the chemical or mineralogical properties of soil. Soil scientists have recognized since the late 1800s that temperature and moisture regimes are closely related to soil properties. In 1965, the U.S. National Cooperative Soil Survey officially began to use direct criteria of soil moisture and temperature in its taxonomic criteria. Although this was a break with the long-standing tradition of not using soil moisture and temperature data for classification, it could be logically argued that a given soil, or given site, had distinct temperature and moisture regimes. Even though these factors were closely related to climatic conditions, the relation was no more indirect than, for example, the association of sandy soils to sandy parent materials, i.e., sandstones and sandy alluvial sediments. Furthermore, soil temperature and moisture could be measured. It was well known that these parameters of a soil varied with time of day and from day to day, season to season, and year to year. It was thus apparent that the use of soil temperature and moisture data in a soil taxonomic system would require criteria based on absolute ranges and probability (3).

One of the roles of the National Cooperative Soil Survey is to provide an inventory of the possible uses of land in the United States. Because much of our land is used for the growth of food and fiber, the soil moisture and temperature criteria used to classify the soil must have some direct interpretation for the growth of plants. Much of our land is also used for buildings and roads, and moisture and temperature conditions at any given site are an integral part of the planning for such condition (1). Flooding, bearing strength, and permafrost are some of the features of direct concern.

SOIL TEMPERATURE CRITERIA

Temperatures near the surface of the soil fluctuate diurnally, seasonally, with the amount and type of plant cover and the amount of water present in the soil. The magnitude of the fluctuations decreases with depth. However, at a given site, the mean annual temperatures at all soil depths, and even below the soil profile, differ only slightly (6). The mean annual soil temperature (MAST) is related most directly to the mean annual air temperature. Daily temperature variations are detect-able to a depth of about 50 cm (20 in). To avoid time-of-day variations, measurements of soil temperature are taken at this depth. Because short-term weather events may influence soil temperatures at 50 cm (20 in), antecedent weather is considered for individual measurements.

One major distinction is made with respect to soil temperature: Those soils for which the mean soil temperature of the three warmest months differs from the mean soil temperature of the three coldest months by less than 5°C (9°F) are referred to as iso and are separated from those soils for which the temperature difference is greater than 5°C (9°F). Except for small areas where the climate is greatly modified by the oceans, these iso areas are confined to the intertropical zone. In the United States iso-temperature soils are found in Puerto Rico, Hawaii, and some coastal areas of California.

Soil temperature regimes in noniso areas and their limits are given in the tables below. The following table gives the characteristics of regimes for which mean winter and summer soil temperatures vary by more than 5°C (9°F).

Regime	MAST
Hyperthermic	>22°C (>72°F)
Thermic	15 to 22°C (59 to 72°F)
Mesic	8 to 15°C (47 to 59°F)
Frigid	<8°C (<47°F) but not cryic or pergelic
Cryic	0 to 8°C (32 to 47°F)
Pergelic	<0°C (<32°F) and permafrost present

Mean annual soil temperatures cited above for soils of the cryic regime depend on the following conditions: (a) not water-saturated [with leaf cover mean summer temperature <8°C (<47°F)]; (b) not water-saturated [without leaf cover mean summer temperature <15°C (<59°F)]; (c) water-saturated in summer [without leaf cover mean summer temperature <13°C (<55°F)]; (d) water-saturated in summer [with leaf cover mean summer temperature <6°C (<43°F)]; (e) organic soils frozen at some depth 2 months after summer solstice or influenced by ocean water.

Characteristics of regimes for which mean winter and summer soil temperatures vary by less than 5°C (9°F) are as follows:

Regime	MAST
Isohyperthermic	>22°C (>72°F)
Isothermic	15 to 22°C (59 to 72°F)
Isomesic	8 to 15°C (47 to 59°F)
Iso Frigid	<8°C (<47°F)

The limits placed on the soil temperature groups were selected to correspond in a general way with the geographic range of major crop plants in the United States. Hyperthermic soils are essentially those in which it is possible to grow citrus successfully. Thermic soils encompass the cotton-growing areas. There is little hazard of frost heaving in construction in these soils. Mesic soils in the United States extend north to the approximate colder limit of corn-growing areas. Frigid soils occur in the still colder areas. Cryic soils are a special condition in the frigid areas that have extremely cold summer temperatures that essentially preclude crop production, while certain crops having a short growing season are possible in frigid soils. Frost heaving is a very real problem in construction in mesic, frigid, and cryic soils. Pergelic soils have permafrost.

SOIL MOISTURE CRITERIA

Water alternating with air occupies the void areas formed by the imperfect fit of the solid particles in the soil. Void volume composes about 50 percent of most soils but ranges drastically depending on particle-size distribution and natural aggregation of the solid particles. The tension with which water is retained in the soil voids is the basis for classifying the various states of soil water.

In Soil Taxonomy three states of soil water are considered. At the dryer end of the range is unavailable water, when soil moisture tension is greater than 1.5 MPa (15 bars) and water is largely not available for plant growth. This soil moisture state is considered dry. The saturated state occurs when there is no tension on the water and all the void space is filled with water. Available water is that water held in the soil at water tensions between 0 and 1.5 MPa (0 and 15 bars) (Table 1). Part of this water [about 0 to 0.03 MPa (0 to 0.3 bars)] drains under the force of gravity and is sometimes referred to as gravitational water. The duration and depth at which each of these soil water states occurs in a given soil are then used to define the various moisture regimes in Soil Taxonomy.

Moisture Control Section

The depths in the soil at which soil moisture criteria are established are defined by the concept of the moisture control section. The upper boundary of the moisture control section is the depth to which a dry soil will be moistened in 24 h after a 2.5-cm (1-in) rain. The lower boundary of the moisture control section is the depth to which 7.5 cm (3 in) of water, introduced through the soil surface, will moisten a dry soil in 48 h or the depth to a root-restricting layer such as hard rock, whichever is shallower. Because of the general relation of void size to particle-size distribution, rough estimates of the control-section depths are (a) between 10 and 30 cm (4 and 12 in) in soil material with either more than 18 percent clay or more then 50 percent silt and less than 15 percent sand, or both; (b) between 20 and 60-cm (8 and 24-in) depths in textures coarser than those given above but less than 70 percent sand if there is no clay or less than 15 percent clay and no silt; (c) between 30 and 90-cm (12 and 35-in) depths if the soil material has more than 70 percent sand and no clay or less than 15 percent clay and no silt. Although cumbersome at first glance, this definition permits rapid computer modeling of soil moisture regimes from soil properties and long-term weather records, which then permits probability predictions of the moisture regime of all soils. In the computer models it is assumed that some part of the moisture control section will be dry after evapotranspiration exceeds rainfall by 7.5 cm (3 in) and all of the control section will be dry after evapotranspiration exceeds precipitation by 17.5 cm (7 in). [A program in COBOL can be obtained on tape or printout from the Soil Conservation Service of the U.S. Department of Agriculture.] Specific soils have to be evaluated to account for runoff and runon.

Criteria for Soil Moisture Regimes

The following soil moisture regimes are identified for use in Soil Taxonomy.

1. Aridic or torric moisture regimes include those soils that have moisture control sections completely dry more than one-half of the time and never moist in any part for as long as 90 consecutive days when the soil temperature at 50 cm (20 in) averages more than 8°C (47°F). In the United States these areas are mainly in the desert Southwest.

2. Ustic moisture regime soils have moisture control sections that are dry in some parts more than 90 cumulative days in 6 out of 10 years. If the mean annual soil temperature is less than 22°C (72°F) and mean summer

Table 1. Soil moisture relations.

Atmospheres (approximate)	Tension (MPa/g)	Soil Moisture Constant	State of Soil Water
10 000	980	Oven dry at 105°C (223°F)	Unavailable water; most plants cannot extract water (dry); pore diameters less than 0.2 μm
15	1.5	Wilting point of many plants	Available water; most plants can take up water held by soil pores larger than 0.2 μm in diameter
0.1 to 0.3	0.08	Field capacity gravitational drainage almost imperceptible	Gravitational water; water moves in response to gravity; plants can use water but pores larger than about 10 μm in diameter drain rapidly under gravitational force
0	0	Saturation, all voids full	Saturated flow, either anaerobic or aerobic, depending on biological activity and duration of saturation

Note: 1 Pa = 1 x 10^{-5} bar; 1°C = (1°F - 32)/1.8; 1 μm = 4 x 10^{-5} in.

Table 2. Use of soil temperature and moisture regimes in soil names.

Regime	Order	Suborder	Great Group	Subgroup	Family
Aridic	Id	Torr	Torr (torri)	Torric[a], torr, aridic	
Ustic		Ust	Usti	Usti[b] (ust)	
Xeric[c]		Xer	Xer (xero)	Xeric[d] (xer)	
Udic		Ud	Ud (udi)	Udic, ud	
Aquic	Ist[e]	Aqu[f]	Sal[g]	Aquic[h] (aqu)	
Flooding		Fluv	Fluv	Fluvic (fluv)	
Low bearing			Hydra		
Pergelic				Pergelic	
Cryic			Cry (cryo)		
Frigid			Bor (boro)	Boric, bor	Frigid[i]
Mesic	Ult[j], ert[j]		Medi[k], medo		Mesic
Thermic			Medi[k], medo[k]		Thermic
Hyperthermic			Medi[k], medo		Hyperthermic
Iso		Trop[l]	Trop[l]	(Tropic)[l]	Iso

[a] Some part of moisture control section dry more than 60 percent of the time in most years.
[b] Ust (ustic) in Aridisols means part of control section moist 25 to 50 percent of the time.
[c] Also < 22°C (< 72°F) MAST if mean summer soil temperature differs more than 5°C (9°F) from mean winter soil temperature.
[d] Xer (xeric) in an Aridisol order may have control section moist 25 to 50 percent of the time.
[e] Ist means Histosol (organic soil) that is saturated, unless artificially drained or in a constantly humid environment recognized as folist.
[f] With aeric in subgroup these soils have deeper saturated zone than in typic subgroup.
[g] Saturated with high-salt-content (saline) water.
[h] Saturation and reduction at greater depth in the soil than when used at suborder level.
[i] Not in families where bor, cry, or pergelic appear at higher level.
[j] Ultisols and Vertisols are mesic, thermic, or hyperthermic, or iso equivalent.
[k] In Histosols (organic soils) med formative element covers everything with MAST > 8°C (> 47°F) and not iso.
[l] Presence of trop means iso, but its absence does not mean not iso.

and winter temperatures differ by more than 5°C (9°F), they are not dry in all parts for more than 45 d in the 4 months following the summer solstice in as much as 6 out of 10 years. These areas of the United States are in the western part of the Great Plains.

3. Xeric moisture regime soils have completely dry moisture control sections more than 45 consecutive days in the 4 months following the summer solstice in at least 6 out of 10 years and are not aridic. Most of these areas are in California, Oregon, and Washington.

4. Udic moisture regime soils have moisture control sections that are not dry, in any part, as long as 90 cumulative days in most years and not dry throughout for as much as 45 consecutive days within 4 months after the summer solstice in more than 6 of 10 years when the soil temperature is above 5°C (41°F). In the United States these areas are generally east of 95° longitude.

5. Aquic moisture regime soils have control sections saturated with water for a sufficient period of time during the year when soil temperatures are above 5°C (41°F) so that reducing conditions will develop that will cause iron to reduce to the ferrous form. These soils can occur in any part of the world where there is a seasonally high water table. Where these soils are subject to freezing, they are susceptible to severe frost heaving (7). In such soils every effort should be made to lower the water table in relation to the grade of a road.

6. Peraquic moisture regime soils are saturated near the surface all year, as in tidal marsh.

Special Moisture Regime Categories

Some soils that are normally saturated with water have very low bearing strength. When this condition becomes severe enough it precludes the grazing of livestock. Such a condition severely limits the use of conventional vehicles. In addition to field observation, the following formula is used to identify these soils:

$$n = (A - 0.2R) + (L + 3H) \quad (1)$$

where

A = percentage of water on an oven-dry-weight basis in the natural state of the soil,
R = percentage of solid material between 0.002 and 2 mm (0.07×10^{-3} and 0.07 in),
L = percentage of solids <0.002 mm ($<0.07 \times 10^{-3}$ in), and
H = percentage of organic matter.

Where the n value exceeds 0.7 the soil behaves as a liquid, squeezes from one's grip when examined in the field, and will not normally support animal or normal vehicular traffic. Such soils are classified in hydric subgroups.

Flooding is a characteristic of many soils. Flooding can of course be observed during the actual event. However, flooding events are often infrequent and may not occur for several consecutive years. However, flooding leaves distinct features in the soil profile that can be observed by careful morphological observation. Thus, it is possible to detect, from observation and analysis of the soil profile, if that soil has been subject to flooding and is therefore subject to future flooding (2, 4). In the normal processes of soil formation organic matter is deposited on the soil surface. When flooding occurs this surface is rapidly buried by mineral material not enriched with organic matter. Thus, while most soils show a regular decrease in organic matter content with depth, soils subject to flooding show an irregular decrease. This irregular decrease in organic matter content with depth, along with associated color and often textural stratification, identifies these soils. Such flood-prone soils are named fluv or fluvic, a shortened form of fluvial in Soil Taxonomy.

USE OF SOIL MOISTURE AND TEMPERATURE REGIMES IN SOIL TAXONOMY

Soil moisture and temperature are only two of the many soil characteristics used to classify soils in Soil Taxonomy. The relative significance of each soil characteristic in combination with the other ambient characteristics determines at what level in Soil Taxonomy that particular characteristic is assigned in the nomenclature (see the paper by Johnson and McClelland in this Record). Strict quantitative rules and keys are used to determine the soil name. Thus, depending on the other soil characteristics, the same characteristic may appear at a different position in the soil name.

Table 2 attempts to give all the ways in which soil moisture and temperature parameters are used in the nomenclature. Most of the moisture regimes are rather uniformly used at suborder, great group, or subgroup levels. Soils that have aridic moisture regimes and certain other profile characteristics are in the Aridisol (id) order. However, a floodplain soil in an aridic area would be recognized for its flooding Fluvent at the suborder level and later for its aridic moisture regime as a Torrifluvent at the great group level.

Most of the soil temperature regimes are identified at the family level, but there are some notable departures from this procedure. Where specific features of the frigid regime, cryic and pergelic, are used to identify the soil at a great group or subgroup level, frigid is omitted in the family name. Also, if boric (boro or bor) is used at a higher level, frigid is omitted in the family name. A soil not having any of these features may still be frigid, in which case frigid appears as a family name.

Two soil orders, Vertisols and Ultisols, are confined to mean annual soil temperatures warmer than 8°C (47°F). Also Histosols, organic soils with a mean soil temperature regime warmer than 8°C (47°F), carry the great group formative element medi (medo) if mean summer and mean winter temperatures differ by more than 5°C (9°F) or tropo if they differ by less than 5°C.

The element iso is used to modify any family temperature names where the difference between mean summer and mean winter temperatures is less than 5°C (9°F). Some soils with iso temperature regimes are also identified by the formative element tropo (trop) in either the suborder or great group position or tropic in the subgroup position. Iso is still used in the family name of such soils because many soils with iso temperature regimes do not carry the formative element tropo.

Using the nomenclature of Soil Taxonomy to identify soil moisture and temperature requires some familiarity with the connotative formative elements. Once a user has a working knowledge of these elements he or she can quickly see the taxonomic name of the soils in a given soil survey area and identify these characteristics. For example, a Typic Hapludult is clayey, kaolinitic, and thermic, with a udic moisture regime (suborder ud), a mean annual soil temperature between 15 and 22°C (59 and 72°F), and mean summer and mean winter temperatures that differ by more than 5°C (9°F) (thermic family). A Typic Ochraquult is clayey, kaolinitic, and thermic and has an aquic moisture regime (suborder aqu). Soil temperatures are in the same range in both soils. A Typic Torrifluvent, a fine-loamy, mixed, thermic soil, (a) is subject to flooding (fluv), (b) is usually dry (torric indicating aridic moisture regime), and (c) has a mean annual soil temperature between 15 and 22°C (59 and 72° F) (thermic).

SUMMARY

Categories of soil moisture and soil temperature are recognized and used to classify soils in Soil Taxonomy. All of these categories are identified in the proper name of a given soil. Some of these parameters are readily seen but, because they occur at different levels in the system, a user needs to have some familiarity with the system of nomenclature.

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Particle Size and Mineralogy in Soil Taxonomy

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Particle size and mineralogical composition are fundamental criteria for grouping series into families of mineral soils. The compositional data are averaged over a discrete thickness of soil, usually the upper 0.25 to 1 m (10 to 40 in), referred to as the control section. Averaging the data through a control section and relying on compositional rather than genetic factors for soil classification both significantly improve the applicability of Soil Taxonomy for use by engineers. Several suggestions are made for further increasing its usefulness, including (a) distinguishing at the family level certain problem soils such as loess, perhaps by including density as a criterion; (b) emphasizing the depth and kind of bedrock when the rock is deeper than the present depth cutoff at 0.5 m (20 in); and (c) recognizing the dominant clay mineral when the clay content is less than the present cutoff at 35 percent.

This paper concerns compositional aspects of the new system of taxonomy for mineral soils. Soil composition, of course, has a high degree of relevance in civil engineering. Categories in the new Soil Taxonomy, from highest to lowest level, and populations currently recognized in each category are as follows:

Category	Population	Category	Population
Order	10	Subgroup	970
Suborder	47	Family	4 500 (U.S.)
Great group	185	Series	10 500 (U.S.)

Particle size and mineralogical characteristics of soils are fundamental for distinguishing families of mineral soils within subgroups. As pointed out in Soil Taxonomy (1), families and the lower category, series, serve purposes that are largely pragmatic. The pragmatism of the soil series lies in its use as an important component of the basic mapping unit appearing on published soil survey maps. But soil series are named for localities and thus are not very descriptive. A series name such as San Saba or Houston Black, for example, may convey little to anyone who has not experienced or excavated or built on or gotten stuck in these Texas pearls (2). The soil order Vertisol, or inverted soil, tells much more and implies a certain instability for volume change. Figure 1 shows such a severely expansive soil, the result of vertical mixing by soil sloughing into shrinkage cracks. In Figure 2, an example is shown of the slickensides that often characterize the individual ped faces of Vertisols and that indicate severe shearing disturbances as a result of expansion pressures.

A suborder name such as Ustert may say something about the climate, in this case seasonally hot. Further down in the classification a great group name such as Pellustert may indicate color, in this case black or gray, in what were previously referred to as Black Cotton soils, Rendzina soils, and Grumusols. Note that the name Pellustert designates the order (Vertisol), suborder (Ustert), and great group (Pellustert). The particle-size class, clayey, has the advantage of being both directly descriptive and in English, and the mineralogy class, montmorillonitic, flags the real problems. The latter terms will occur within descriptions of individual series, but they are essentially family descriptors.

Family differentiae for mineral soils are listed in Soil Taxonomy as follows: particle-size classes, mineralogy classes, calcareous and reaction classes, soil temperature classes, soil depth classes, soil slope classes, soil consistence classes, classes of coatings (of sands), and classes of cracks. That is, classes defined on the basis of variations in these properties are used to distinguish families of mineral soils within a particular subgroup.

It may be noted that the new Soil Taxonomy is modeled from biological classification and uses some of the same words. There is an important distinction between soil and biological classifications: In biological systems, evolution occurs along discrete stems so that intergrades ordinarily do not occur above the genera level, whereas soils evolve in response to climatic and other factors that are not discrete. Soils, therefore, suffer intergrades at every classification level. This is recognized by defining intergrade subgroups that are still within a group but show intergrading tendencies to a different group, suborder, or order.

TEXTURAL CLASSES

Texture Versus Particle Size

Soil Taxonomy defines particle size as the entire particle-size distribution of a soil, whereas texture refers only to the fraction finer than 2 mm. Most engineers are familiar with the use of textural triangles to define textural terms such as silt loam and loam and probably realize the arbitrary nature of the subdivisions. The parent diagram [Figure 3(a)], still a commonly used chart in engineering, was originally devised in the 1930s by the predecessor of the U.S. Department of Agriculture, the U.S. Bureau of Chemistry and Soils. In the 1940s the triangle was changed [Figure 3(b)] to reflect a change in the definition of clay size from <0.005 to <0.002 mm. The revised chart, the one currently used by U.S. soil scientists, is more complicated, partly because it attempts to maintain the same class names for the same soils but introduces two additional classes, loamy sand and silt. In this system silt, like clay, may refer to either a particular range in particle sizes or to a textural class that combines several particle-size ranges. In the textural triangle proposed in the new Soil Taxonomy to differentiate soils at the family level, that ambiguity is avoided by changing clay to clayey and silt to silty [Figure 3(c)]. Furthermore, the new version has 7 classes instead of the previously defined 10 or 12, which many acknowledge as desirable. The new textural class boundaries also relate more closely to engineering classifications by having fewer subdivisions based on variability of sand contents.

Texture Versus Plasticity

The textural and engineering soil classification systems are not directly translatable because the latter are not based purely on texture (grain size) but also use plasticity data and thus reflect clay mineralogy. Furthermore, it is unlikely that a precise translation between textural and engineering classifications will ever be made because their purposes differ. Engineering classifications are directed toward variations in soil behavior relevant to engineering, and textural classifications are more concerned with scientific description. Although attempts to adapt an engineering classification to a textural triangle

[Figure 4(a)] must include gradational boundaries, such an adaptation is valuable for showing approximate interrelationships: The clays or clayey soils used in Figure 3 are usually A-7, the silty soils A-4, the sandy soils A-3, and so on. On this basis, the Soil Taxonomy textural triangle shown in Figure 3(c) correlates much better with engineering classes than the earlier textural triangles.

A more accurate presentation of engineering classes in the triangular form can be made by substituting the plasticity index for percentage of clay and liquid limit for percentage of silt [Figure 4(b) and (c)]. The resulting diagrams are comparable to one another and somewhat comparable to the previous textural triangles, except that in the American Association of State Highway Officials (AASHO) and Unified Soil Classification systems the percentage of sand is ignored below 65 and 50 percent (on a gravel-free basis) respectively. Note that different size boundaries are used to define the gravel fraction.

Texture as a Criterion in Soil Taxonomy

The textural terms in Figure 3(c) present a further compromise with the common engineering definition of the sand-silt break at the No. 200 (0.074-mm) sieve because here the soil scientists' very fine sand (0.100 to 0.050 mm) is treated as silt for family groupings of silty soils or as sand for groupings of sandy soils. The use of particle size to define soil families is direct and graphic: Clayey means soils averaging 35 percent or more clay, fine means soils with 35 to 60 percent clay, very fine means soils with 60 percent or more clay, and so on.

Figure 1. Vertisol.

Figure 2. Slickensides in a Vertisol.

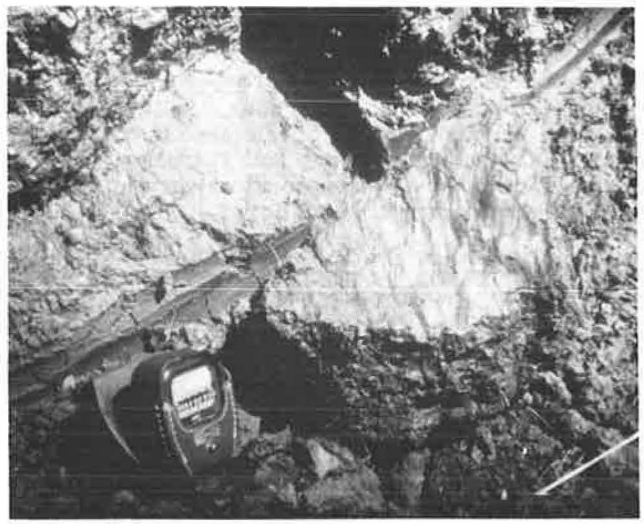
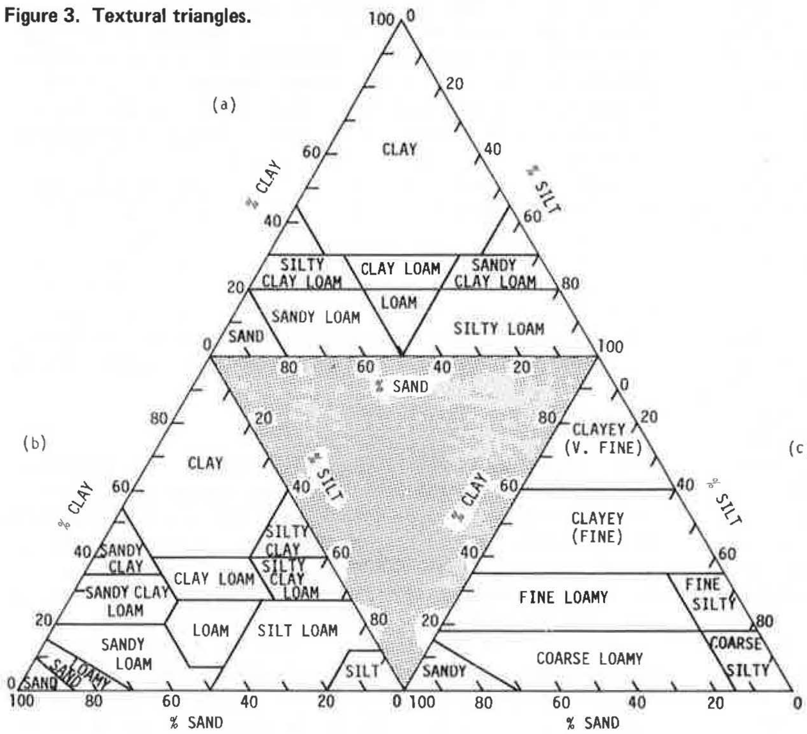


Figure 3. Textural triangles.



Particle-size classes for family groupings are as follows (1):

1. Fragmental: Particles are stones, cobbles, gravel, and very coarse sand, with too little fine earth to fill interstices larger than 1 mm.
2. Sandy-skeletal: Particles coarser than 2 mm are 35 percent or more by volume, with enough fine earth to fill interstices larger than 1 mm; the fraction finer than 2 mm is that defined for the sandy particle-size class.
3. Loamy-skeletal: Coarse fragments are 35 percent or more by volume with enough fine earth to fill interstices larger than 1 mm; the fraction finer than 2 mm is that defined for the loamy particle-size class.
4. Clayey-skeletal: Coarse fragments are 35 percent or more by volume, with enough fine earth to fill interstices larger than 1 mm; the fraction finer than 2 mm is that defined for the clayey particle-size class.
5. Sandy: The texture of the fine earth includes sands and loamy sands, exclusive of loamy very fine sand and very fine sand textures; coarse fragments are less than 35 percent by volume.
6. Loamy: The texture of the fine earth includes loamy very fine sand, very fine sand, and finer textures with less than 35 percent clay; coarse fragments are less than 35 percent by volume. Table 1 gives data for four loamy particle sizes.
7. Clayey: The fine earth contains 35 percent or more clay by weight and coarse fragments are less than 35 percent by volume. Clayey includes (a) fine, a clayey particle size that has 35 to 60 percent clay in the fine-earth fraction; and (b) very fine, a clayey particle size that has 60 percent or more clay in the fine-earth fraction.

In three cases particle-size names are replaced by other modifiers.

1. Psamments and Psammaquents are by definition sandy soils; a particle-size class name is redundant.
2. No size class is used for soils containing appreciable amounts of amorphous gels, such as Andepts and Andic subgroups.
3. Particle-size class names are not used if the organic content is high and particle size has little bearing on chemical and physical properties.

In the second and third cases given above, the following terms may substitute for particle-size class names, reflect both particle size and clay mineralogy, and substitute for both (1):

1. Cindery: More than 60 percent (by weight) is volcanic ash, cinders, and pumice and 35 percent or more (by volume) is 2 mm or larger (weight percentages are estimated from grain counts, and a count of one or two dominant size fractions of conventional mechanical analysis is usually sufficient for the placement of the soil).
2. Ashy and ashy-skeletal: Ashy is 60 percent or more (by weight) volcanic ash, cinders, and pumice and less than 35 percent (by volume) is 2 mm or larger. Ashy-skeletal is 35 percent or more coarse fragments (by volume), and fine earth is ashy.
3. Medial and medial-skeletal: Medial is less than 60 percent (by weight) volcanic ash, cinders, and pumice in the fine earth; less than 35 percent (by volume) is 2 mm or larger; and the fine-earth fraction is not thixotropic. Medial is dominated by amorphous material. Medial-skeletal is 35 percent or more coarse fragments (by volume), and the fine-earth fraction is medial.
4. Thixotropic and thixotropic-skeletal: Thixotropic is less than 35 percent (by volume) 2 mm or larger, and the fine-earth fraction is thixotropic. Thixotropic-skeletal is 35 percent or more coarse fragments (by volume), and the fine-earth fraction is thixotropic.

Particle-size classes in vertical sequences within a profile that differ significantly in pore-size distribution, so that movement and retention of water are seriously affected, are recognized as strongly contrasting particle-size classes. The transition zone between two contrasting layers must be less than 12.5 cm (4 in) thick to be designated as strongly contrasting. Examples of strongly contrasting particle-size classes are (a) sandy over clayey, (b) loamy-skeletal over fragmental, and (c) fine-silty over sandy. Forty combinations listed in Soil Taxonomy qualify for strongly contrasting particle-size classes (1).

CONTROL SECTION

The control section is the depth range through which particle-size and mineralogy data are averaged. It is a concept that should be favored by engineers, particularly when it is contrasted with the previous practice of designating the texture of the A horizon only, which ordinarily is not even used in engineering. The control section reaches much deeper, although for engineering purposes it probably can never go deep enough. The control section shown in Figure 5 is 0.25 to 1 m (10 to 40 in) in depth. Textural and mineralogical data from the control section are now averaged for classification at the family and series levels. The A, B, and C horizons in the soil profile still designate topsoil, subsoil, and parent materials.

The control section roughly means the following:

1. In shallow soils less than 0.36 m (14 in) thick over rock or a hard layer (fragipan or duripan or petrocalcic horizon) or perennial frost, the entire thickness above the contact is used.
2. In deeper soils with argillic horizons, the control section is the upper 0.5 m (20 in) of the clay-enriched horizon or the entire horizon if it is thinner than this. Overlying A horizon and underlying fragipan or duripan or petrocalcic horizon are not included.
3. In deeper soils with argillic horizons and contrasting textures, the depth is extended to 1 m (40 in) and both textures are named, e.g., sandy over clayey.

Detailed definitions of the control section are found in Soil Taxonomy (1). Advantages for engineering use are that the subsoil rather than the topsoil is emphasized and data are averaged over a significant depth rather than presented for minuscular sublayers such as B_{21}. It must be recognized that little or no emphasis is given the underlying material, which may still comprise a major portion of what engineers use. Instead, the control section tends to represent a finer grained extremity of the soil, which also supplies some of the most aggravating engineering problems.

MINERALOGICAL CRITERIA

Clay Mineralogy

The dominant clay mineral in the <0.002-mm (clay-size) fraction of clayey soils gives a classification of halloysitic, kaolinitic, montmorillonitic, illitic, vermiculitic, or chloritic. If no one clay mineral dominates, the class is referred to as mixed. Because the clay mineralogy determined by X-ray diffraction is not absolutely quantitative, other properties such as volume change and chemical properties often provide clues, and the domi-

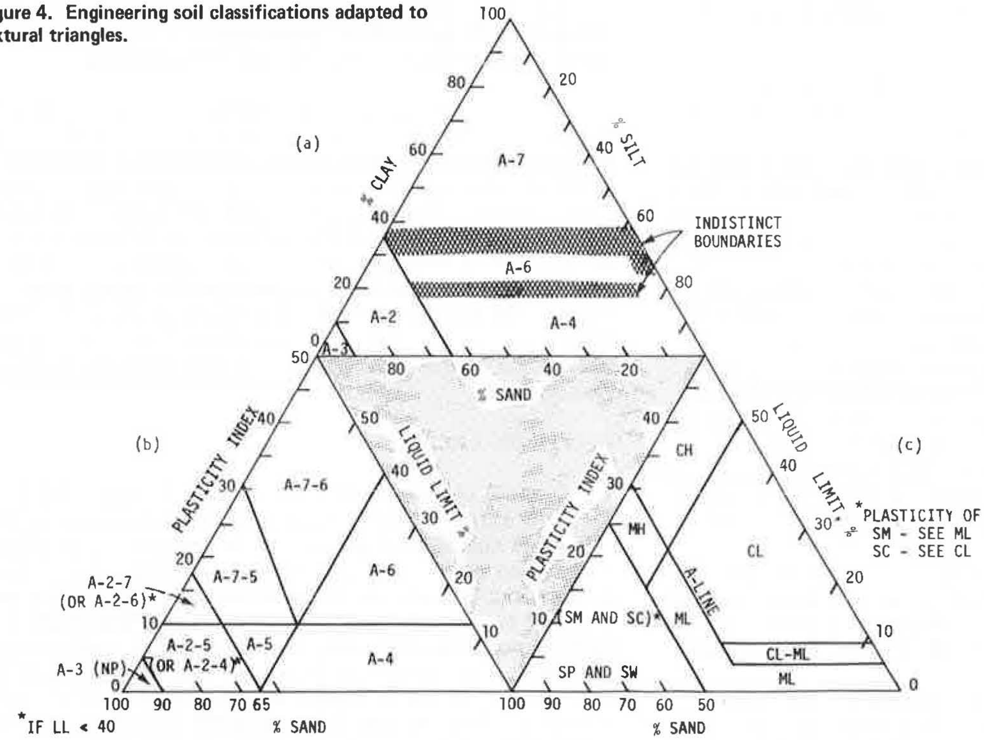


Figure 4. Engineering soil classifications adapted to textural triangles.

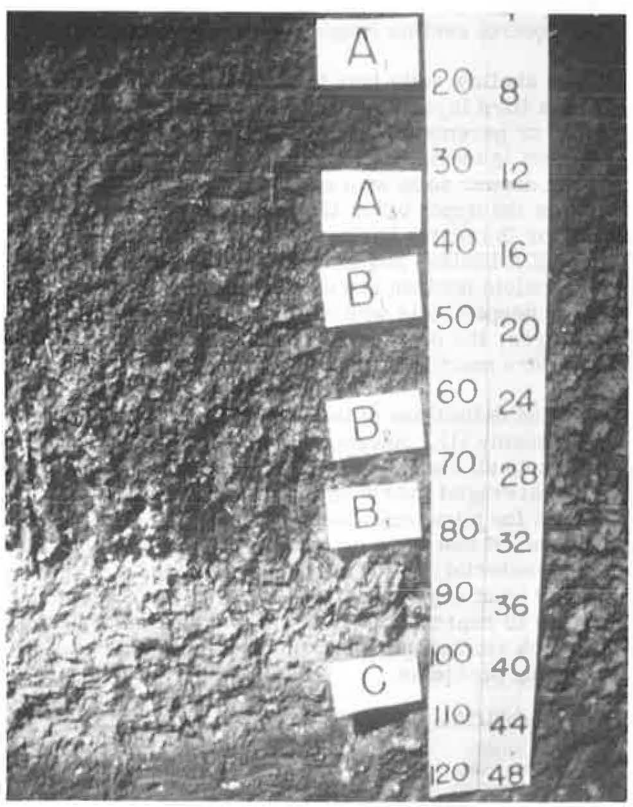


Figure 5. Control section.

nant mineral may be identified insofar as it affects behavior. Amorphous material may be identified by the absence of a substantial X-ray pattern and by a very high pH-induced cation exchange capacity (1).

A supplementary volume-change test referred to as the coefficient of linear extensibility (COLE) takes the following form:

Table 1. Contents of loamy particle sizes.

Particle Size	Content: Fine Sand or Coarser Particles: Percentage by Weight	Size (mm)	Fragments (cm)	Clay in Fine-Earth Fraction (%)
Coarse loamy	≥15	0.25 to 0.1	≤7.5	<18
Fine loamy	≥15	0.25 to 0.1	≤7.5	18 to 35
Coarse silty	<15	0.25 to 0.1	≤7.5	<18[a]
Fine silty	<15	0.25 to 0.1	≤7.5	18 to 35

[a]Carbonates of clay size are not considered clay but are treated as silt.

$$COLE = (L_m - L_d)/L_d = (L_m/L_d) - 1 \quad (1)$$

where

L_m = length of an intact soil clod after equilibration at 0.33-bar (33-kPa) moisture and
L_d = length when dry.

Hallberg (3) recently showed the relations between COLE and the more conventional engineering measures, shrinkage limit (SL) and shrinkage ratio (SR):

$$SL = 100\,[MC - (1/Dbm) - (1/Dbd)] \quad (2)$$

$$SR = Dbd \quad (3)$$

$$COLE = (Dbd/Dbm)^{1/3} - 1 \quad (4)$$

$$VC = 100[(COLE + 1)^3 - 1] \quad (5)$$

where

MC = moisture content as a fraction,
Dbd and Dbm = dry and moist bulk densities respec-

tively measured in the COLE test, and
VC = percent volume change.

It would appear that the COLE test may give a more meaningful measure of volume-change characteristics than shrinkage limit because it is performed on undisturbed soil samples rather than after drying, pulverization, and sieving and thus includes effects from the natural soil structure.

Silt, Sand, and Whole-Soil Properties

Class names are also designated if nonclay minerals such as carbonates, iron oxides, or micas tend to dominate soil properties. Selected examples of these mineralogy classes are given below.

Class	Description
Carbonatic	>40 percent carbonates plus gypsum, of which carbonates are 65 percent
Gypsic	>35 percent carbonates plus gypsum, of which carbonates are 65 percent
Micaceous	>40 percent mica (by weight, based on grain counts)
Siliceous	>90 percent quartz, chalcedony, and opal
Ferritic	>40 percent iron reported at Fe_2O_3
Oxidic	>40 percent iron, but percentage iron plus percentage gibbsite exceeds ⅕ of percentage clay
Mixed	<40 percent any one mineral except quartz

Calcareous and reaction classes are recognized in selected taxa. Calcareous classes are applied to a section between a depth of 25 and 50 cm (10 and 20 in) unless a lithic or paralithic contact is present. They are used only in the names of families of Entisols, Aquepts, and most Aquolls. Calcareous is applied to the above taxa when the fine-earth fraction effervesces in all parts of the depths listed above with dilute HCl. Noncalcareous indicates that the soil does not effervesce in all parts listed above, but it is not used as a part of the family name. The term calcareous, if used as a part of the family name, is considered to be a subclass of mineralogy and is shown in parenthesis, i.e., fine-loamy, mixed (calcareous) mesic Typic Haplaquoll.

Reaction classes of acid and nonacid are used in selected taxa and are defined as follows:

1. Acid—pH is 5.0 in 0.01 mole $CaCl_2$ (2:1) throughout the control section (or about 5.5 in H_2O, or 1:1).
2. Nonacid—pH is 5.0 or more in 0.01 mole $CaCl_2$ (2:1) in at least some part of the control section. The term nonacid is not used in the family name of calcareous soils.

Reaction classes are used only in names of families of Entisols and Aquepts; they are not used in sandy, sandy-skeletal, and fragmental families of these taxa nor in Sulfaquepts and Fragraquepts or families that have carbonatic or gypsic mineralogy.

Except for the calcareous classes, the control section for mineralogy classes is the same as that used for particle-size classification. Contrasting mineralogy modifiers are not recognized except where substitutes for particle-size class modifiers have been used. If there are layers of contrasting particle size in the control section, the mineralogy class of the upper part of the control section is definitive of the family mineralogy.

LIMITATIONS

Parent Material

The family category was designed to provide the primary grouping within a subgroup for properties that are useful in evaluating the potential for plant growth as well as engineering purposes. However, at present there are contrasting soils not separated at the family level.

Mahaska and Adair are two midwestern soil series with contrasting properties that are important to recognize for either agronomic or engineering uses. Both are classified as members of the fine montmorillonitic mesic family of Aquic Argiudolls. Properties of soils in these two series are estimated in Tables 2 and 3.

The Adair series (Table 2) consists of moderately well-drained to somewhat poorly drained soils with clayey subsoils. These soils form in reddish clayey Late Sangamon Paleosols developed in Kansan glacial till, under a native vegetation of tall prairie grasses. Adair soils typically have a black to very dark gray clay loam surface layer 43 cm (17 in) thick. A stone line is at the base of the surface layer. The subsoil from 43 to 63 cm (17 to 25 in) is a mottled dark brown and dark reddish-brown clay. Below this is a mottled dark yellowish-brown clay loam to a depth of 152 cm (60 in). The Adair series soils in Table 2 had a few concretions of lime in the lower part and slopes from 5 to 18 percent.

The Mahaska series (Table 3) consists of nearly level to gently sloping, somewhat poorly drained soils formed in Wisconsin loess under a native vegetation of tall prairie grasses. These soils occur on moderately wide upland ridges, in coves of drainageways, and on high stream benches. Mahaska soils typically have a black silty clay loam surface layer 45 cm (18 in) thick. The subsoil, which extends to 152 cm (60 in), is mottled dark grayish-brown to olive-brown silty clay loam in the upper part and mottled light olive-gray medium silty clay loam in the lower part. The substratum is gray silty clay loam, and slopes range from 1 to 5 percent.

Maximum dry density of these loess-derived soils ranges from 1400 to 1600 kg/m^3 (90 to 100 lb/ft^3). The glacial till in the lower solum of Adair soils has a maximum dry density of 1750 to 1900 kg/m^3 (110 to 120 lb/ft^3). The AASHO classification of Mahaska is A-7; the Adair soils generally classify as A-6. Other significant differences not recognized at the family level concern the percentage of material less than 7.5 cm (3 in) in diameter passing selected sieve sizes, especially the No. 40 and 200 sieves, and the liquid limit and plasticity index (Tables 2 and 3).

It is important in evaluating the potential of an area for engineering purposes to recognize the type of parent material from which the soils formed (such as Wisconsin loess or Kansan glacial till). Because the new Soil Taxonomy is nongenetic, soils from contrasting parent materials occurring on the same landscape may be grouped in the same family. Figure 6 shows an example of loess (the lighter soil in the figure) overlying glacial till. The physical properties of loess-derived soils in situ often are in strong contrast to the properties of till-derived soils, mainly because of a difference in density. Loess-derived soils are normally consolidated and, close to the source, are underconsolidated or collapsible (4); till-derived soils are normally consolidated or overconsolidated. Loess is more erodible and generally has a higher permeability and a much lower bearing capacity than glacial till with the same clay content. Loess soils exert a much higher active pressure on retaining walls and bridge abutments. These characteristics are closely related to and predictable from the parent material, which should therefore be recognized in the family category.

Depth to Rock

Another contrasting property not recognized at the family

Table 2. Estimated properties of Adair series soils.

Item	Depth (cm) 0 to 43	43 to 86	86 to 152
USDA texture	CL	SIC, C, CL	CL
Classification			
Unified	CL	CL, CH	CL
AASHO	A-6	A-6, A-7	A-6
Fraction >7.5 cm, %	0	0	0
Material <7.5 cm passing sieve, %			
No. 4	95 to 100	95 to 100	95 to 100
No. 10	80 to 95	80 to 95	80 to 95
No. 40	75 to 90	70 to 90	70 to 90
No. 200	60 to 80	55 to 80	55 to 80
Liquid limit	30 to 40	45 to 55	35 to 40
Plasticity index	11 to 20	20 to 30	15 to 25
Permeability, cm/h	0.5 to 1.5	0.15 to 0.5	0.5 to 1.5
Available water capacity, cm/cm	0.43 to 0.48	0.33 to 0.4	0.35 to 0.4
Soil reaction, pH	5.6 to 6.5	5.6 to 6.5	5.6 to 6.5
Shrink-swell potential	Moderate	High	Moderate
Corrosivity			
Steel	High	High	High
Concrete	Moderate	Moderate	Moderate
Erosion factors			
K	0.43	0.43	—
T	3	—	—
Wind erosion group	6	—	—

Notes: 1 cm = 0.39 in.
Iowa soils examined in November 1973. No measurable salinity.

Table 3. Estimated properties of Mahaska series soils.

Item	Depth (cm) 0 to 45	45 to 129	129 to 185
USDA texture	SICL	SICL	SICL
Classification			
Unified	CL, OL	CH	CL
AASHO	A-7	A-7	A-7
Fraction >7.5 cm, %	0	0	0
Material <7.5 cm passing sieve, %			
No. 4	100	100	100
No. 10	100	100	100
No. 40	100	100	100
No. 200	95 to 100	95 to 100	95 to 100
Liquid limit	41 to 50	50 to 60	41 to 50
Plasticity index	15 to 25	20 to 30	15 to 25
Permeability, cm/h	1.5 to 5	0.5 to 1.5	1.5 to 5
Available water capacity, cm/cm	0.53 to 0.58	0.35 to 0.45	0.45 to 0.5
Soil reaction, pH	5.1 to 6	5.1 to 5.5	5.6 to 6.3
Shrink-swell potential	Moderate	High	High
Corrosivity			
Steel	High	High	High
Concrete	Moderate	Moderate	Moderate
Erosion factors			
K	0.37	0.43	—
T	4	—	—
Wind erosion group	7	—	—

Notes: 1 cm = 0.39 in.
Iowa soils examined in March 1973. No measurable salinity.

Figure 6. Loess overlying glacial till.

Figure 7. Bedrock at a depth not recognized in the family category.

level is the presence of bedrock at a depth of 0.5 m (20 in) or more. For example, Dubuque soils are developed in the 0.5 to 1 m (20 to 40 in) of loess overlying limestone bedrock and are classified as members of the fine-silty mixed mesic family of Typic Hapludalfs. The family name gives no indication of the bedrock hazard within the 0.5 to 1-m (20 to 40-in) depth. The engineering significance of bedrock at the 0.5 to 1-m (20 to 40-in) depth scarcely needs elaboration: Rock may increase the cost of excavation by a factor of 10 or more and will severely restrict the amount of soil available for borrow. Bedrock at the depth shown in Figure 7 is not currently recognized at the family level. Recognition of lithic content would greatly improve the usefulness of the family category for engineering purposes. Identifying the rock type would further aid in predicting leakage potential for ponded reservoirs or pollution of aquifers from sanitary disposal sites.

Clay Mineralogy

A question can be raised as to why the clay mineralogy of soils classified as fine-silty or fine-loamy (clay content of 18 to 35 percent) is not recognized at the family level. Soils with different clay mineralogies have contrasting behavior and nutrient-supplying potential at the lower clay contents as well as within the clayey range. Clay mineral differences in fine-silty and fine-loamy particle-size classes could be recognized at the family level by using criteria currently used for clayey soils.

SUMMARY AND RECOMMENDATIONS

1. Soil Taxonomy, the new soil classification system adopted by the Soil Conservation Service of the U.S. Department of Agriculture, emphasizes various measured soil properties, including particle size, clay mineralogy, color, and field relationships, to define soil orders, suborders, great groups, subgroups, and families. This is in contrast to earlier systems, which had a genetic emphasis. The advantage of the new system for engineering is that it rests on hard data and thus reduces the role of speculation and changing opinion concerning soil origins.

2. The expressed intent of the family category is to group soils having similar physical and chemical properties that affect their response to management and manipulation. One disadvantage of going to a nongenetic classification is that important information that does relate to soil genesis may be lost or relegated to a secondary role. An example cited in this paper is that of loess and till-derived soils occurring in the same family despite significant differences in physical properties. In that case a family distinction could be made on the basis of dry density or other factors. Such separations seem appropriate to increase the usefulness of the system for engineers.

3. The new Soil Taxonomy uses the concept of the control section to define the range of depths over which soil properties are averaged for classification. The control section emphasizes soil properties at greater depths than did previous classifications, which tended to emphasize properties of topsoil, a concept little used in engineering. The definition and use of control sections are therefore highly advantageous for engineers.

4. In this connection, an important contrasting property not presently recognized in the family category but that appears to deserve recognition because of its major influence on engineering uses is bedrock deeper than 50 cm (20 in). Although it may be argued that such an occurrence does not in itself strongly influence soil properties, the family designation is intended to be pragmatic in purpose and, from an engineering viewpoint, nothing could be more pragmatic than the knowledge that rock occurs at a depth of 0.6 to 0.9 m (2 to 3 ft).

5. The COLE value, a measure of the shrinkage of undisturbed soil clods, should be relevant to engineering uses and in fact may be more relevant than traditional engineering tests such as the shrinkage limit, which uses mixed and remolded soil.

6. Finally, the authors feel that the clay mineralogy of soils classified as fine-silty or fine-loamy (clay content of 18 to 35 percent) is pertinent and should be recognized at the family level.

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Soil Series and Soil Taxonomy

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Soil series are the lowest and most narrowly defined units in Soil Taxonomy. They have from the beginning been the primary vehicle through which information gained from experience with and research on soil performance has been accumulated, organized, and presented to assist with land-use and management decisions. Soil series are defined according to the kind, sequence, and thickness of soil horizons and the physical and chemical properties of each horizon. The occurrence of a soil series is limited to unique kinds of geologic formations, landscape positions, and climates. Most soil series are subdivisions of soil families in which specific ranges in composition, thickness, structure, or other properties are narrower than they are for the soil family. Some soil series include the full range of the soil family. Among the soil properties used to define each horizon of soil series are those that determine the performance of the soil as an engineering material. Important in situ properties such as density and seasonal moisture content have narrow ranges in each horizon of soil series.

Soil series are the lowest categorical level of Soil Taxonomy (13). They have a narrower range in properties and thus in occurrence and in performance than classes at the five higher categories in the system. Each soil series is uniquely placed into one of the classes of higher categories. Because all classes in Soil Taxonomy are mutually exclusive, the limit in all definitive properties used at categories above the series becomes part of series definitions. A soil series is thus confined within the range of one family. Most series are defined to include only a portion of a family although some cover the entire range of the family in most or all properties.

Soil series have been used as the basic unit of soil classification since the beginning of soil surveys in the United States in 1899. Soil series are the focal point of all of the information that soil scientists accumulate about soils. They are named after places where they were first identified, e.g., Miami.

HISTORY OF THE SOIL SERIES

The term soil series goes back to the idea of early pedologists that they would find on each kind of parent material a complete series of soils of various textures ranging from sand to clay. The member of the soil series having a different texture, the surface soil, was called the soil type. The Miami series was thought to encompass all soils on glacial drifts—from the soil type Miami sand on outwash to the soil type Miami clay on some unusually fine-textured glacial till. It is not surprising that with such a broad definition the Miami series appeared on early soil maps from Illinois to the New England states. As our knowledge of soils has increased and soil survey procedures have become more sophisticated, the definition of soil series has become progressively narrower in range of properties.

In 1913, Marbut defined a soil series as "a group of soils having the same range in color, the same character of subsoil, particularly as regards color and structure, broadly the same type of relief and drainage, and a common or similar origin" (12). In 1938 (1), the soil series was defined as a group of soils "having genetic horizons similar as to differentiated characteristics and arrangement in the soil profile, except for the texture of the surface soil, and developed from a particular parent material."

By 1965, when the National Cooperative Soil Survey adopted Soil Taxonomy, the definition of soil series had become so narrow that relatively few series had more than one or two soil types. Hence, soil type was dropped from the classification system although the texture of the surface soil is still used in the names of soil phases.

An important practical consequence of these changes in the series concept is that soil series defined by various soil surveys are not necessarily the same. Soil series of older surveys tend to be much more broadly defined than those of surveys completed in the last 20 years. And, since soil surveys in adjacent counties may have been completed some 10 or 20 years apart, the series concept in those two surveys may be different. It is important, therefore, that a knowledgeable soil scientist be consulted if an old survey must be used for planning purposes. In particular, soil surveys completed before 1956 and published on line maps may not meet modern standards.

ROLE OF THE SOIL SERIES

About 12 000 soil series are now in use in the United States. Soil scientists have described all of these series in considerable detail in terms of both their morphological characteristics and their behavior for many uses, including engineering uses. Each soil series is different from any other soil soil series in one or more of the set of definitive soil properties. A wide range of activities have been carried out on most soil series: Crops have been grown, cattle grazed, houses and roads built, and other activities performed that are influenced by the nature of the soil. The soils performed well for some activities and not for others. Through past decades, by trial and error, soil scientists have collected an enormous volume of such field data on soil performance, organized by soil series.

Research has also contributed a great deal to our understanding of soils and their performance. Early work focused on learning how to manage soils for crop production. More recently, substantial research has been done to learn more about the engineering behavior of soil series. One early example of such research was the cooperative effort initiated by the U.S. Bureau of Public Roads, in cooperation with the Soil Conservation Service, to sample major soil series in the United States and determine important engineering index properties. This effort is being continued in many states by state highway departments. Thousands of soil profiles have been analyzed, and a significant conclusion is that specific horizons of soil series do in fact have a specific pattern of test results.

The first major role of the soil series is to provide a basis for organizing knowledge about soils. A structure is necessary through which knowledge gained from experience and research can be aggregated. Considering the vast amount of data available, such an aggregation is required in order to determine meaningful relations between soil properties and soil performance. Soil series, as well as the higher categories of Soil Taxonomy, provide the required structure.

A second major role of the soil series is to provide a basis for the transfer of information about soils from points where specific measurements are made to other areas. Such transfer has been the basic goal of soil surveys from the beginning, through the process referred to as soil interpretations. This principle has been used by the Michigan Department of State Highways and Transportation for many years. More recently, extensive application of soil interpretations has been made in South Dakota (3) and Ohio (5). Establishing confidence in this procedure requires that data be organized and evaluated by soil series. Such data must include validation in terms of both test data and observations of actual performance. That validation has been accomplished in the states mentioned above.

A third role of the soil series is to provide a structure for research and testing to improve understanding of the parameters that affect soil performance. It has been said that the main goal of classification is to give soil scientists the greatest command of what they already know and to lead them most directly to the acquisition of more knowledge (8). For many research projects, specific kinds of soils must be chosen for study. Choosing specific soil series provides a good basis for obtaining the soil samples needed. For each soil series a type location has been established; that is, a soil that has the grain-size distribution, clay mineralogy, and other physical and chemical properties typical of the series is found at that location. Extensive testing to characterize the soil has already been done at the type location of many soil series. As a result, soils that are known to meet the requirements of the research project can be selected. This was done in a recent study of chemical compaction aids sponsored by the Federal Highway Administration and carried out by the Civil Engineering Department of Iowa State University in which roughly 25 soil series from throughout the United States, representing fine-grained soils of known clay mineralogy and kind of parent material, were selected for testing.

PEDOLOGIC VERSUS ENGINEERING APPROACH TO SOIL CLASSIFICATION

The in situ soil profile, each series in which has specific kinds and arrangements of soil horizons, is what pedologists classify. Emphasizing a set of soil horizons, each with a defined set of properties, is in contrast to the common engineering approach of using a specific sample, chosen to represent conditions at a given site and stratum, as the basic unit of classification. This basic difference is highly important in contrasting the approaches to soil classification by the two disciplines.

The pedologic classification considers soil as a product of its natural environment and incorporates into the classification several aspects of that environment. Climate and vegetation, for example, are important factors in soil formation. Both mean annual soil temperature (MAST) and degree of seasonal variation in soil temperature are criteria in pedologic classification. Soil moisture regimes and their seasonal variation, in relation to both climate and local relief, as well as marks left by natural vegetation, such as the thickness and organic matter content of the A horizon, are also used as classification criteria.

Both the American Association of State Highway Officials (AASHO) and Unified Soil Classification systems consider a specific sample, but the classifications themselves neglect the environmental conditions in which the sample exists in situ. To the pedologist these conditions are important soil properties that may have a great influence on the performance of the soil. In reports of soil engineering investigations of specific sites, soil moisture states at the time of the investigation are commonly referred to and general information is sometimes available on the seasonal variations in both soil moisture and temperature for the area. Differences between local soils in the pattern of seasonal moisture variation are often overlooked in engineering investigations, with unfortunate results. This information is among the most useful of the pedologist's contributions to the engineer.

CRITERIA USED IN RECOGNIZING AND DEFINING SOIL SERIES

Of the 5100 families in Soil Taxonomy, about 3100 have only 1 series, another 1500 have between 2 and 4 series, and only about 100 have more than 10 series. Criteria for subdividing families vary widely: Some have to do with difference in soil texture in critical horizons, some with differences in soil moisture regimes, some with the thickness or presence or absence of certain horizons, and some with differences in composition or mineralogy that may reflect different parent materials.

Characteristics used in defining soils either are observable in the field or by visual and tactile examination and simple field tests or they are inferred from observable features. The principal observable features are the kind, number, thickness, and arrangements of horizons in the profile and—for each horizon—the color, including patterns of mottles, and the texture, structure, consistency, and reaction (pH). Other observable features used in classification are the presence of coarse fragments such as gravel or cobbles and the presence of carbonates, gypsum, and soluble salts.

The thickness and degree of expression of a diagnostic soil horizon are common criteria used to separate series within a soil family. Such a horizon may range in thickness from several centimeters to a meter or more. It may be thin but strongly expressed or thick but weakly expressed.

The principal inferred properties used in classification are moisture and temperature regimes; the number of days during most years when the soil is dry, moist, or saturated; average and summer soil temperature; percentage base saturation; percentage sodium saturation; the cation exchange capacity of the clay fraction; and the mineralogy of both the clay and larger particles. In addition, soil scientists infer and measure many other soil parameters that are important for the use and management of soil series. Among them are the standard index properties for the engineering classification of soils, available water capacity, permeability, soil reaction, shrink-swell potential, corrosivity of steel and concrete, susceptibility to water and wind erosion, susceptibility to flooding, depth to water tables, susceptibility to subsidence, hydrologic groupings, and other properties.

A carefully planned soil testing program is used to verify the relations required to accurately infer soil properties. Through such testing, the local relations between the five soil-forming factors—parent material, climate, organisms, topography, and time—and the properties of soils are determined. State agricultural experiment stations, state highway departments, and others contribute to the test program. Through these cooperative efforts a vast amount of data about the properties of soils has been assembled.

Soil series are the equivalent of the species of botany or zoology. Just as not all members of a species of plants are identical, so also are there differences among members of a soil series. It is necessary to define ranges in soil properties, ranges that are sufficiently limited or narrow that reasonably specific and narrow ranges in performance for a soil series will result. In defining soil series, pedologists try to meet this requirement, and the attempt appears to have been successful. (Continuing investigation of the effectiveness of this procedure would be a useful cooperative project for engineers and pedologists in the future.)

The pedologist's insistence that slope is a soil property is contested by many engineers and deserves some explanation. In the first place, soils are considered three-dimensional bodies with areal extent. Thus the configuration of the surface is an important property of those bodies. Perhaps more important is the configuration of the boundaries between soil horizons in the soil profile. In most soils the permeability of adjacent horizons is different. Thus, slope not only affects the total amount of water that infiltrates into the soil but also strongly influences the fate of the water after it enters the soil surface. Seep lines resulting from the lateral flow of free water above the sloping boundary of a subsurface horizon that is of slower permeability than overlying horizons are the source of many engineering problems. Location of such seep lines may be predicted if the soil series and its slope are known.

SOIL CLASSIFICATION BELOW THE SERIES LEVEL

For many practical purposes, it is necessary to subdivide soil series into soil phases. For example, some soil series are found on a wide range of slopes, from gently sloping to very steep. Because recognition and mapping of several slope classes of the same series may provide valuable information needed for planning the use and management of the soil, phases of soil slope are established.

In addition to the degree of slope, the degree of past erosion is a common criterion for soil phases. Besides its obvious importance to the growth of plants, it may be of interest to the highway engineer. Eroded A horizons do not have to be excavated and wasted in construction. The nature and amount of the A horizon available for topsoiling are also important, as is the effect of past erosion on vegetating ungraded areas such as rest areas and roadside parks.

Other soil characteristics of importance to the engineer, such as stoniness or depth to rock, are frequently used as phase criteria. Soil phase criteria are simple and can be described by simple modifiers so that, if one understands a soil series, one can readily understand the phase from the additional descriptors. Miami silt loam, 0 to 3 percent slope, is a phase name. The soil phase name is used to put a label on soil mapping units, but phases and soil mapping units are not synonymous. The soil phase is a taxonomic unit—an abstraction—whereas the mapping units are the land areas that are used and managed. This distinction is important because mapping units can commonly have "inclusions" of con-

Table 1. Moisture content data for Canfield and Geeburg soils.

Soil Series and Horizon	Sites	Moisture Content					
				In Situ			
		33-kPa Tension	Optimum	Autumn	Optimum (%)	Spring	Optimum (%)
Canfield							
Bt	15	19.1	16.2	17.7	109	21.2	131
Bx	15	14.1	14.3	13.3	93	16.2	113
B3	15	12.6	12.6	12.9	102	14.5	115
Geeburg							
Bt	12	18.9	21.3	17.1	80	23.3	109
C	12	20.3	21.1	16.3	77	18.6	88

Note: 1 Pa = 1 x 10^{-5} bar.

Table 2. Density measurements for Canfield and Geeburg soils.

Soil Series and Horizon	Site	Oven-Dry Density (g/cm^3)	33-kPa Density (g/cm^3)	Maximum Dry Density (g/cm^3)
Canfield				
Bt	SK-4	1.57	1.54	1.73
	SK-30	1.58	1.53	1.80
	ST-5	1.59	1.52	1.74
	WN-S41	1.57	1.54	1.71
	WN-S42	1.63	1.62	1.78
	Mean	1.59	1.55	1.74
Bx	SK-4	1.81	1.79	1.93
	SK-30	1.89	1.82	1.82
	ST-5	1.80	1.77	1.93
	WN-S41	1.80	1.79	1.81
	WN-S42	1.83	1.79	1.86
	Mean	1.83	1.79	1.87
B3	SK-4	1.82	1.81	1.89
	SK-30	1.79	1.81	2.03
	ST-5	1.79	1.80	2.05
	WN-S41	1.80	1.78	1.89
	WN-S42	1.79	1.80	1.94
	Mean	1.80	1.80	1.96
Geeburg				
Bt	MH-2	1.86	1.70	1.65
	MH-13	1.87	1.73	1.70
	PG-S12	1.82	1.62	1.63
	SK-11	1.78	1.55	1.63
	TR-8	1.78	1.66	1.68
	Mean	1.82	1.65	1.66
C	MH-2	1.86	1.71	1.66
	MH-13	1.92	1.78	1.71
	PG-S12	1.87	1.72	1.66
	SK-11	1.83	1.66	1.65
	TR-8	1.89	1.80	1.76
	Mean	1.87	1.73	1.69

Notes: 1 Pa = 1 x 10^{-5} bar; 1 g/cm^3 = 0.58 oz/in^3.
All values are means of tests on 3 clods 250 to 400 g in weight. Average mean deviation in sets of 3 clods is 0.02 g/cm^3; minimum is 0 g/cm^3; and maximum is 0.13 g/cm^3.

trasting soils but phases cannot.

SOIL SERIES VERSUS SOIL MAPPING UNITS

Soil series names are used to identify mapping units in soil surveys. Mapping units are named after the dominant soil series, or phase of a soil series, in the mapping unit. At least 85 percent of a mapping unit named for a single soil series consists of soils identical to or very similar to the series named. Because of cartographic limitations, most mapping units contain some inclusions of soils other than the one given in the name. These inclusions, if they are quite contrasting, may comprise as much as 15 percent of the area of the mapping unit; they may have a steeper slope, a finer texture, or a different moisture regime. Only in large-scale, experimental surveys can all contrasting taxonomic units be delineated. On scales between 1:15 840 and 1:24 000, the scales of most published modern soil surveys, it is impossible to delineate small areas of contrasting soils. It is therefore important that, for critical uses, soil surveys be supplemented by on-site investigations.

USE OF SOIL SERIES DATA IN ENGINEERING

To illustrate the kind of data about soils that may be obtained through knowledge of soil series and soil horizons, two soil series were chosen: Canfield and Geeburg, soil series found in eastern Ohio and western Pennsylvania respectively. Both soils formed in glacial till of late Wisconsin age. The unweathered till below both soils is weakly calcareous. Both occupy convex portions of the landscape where runoff exceeds runon and where good soil drainage would be expected. Both soils formed under deciduous hardwood forest, and both occur in very similar climates. The striking differences in the two soils result mainly from the fact that the Canfield soils formed in glacial till of loam texture, a sandy silt or ML in engineering classification, whereas the Geeburg soils formed in silty clay to clay (CH) glacial till. Water moves more readily through the Canfield soil and causes the profile to be altered to a greater depth [2 m (6.6 ft)] than it is in the Geeburg soil [1 m (3.3 ft)].

In Soil Taxonomy, Canfield soils are Aquic Fragiudalfs in the fine-loamy, mixed, mesic family; Geeburg soils are Aquic Hapludalfs in the fine, illitic, mesic family. Both Canfield and Geeburg soils have ochric epipedons and argillic horizons. The thickness and organic content of the ochric epipedons are about the same in the two soils. The argillic horizon is 1 to 2 m (3.3 to 6.6 ft) thick in Canfield soils but only 0.3 to 0.8 m (1 to 2.6 ft) thick in Geeburg soils. But the most striking difference in soil horizons is the presence of a fragipan within the argillic horizon of the Canfield soils and its lack in Geeburg soils. The fragipan is a very dense, compact layer with slow permeability and poor soil structure.

Seasonal Moisture Content

The classification of Canfield and Geeburg soils in aquic subgroups reflects the presence of mottles in the upper part of the B horizon that indicate saturated conditions in the B horizon during short periods of time in late fall or early spring. If the soils were saturated for longer periods of time, gray colors would predominate immediately below the surface soil and the soils would be classified in the Aqualf suborder.

Data in Table 1 were obtained in Ohio in a study by McCormack and Wilding (7). The in situ moisture con-

Table 3. Atterberg limits for Canfield and Geeburg soils at five sites.

Soil Series and Horizon	Liquid Limit		Plastic Limit		Plasticity Index	
	Mean	Range	Mean	Range	Mean	Range
Geeburg						
Bt	53.6	48.5 to 58.5	26.3	24 to 30	27.3	22.5 to 33.5
C	48.8	42 to 54	25	23.5 to 27	23.8	17 to 28.5
Canfield						
Bt	25.3	31.5 to 37.5	22	22 to 23.5	13.1	11.5 to 14
Bx	29.4	25.5 to 33.5	18.8	15.5 to 21.5	10.6	9 to 12
B3	24.5	20 to 29.6	17.6	15.5 to 21.5	6.9	4.5 to 10

tent of all Canfield horizons is near the optimum moisture content in the autumn but well above it in the spring. In the Geeburg soils, both the Bt and C horizons have in situ moisture contents well below optimum in the autumn. In the spring the Geeburg Bt horizon is slightly more moist than the optimum moisture content. Where soil material is to be excavated for compacted fills, a knowledge of the seasonal in situ moisture content of soil horizons of specific soil series should be valuable to the engineer.

Many studies have demonstrated the relation between soil moisture classes and the depth to free water in soils (4, 6, 14), and this relation is reported for all soils in published soil surveys. Depth to free water has an important influence on the ease of excavation and is one of the soil properties influencing frost heaving.

Soil Density

The kind and arrangement of soil particles—which are strongly influenced by the range in particle sizes or grading—and the shape and the packing of the particles determine soil density and strongly influence several aspects of the engineering behavior of soils. Most engineering texts discuss the importance of desiccation and weathering on the engineering behavior of soils derived from specific kinds of parent materials. In the definition of soil series, not only is the kind of parent material specified but also the conditions of weathering history, including climate, vegetation, and relief or landscape position, as well as the relative age of the surface during which weathering has been in progress are confined into definite ranges. Considering the unique phenomena that act on a soil element in a specific kind of geologic material at a given depth, the in situ density of given horizons of a soil series should not vary widely.

This premise was tested for each major horizon of the Canfield and Geeburg soils by measuring the density at 0.33-bar (33-kPa) tension and oven dryness of undisturbed clods, following standard procedures (2). The results are given in Table 2. The set of five samples from each horizon, taken from sites as far as 100 km (60 miles) apart, show a very narrow range in density. In fact few of the measurements vary from the mean by more than the 3 to 5 percent coefficient of variation often cited as normal experimental error in density measurements. The compaction characteristics within samples of each horizon also fall within a narrow range.

Soil Texture

Soil texture is a highly important soil property that is recognized and used for classification at levels above the soil series, principally at the family level. In the definition of many soil series, the range in texture of the family is subdivided and the range in thickness of horizons with defined textures is specified. Soil families recognize only the texture of specified parts of the soil profile, e.g., the texture of the upper 50 cm (20 in) of the argillic horizon. Soil series definitions specify the textural range of all parts of the soil profile.

In Canfield soils, only a part of the full range in texture of the fine-loamy family is included. The clay content of the argillic horizon above the fragipan is 18 to 27 percent whereas the fine-loamy family of which Canfield is a member ranges up to 35 percent in clay content. Canfield soils also have 10 to 25 percent gravel and cobbles in the soil profile whereas other series in the same family are free of gravel.

The definition of Geeburg soils also subdivides the textural range of a soil family. Clay content for the fine family ranges from 35 to 60 percent. Geeburg soils have 46 to 60 percent clay in the argillic horizon. Ellsworth soils, otherwise closely similar to Geeburg, have 35 to 45 percent clay.

Atterberg limits are closely related to soil texture where clay mineralogy, organic content, and carbonate content are constant. In Table 3, the means and ranges in liquid limit (LL), plastic limit, and plasticity index (PI) from five sites of each of the two soil series are given. The sites were chosen to represent the full range in texture of each of the two soil series. In multiple regression analysis of the data, clay content was found to explain a very high proportion of the variation in LL and PI. The following equations were derived.

$$LL = 9.51 + 0.81C \quad r^2 = 0.96 \tag{1}$$

$$PI = 4.28 + 0.591C \quad r^2 = 0.95 \tag{2}$$

Data from 25 samples were used in the analysis.

As indicated by the limited range in grain-size distribution, mineralogy, and plasticity, specific horizons of soil series fall into a narrow range of Unified Soil Classification System and AASHO classes. For the five Geeburg pedons tested, all samples of both the Bt and C horizons were in the A-7-6 AASHO class. For the Bt horizon four samples were CH and one was CL borderline to CH. All samples for the C horizon were near the CL-CH boundary; three placed as CL and two as CH. For the five Canfield profiles, all samples of the Bt horizon placed as A-6 and CL, on the low plasticity side. All samples from the Bx horizon were CL; three were A-6 and two were A-4. All samples from the B3 horizon placed as A-4; three placed as CL, one as CL-ML, and one as SM-SC.

Clay Mineralogy

Because all soils in a soil series have formed in a similar parent material and have been subjected to similar soil weathering, the kind of clay minerals is relatively uniform within the series. In both Canfield and Geeburg soils the dominant clay mineral is illite (7).

Soil Structure

Each horizon of the soil series has a limited range in soil structure; soil weathering and the parent material are similar wherever the soil occurs. Soil structure is one of the major determinants of soil permeability and also affects the ease of soil excavation. For example, the fragipans of Canfield soils, which have a weak, platy structure, are very dense, very hard when dry, and more difficult to excavate than horizons above and below. The C horizons of Geeburg soils are also compact, but the high clay content of Geeburg soils causes them to be sticky and difficult to grade when they are moist or wet. In both soils, the blocky structure of the upper B horizon results in easy excavation.

Soil pH and Exchangeable Cations

These properties are important in preparing specifications for concrete, and they also influence the proper use of lime or other chemicals for stabilization of soils as subgrade. Again, as a result of the same kind and degree of soil weathering in similar parent material, given horizons of soil series have a narrow range in these properties.

SUMMARY

Soil series are the lowest category in Soil Taxonomy, having a narrower range in both properties and performance than any of the five higher categories. Soil series occupy unique landscape positions and have narrow ranges in important site and environmental conditions that are considered soil properties in pedology but not in soil mechanics.

Confined in their ranges by the limits of the higher categories, soil series represent the product of a specific kind and degree of soil weathering. Of particular importance is a limited and specifically defined range in composition (especially in mineralogy and particle size) that relegates the occurrence of soil series to a specific kind, or very similar kinds, of parent material. Knowledge of the soil series thus identifies, within narrow ranges, not only the parent material but also the grain-size distribution, composition, and chemical properties of each horizon, the thickness and structure of each, and the seasonal soil temperature and wetness at the site.

Soil series provide a structure for organizing knowledge about soils and a basis for predicting the performance of soils in highway construction and for other engineering uses. Identifying soil series is helpful in planning the testing programs required for highway design.

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Application of Soil Taxonomy in Engineering

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Transferral of soil information among the disciplines concerned with soil is important. One of the traditional sources of basic soils information for engineering uses at the reconnaissance level has been the pedological maps and soil surveys prepared by the Soil Conservation Service. The new Soil Taxonomy incorporated by the Soil Conservation Service and other, cooperating agencies into all recent pedological mapping and reports contains key formative elements as building blocks for constructing soil classifications. Engineers may obtain useful information concerning soils on a regional basis by becoming familiar with the new Soil Taxonomy. Individual soil profiles are classified and the formative elements give clues

to general climatic conditions and more specific information on such criteria as soil moisture, texture, and soil particle mineralogy. Examples are given of information that can be inferred with accuracy, and limitations are stressed at category levels above the soil series. Soil series will remain the basic unit for engineering interpretations of soil surveys because of their familiarity and the availability of extensive quantitative data.

There are many related disciplines that concern themselves with the unconsolidated material at and below the surface of the earth. Soil scientists, geologists, and geotechnical engineers each study, define, classify, and utilize soil for their own purposes, and much of the resulting information is transferred from one discipline to another. It is necessary, therefore, for each discipline to keep informed about recent developments in the others.

In 1960 a revised descriptive taxonomy popularly known as the 7th Approximation was published by the Soil Conservation Service of the U.S. Department of Agriculture (1). The taxonomy has had many growing pains through the years and is just now beginning to become known to the engineering profession. Johnson and McClelland, in a paper in this Record, have explained the history and philosophy of Soil Taxonomy.

Reactions to the new Soil Taxonomy have ranged from a humorous introduction by Handy (2) to a less than enthusiastic reception of the nomenclature by Hunt (3). The question seems to be, What are soil scientists attempting to do by introducing a new taxonomy, and why is it of any importance to geotechnical and other engineers? The system classifies soils as naturally occurring bodies in their natural setting and introduces quantitative values as well as qualitative determinations, thus, in part, satisfying the engineer's quest for numbers. It also enables one to become familiar with basic concepts of soil properties over large areas. Of course the engineer is mostly interested in small sites; as the classification narrows, more detailed information becomes available. However, for reasons explained later in this paper, it appears that the soil series will still provide the most data to engineers for some time to come.

The Soil Taxonomy system, built on diagnostic soil horizons, has been detailed by Bartelli in a paper in this Record. These diagnostic horizons are specific combinations of physical and chemical properties that define a central concept. Most of the distinguishing characteristics of the system are based on the presence or absence of the specific diagnostic horizons or on their existence in specified portions of the soil profile.

PAST USE OF SOIL SURVEY DATA

The practice of preparing engineering soils maps from soil survey information has been common since the close of World War II. Soil surveys have been used in conjunction with air-photo interpretation, geologic mapping, and groundwater investigations to provide basic data for the deductive reasoning processes that lead to the engineering soil map at the reconnaissance level. Many states have been using soil surveys for these purposes for many years. Some states, such as Illinois (4) and South Dakota (5), now incorporate statistical evaluations of engineering data of soil series in their work.

In New York State, Bennett and McAlpin (6) pioneered engineering soil mapping. Refinements of these early efforts (7) used soil surveys to a greater extent for basic soils data, and the other data sources became supportive. As in most work using soil surveys, the basic information block was the soil series. The soil series was converted to a landform-depositional process map unit based on geologic origin and type of parent material. In time, as soil scientists refined their discipline, the number of soil series multiplied. Arnold (8) indicates that the explosion of soil series information made it difficult for any one individual to become knowledgeable about the hundreds of soil series except by constantly using them in routine work. But that makes it difficult to extrapolate knowledge into areas where no familiar soil series exist.

APPLICATION OF SOIL TAXONOMY FOR ENGINEERING DATA

A basic knowledge of a few key words can provide the engineer with soils information on a regional basis. For example, the soils of New York State are geologically young, the result of glacial and postglacial deposits in a temperate, humid climate. All soils in New York are classified into 5 orders, excluding the Histosols or organic soils. These include only 10 suborders and 17 great groups. The following table gives the higher classification of the mineral soils of New York State.

Order	Suborder	Great Group
Entisols	Aquents	Fluvaquents
		Psammaquents
	Orthents	Udorthents
	Psamments	Udipsamments
		Aquipsamments
Inceptisols	Aquepts	Fragiaquepts
		Haplaquepts
		Humaquepts
	Ochrepts	Dystrochrepts
		Eutrochrepts
		Fragiochrepts
Mollisols	Aquolls	Haplaquolls
Spodosols	Aquods	Fragiaquods
		Sideraquods
	Orthods	Fragiorthods
		Haplorthods
Alfisols	Aqualfs	Ochraqualfs
	Udalfs	Hapludalfs

Knowing only information up to the great group level, the engineer with no knowledge of New York soils would recognize their geological youthfulness. The formative elements ent and ept would indicate little or minimum change in the parent material on which the soil profiles are produced. The engineer would also recognize those soils that have characteristics associated with seasonal wetness (Aquents, Aquepts, Aquolls, Aquods, and Aqualfs). The formative element ud, as in Udalf or Udorthent, indicates that the soil is a well-drained soil of the humid, temperate climates, as contrasted to the Uoralfs of colder areas or the Ustalfs of drier areas. It is this type of information that allows the engineer easily to become familiar with soils at a regional level. Buol, in a paper in this Record, has explained how soil moisture and temperature regimes are used in Soil Taxonomy.

At the next level of the system, the subgroup, a modifying work is added to the classification. The great group level identifies soils that satisfy a central concept or set of criteria. The subgroup modifier identifies a feature or features that fall outside of this central concept. One example of this that is of interest to the engineer is lithic, which denotes a rock contact within the control section.

As the classification becomes more specific more engineering information is revealed that, in turn, enables inferences and predictions to be made intelligently. Handy and Fenton, in a paper in this Record, explain in detail the information used at the family level of classification, including textural properties, mineralogy of clays and coarser particles, and other criteria.

Most engineering properties of soils are the result of moisture and texture relations. Particle-size distribution, mineralogy of the soil particles, and moisture content are among the most basic information needs of the geotechnical engineer. From these parameters many behavior characteristics of soils may be intelligently estimated. Such basic soil properties as suitability for cross-country trafficability, shrink-swell characteristics, and plasticity may be determined. It is quite obvious that a soil classified (at the family level) as sandy, siliceous; as coarse loamy over sand; or as sandy-skeletal, mixed will behave much differently from the soil classified as very fine, illitic.

Features such as frost potential may be inferred from the texture, moisture, and temperature parameters found at the family level. Coarse silty, fine silty, and fine loamy soils fall into the optimum permeability-capillarity range for frost susceptibility. Soil strength is a feature not easily estimated from the information at the family level and will be discussed further. However, in the fine and very fine textural classes, the mineralogy of the clay is an important feature in qualitatively determining strengths and behavior. It is important if the soil scientist can identify the clay minerals, and a large volume of X-ray data identifying the kind of clay minerals by horizon of soil series now exists.

LIMITATIONS OF SOIL TAXONOMY FOR ENGINEERING APPLICATIONS

All classification systems regarding soils and soil properties are limited when they are used for something other than that for which they were designed. Orvedal (9) points out that the problem with Soil Taxonomy for geotechnical engineers is the same as that with previous pedological classification systems, namely, the relatively shallow depth [usually 1 m (3.3 ft) but sometimes deeper] on which Soil Taxonomy is built. Users of soil surveys for engineering purposes have long recognized this shortcoming but nevertheless have extrapolated this information to deduce deeper soil characteristics. Because soil surveys are usually made for large areas, many borings to determine the deeper materials within the area cannot be expected.

Parent material as such is not a soil property in Soil Taxonomy. One problem encountered in working with levels of the taxonomy above the soil series is that without going to the soil series description it is often impossible to determine the parent material on which the soil has developed from the information contained even at the family level. For example, several soil series, given in the table below, are classified as Mollic Haplaquepts but are formed on various parent materials that have widely differing engineering properties.

Soil Series	Parent Material	Soil Series	Parent Material
Alden	Glacial till	Lamson	Glacio-lacustrine fine sand
Atherton	Glacio-fluvial sand and gravel	Fonda	Glacio-lacustrine silt and clay

Even at the family level, different parent materials give rise to the same classification. The following table gives variations of the parent material, Glossoboric Hapludalf, for various soil series.

Soil Series	Parent Material
Cayuga	Glacio-lacustrine over glacial till
Riga and Lairdsville	Frost-fractured material and glacial till over soft shale bedrock
Hudson and Schoharie	Glacio-lacustrine silt and clay

Although all five soil series in this example are classified at the subgroup level as Glossoboric Hapludalfs and at the family level as fine, illitic, mesic, one is formed on a glacio-lacustrine veneer over glacial till; two are formed on frost-fractured material mixed with glacial till moderately deep over soft, weathered shale bedrock; and two are formed on layered glacio-lacustrine silt and clay deposits. Engineering properties such as bearing capacity and consolidation characteristics of the deeper material vary greatly among soils in the same family.

Perhaps the easiest limitation to overcome is the nomenclature. The most useful terms have been explained by Philipson, Arnold, and Sangrey (10). As pointed out by Pheasant (11), the entire system need not be known to be of value in determining soil characteristics at a general level. The formative elements can be learned in a relatively short time.

ENGINEERING INFORMATION FROM SOIL SERIES

McCormack and Flach, in a paper in this Record, explain why the soil series has been retained in Soil Taxonomy. As early as 1963 Orvedal (9) stated that most data collected for engineering purposes have been collected at the series level. This is even more true today, especially in those states where there exist cooperative testing programs between the Soil Conservation Service and the state highway or transportation agency. Many qualitative data are given in the soil series description that complement and enhance the information available from both higher levels of soil classification and detailed quantitative data. These qualitative data include depth to contrasting material, drainage class, parent material, and landforms. Flooding, ponding, permeability characteristics, and internal structure are important characteristics of soil series.

As indicated earlier, the geologic relation and the origin of the parent material on which the soil-forming factors of time, climate, and biologic activities have been working are especially important. For example, the internal fabric or structure described for a series provides valuable engineering information relating to relative permeability. The descriptions also usually go beyond the thickness of the control section.

The soil series has long been familiar to geotechnical engineers interested in soil mapping. It will undoubtedly remain the basic information source.

CONCLUSIONS

Soil Taxonomy information can be a valuable extension of tried and proven methods for preparing engineering soil maps and interpretations. Much valuable information exists in the system and is reflected in the descriptive nomenclature by key formative elements. As in any classification scheme, the limitations of both the system and the nomenclature must be recognized. Members of the various disciplines concerned with soil should acquire a working knowledge of Soil Taxonomy so that information can be shared and the new taxonomy can be made more meaningful for all.

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Part 2
Soil Properties

Prediction Model for Unsaturated Hydraulic Conductivity of Highway Soils

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A method of predicting the hydraulic conductivities of subgrades and highway soil materials is discussed. In this method, the relation of soil moisture content and suction head is used to calculate the unsaturated hydraulic conductivity of soil. The value of the hydraulic conductivity at saturation (the soil permeability) is used as a matching factor during the calculations. The soil moisture content and suction head relation and the saturated conductivities of subgrades were determined in the laboratory by using the commercially available Tempe cell. Disturbed and undisturbed samples of Drummer and Fayette-C subgrades, Ottawa sand, and class X concrete sand were used in this study. The comparison between the experimental and the calculated values shows that the method successfully predicts the hydraulic conductivities of highway soil materials.

The engineering problems associated with the behavior of highway subgrade soils and pavement systems in response to moisture changes have been widely studied. The seasonal change in moisture content of subgrade soils and its effects on structural pavement performance are of particular interest to many highway engineers. That the shearing strength of a subgrade soil can be greatly reduced by the influx of moisture during spring thaw or long periods of heavy rainfall is well documented (1). This reduction in strength is generally attributed to an increase in moisture content of the subgrade soil and results in low soil suction (negative pore pressure) between the soil particles and sometimes an associated decrease in soil density. Consequently, the bearing capacity of the subgrade will be significantly reduced, and extensive deflection of the highway pavement may result (2).

It is generally accepted that the shearing strength and the bearing capacity of a fine-grained subgrade soil reach their lowest values at the beginning of the thawing period in the spring when soil suction reaches minimum. During this time frost boils, pumping, and pavement breakup may occur under a moving load (3). After the thawing period low soil suction will gradually increase with time, and as a result the subgrade will gradually gain in strength (4).

Dempsey and Elzeftawy (5) found that numerical models can be used to accurately predict moisture content and its movement in subgrade soils and pavement systems in conditions of constant or variable water-table depths. The mathematics in the numerical method are simple, flexible, and well suited for programming on a digital computer. Several methods of calculating unsaturated hydraulic conductivity by using data on pore-size distribution have been proposed for agricultural soils (6, 7). The calculated values have subsequently been compared with experimentally determined conductivities by many researchers (7). Elzeftawy and Mansell (8) recently concluded that a slightly modified Green and Corey method (7) can be successfully used to predict the hydraulic conductivity and soil moisture diffusivity of a fine sandy soil.

OBJECTIVES

Highway engineers have often questioned whether the moisture properties (parameters) of highway soils can be predicted or calculated for unsaturated or saturated water flow from a simple laboratory test. The purposes of this paper are (a) to show that the moisture properties of highway soils and subgrade can be predicted by using relations between soil moisture content and suction and (b) to propose a simplified laboratory procedure to determine the moisture content-suction relations for highway soils.

BACKGROUND

The transmission of water by soils has widespread relevance to engineering, geologic, and agricultural problems. It is customary to treat flow problems as essays in the solution of Laplace's equation, assuming that the soil-water body obeys Darcy's law, which may be written

$$v = -K \text{ grad } \phi \quad (1)$$

where

- v = flow velocity commonly expressed as $cm^3/s/unit$ area normal to v,
- ϕ = hydraulic potential, and
- K = constant characteristic of the soil, called the permeability of soil to water or hydraulic conductivity.

This law seems to be valid for Reynold numbers less than unity (9).

The one physical property of the soil that enters into a flow problem is the permeability; it must be known if a complete solution is to be obtained. In principle, a measurement of K is a simple matter of measuring the rate of flow of water in a column of the soil between planes of measured separation and hydraulic potential. Permeability has been held to decrease with time because of the percolating water releasing dissolved air into the soil pores, the swelling of colloidal materials, the growth of organisms in the pore spaces, the mechanical blocking by movement of the finest particles of noncemented material, and the chemical effect of the flowing water on the soil.

It has been more common to describe a granular material in terms of particle-size distribution (mechanical composition) than to regard it as a porous material with a given pore-size distribution. The best known procedure to calculate hydraulic conductivity (K) is perhaps that of Kozeny (10), but somewhat similar expressions have been derived by Terzaghi (11), Zunker (12), and others. The generalized Kozeny equation can be written as follows:

$$K = (g\rho/k\eta)(1/A^2)f^3/(1 - f)^2 \quad (2)$$

where

g = gravitational constant;
ρ and η = water density and viscosity respectively;
k = arbitrarily determined pore-shape factor, commonly in the range from 2.0 to 2.5;
A = specific surface area of soil, namely, the total surface of the solid part divided by the volume of that solid part; and
f = soil porosity.

However, it can be shown on theoretical grounds (13) that an expression such as Equation 2 is not applicable to a bundle of capillary tubes if the radii are distributed over a wide range of sizes. Surprisingly, the Kozeny formula does give approximately correct values of conductivity for a variety of industrial powders; in practice, however, it is not possible to vary the porosity over a sufficient range to provide a searching test of the formula in regard to the porosity factor.

Dependence of Hydraulic Conductivity on Moisture Content of Soil

Engineers know that Darcy's law (Equation 1) is valid for a wide texture range of soils saturated with water for Reynold numbers less than unity. The validity of this law when the soil is unsaturated (the degree of saturation is less than 100 percent) has been established during the last 10 years. In its wet state a typical soil contains pores with an upper size limit of about a millimeter, and very little water is lost until the suction exceeds something of the order of a few centimeters of water. Emptying a pore at such suction leaves the solid walls coated with a very thin film of water in which liquid flow takes place slowly (compared with liquid flow when the pore is full). An empty pore thus contributes only negligibly to the total hydraulic conductivity of the soil body. A reduction of the moisture content is thus equivalent to a reduction of effective porosity for the purpose of assessing conductivity and results in a reduction of that conductivity. Because the moisture content is progressively reduced by a progressive increase of suction, the larger pores are emptied in the earlier states of unsaturation and the smaller pores are left full of liquid water. It follows that the earlier stages of moisture reduction are more effective than the later stages in reducing conductivity. It should be emphasized that a pore full of air is not merely ineffective as a conductor but also becomes an obstacle: Liquid water that originally passed through when the pore was full of water is deflected around it when it is dried. In effect the true flow paths become more tortuous and therefore longer; i.e., the drier the soil becomes, the more tortuous are the flow paths.

Model to Predict Hydraulic Conductivity

Childs and Collis-George (13), Millington and Quirk (14), Green and Corey (7), and others have explored the possibility of predicting the hydraulic conductivity of soils and porous materials from data on pore-size distribution. Such predictions are of interest because the hydraulic conductivity-moisture content function is relatively difficult to measure whereas pore-size distribution is easily characterized by the standard measurement of moisture content versus suction.

The conductivities are obtained by dividing the relation of moisture content and suction head [$h(\theta)$] into n equal water-content increments, obtaining the suction (h) at the midpoint of each increment, and calculating the conductivity by using the following equation:

$$K(\theta)_i = (30\gamma^2/\rho g \eta)(\epsilon^p/n^2) \sum_{j=i}^{m} [(2j + 1 - 2i)h_j^{-2}] \qquad i = 1, 2, \ldots, m \qquad (3)$$

where

$K(\theta)_i$ = calculated conductivity for a specified moisture content corresponding to the ith increment (cm/min);
θ = moisture content (cm^3/cm^3);
γ = surface tension of water (N/cm);
ρ = density of water (g/cm^3);
g = gravitational constant (cm/s^2);
η = kinematic viscosity of water (cm^2/s);
θ_s = saturated moisture content (cm^3/cm^3);
ϵ = water-saturated porosity (cm^3/cm^3), i.e., $\epsilon = \theta_s$;
p = constant whose value depends on the method of calculation (7), equal to 2 in these calculations;
θ_o = lowest moisture content on the experimental $h(\theta)$ curve;
n = total number of pore classes between $\theta = \theta_o$ and θ_s {$n = m[\theta_s/(\theta_s - \theta_o)]$};
i = last moisture-content increment on the wet end (e.g., $i = 1$ identifies the pore class corresponding to θ_s and $i = m$ identifies the pore class corresponding to θ_o);
h_j = suction (negative pressure) for a given class of moisture-filled pores (centimeters of water head); and
30 = the composite of the constant 1/8 from Poiseuille's equation, 4 from the square of $r = 2\gamma/h$, where r is the pore radius and 60 converts from seconds to minutes.

Elzeftawy and Mansell (8) and Green and Corey (7) conclude that Equation 3 yields reasonable values of the hydraulic conductivities for a range of soil types if a matching factor (usually the ratio of the measured to the calculated saturated conductivity) is used. Elzeftawy and Mansell (8) state that matching at water saturation has a distinct advantage over matching at desaturated moisture contents because inaccuracies in calculated $K(\theta)$ can be more easily tolerated at lower moisture contents than at high moisture contents when calculated results are to be used in subsequent prediction of the movement of water in field soils. They also mention that determinations of water-saturated conductivities are much simpler and quicker to evaluate experimentally than those of unsaturated conductivities. Equation 3 can be written then by using the matching factor (K_s/K_{sc}) in the following form:

$$K(\theta)_i = (K_s/K_{sc})(30\gamma^2/\rho g \eta)(\epsilon^p/n^2) \sum_{j=i}^{m} [(2j + 1 - 2i)h_j^{-2}] \qquad (4)$$

where K_s is the measured saturated hydraulic conductivity and K_{sc} is the calculated saturated conductivity. Equation 4 is being used in calculations of $K(\theta)$ for highway and subgrade soils in this study. The only necessary laboratory test is the determination of K_s and the moisture content versus suction for each highway soil [details on the derivation of Equations 3 and 4 are given by Childs and Collis-George (13) and Millington and Quirk (14)].

MATERIALS AND METHODS

Soils

Disturbed and undisturbed soil core samples 5.4 cm (2 in) in diameter and 3 cm (1.2 in) in height were used to determine relations between soil moisture content and suction characteristics of several highway soils. The undisturbed core samples were collected from three profile depths of Drummer subgrade soil at a pavement test site in Piatt County, Illinois. The disturbed core samples were prepared in the laboratory by using Illinoian till, Fayette-C, two grades of Ottawa sand (2 to 0.84 mm and 0.50 to 0.05 mm), and a class X concrete sand. The engineering properties of all soil samples used in this study are given in Table 1.

Equipment

For many years soil physicists removed moisture from soil by creating a pressure difference, generally by suction across a porous ceramic material that served as a link between soil moisture and outside water. Pressure membrane and pressure plate extractors are a modification of this principle. If pressure is applied inside the chamber of the apparatus, a pressure difference is maintained across a porous plate or membrane, the bottom of which is at atmospheric pressure.

For the low range of pressure, 0 to 101.3 kPa (0 to 1 atm), the soil cores were placed in Tempe pressure cells saturated with water and then allowed to drain following sequential subjection to air pressures. Volumetric moisture content was determined from the weight of the cell corresponding to each static equilibrium pressure and the oven-dry weight of the soil core. Before drying, the same cores were resaturated for determination of water-saturated hydraulic conductivity (K_s). A 1519.8-kPa (15-bar) ceramic plate extractor was used to determine the moisture content for all soil samples for the high range of air pressure (101.3, 506.6, and 1519.8 kPa) (1, 5, and 15 atm), as reported by Richards (15).

RESULTS AND DISCUSSION

Data from some agricultural soils were selected from the literature on the basis of having K(θ) values over a wide range of moisture contents and a detailed moisture content-suction head relation. Soils selected were the Lakeland fine sand of Elzeftawy and Mansell (8), the 1 to 0.5-mm sand of Childs and Collis-George (13), the Botany sand of Watson (16), the Guelph loam of Elrick and Bowman (17), and the Dana loam of Elzeftawy. These data were obtained in the laboratory under conditions that allowed the hydraulic conductivity, moisture content, and suction head to be measured on the same soil sample.

Figures 1, 2, and 3 show the relations of hydraulic conductivity and moisture content for agricultural soils, Lakeland fine sand, 1 to 0.5-mm sand and Botany sand, and Guelph and Dana loam respectively. The lines represent calculated values using the saturated hydraulic conductivities (K_s) (permeability) as matching factors. The symbols represent experimental data. The dry densities and moisture-saturated hydraulic conductivities for the three depths of Lakeland fine sand (AASHO classification A-3) are given in Table 2 (8). The variation in dry density with depth of the field soil profile was almost negligible; however, the hydraulic conductivity (K_s) of the bottom layer is much higher than that of the surface layer. From the data shown in Figures 1 to 3 it can be concluded that measured and calculated values of hydraulic conductivities were in good agreement for the agricultural soils. However, there is some pronounced deviation between calculated and measured conductivities, especially for lower values of volumetric moisture content (θ). This observation supports the suggestion by Elzeftawy and Mansell (8) that multiple matching factors are needed somewhat below the bubbling pressure to calculate hydraulic conductivities for dry soils that are found particularly in arid and semiarid regions.

Characteristic curves for soil moisture content versus suction, obtained by stepwise drainage, are shown in Figure 4 for Drummer subgrade [0 to 30-cm (0 to 12-in) depth], Illinoian till, and class X concrete sand highway soils. It is obvious that the soil-moisture characteristic curve is strongly affected by soil texture. The greater the soil-fines content (silt and clay) is, the greater is the water content at any particular suction and the more gradual is the slope of the curve. In sandy soil most of the pores are relatively large; once these large pores are emptied at a given suction, only a small amount of water remains. In a clayey soil the pore-size distribution is more uniform and more of the water is absorbed so that increasing the suction causes a more gradual decrease in water content.

The calculated and experimental hydraulic conductivities for the three profile depths of Drummer subgrade soil (AASHO A-7-6)—0 to 30, 30 to 75, and 75 to 90 cm (0 to 12, 12 to 30, and 30 to 36 in)—are shown in Figure 5. The experimental data were obtained by a method that uses the steady-state flow concept and is similar to that of Elzeftawy and Mansell (8).

Figure 6 shows the hydraulic conductivity [K(θ)] of Illinoian till subgrade as a function of the subgrade soil moisture content. The experimental values were obtained from a compacted laboratory soil column (18). This Illinoian till was compacted at an optimum moisture content of 11 percent and a density value of 1.72 g/cm^3 (107.1 lb/ft^3). Notice that an increase in the soil moisture content (θ) from 0.28 to 0.42 cm^3/cm^3 (in^3/in^3) has increased the hydraulic conductivity from 3.1 nm/h to 1.9 mm/h (0.12×10^{-6} to 0.07 in/h) respectively.

The hydraulic conductivities of Ottawa sand and class X concrete sand are shown in Figure 7 and Fayette-C subgrade and Beer Farm agricultural soil in Figure 8. These soils were compacted air-dry in the Tempe pressure cells to determine the soil moisture content versus suction relation [h(θ)] for each soil. The saturated hydraulic conductivities [soil permeability (K_s)] for these highway soils were determined by using the same soil core samples. The solid lines in the figures represent the calculated values of K(θ) and the circles, squares, and triangles represent the experimental data. These highway soils were selected to cover a wide AASHO classification range—from A-3 to A-7. They also represent a wide range of pore-size distributions on which the calculations of hydraulic conductivities are based. The saturated conductivities (permeability) ranged from 0.22 cm/h (0.019 in/h) for Fayette-C to 16.7 cm/h (6.6 in/h) for the class X concrete sand. It is very clear that the calculations of K(θ) are in excellent agreement with the experimental data.

Just as the flow of heat can be expressed in the form of a diffusion equation familiar to engineers, in which the diffusivity is expressed in terms of thermal conductivity, density, and specific heat of the material, so Darcy's law (Equation 1) may be put into a diffusionlike form in which moisture diffusivity is given by

$$D(\theta) = K(\theta)/C(\theta) \quad (5)$$

where $C(\theta) = \partial\theta/\partial h$ is the specific water capacity of the soil. Since the soil moisture content-suction function [h(θ)] is hysteretic (θ depends on drying or wetting of the soil system), it follows that soil moisture diffusivity is also a hysteretic function. In calculating D(θ) of highway soils and subgrades from the available K(θ) data, attention should be paid to the drying or wetting pro-

Table 1. Engineering properties of soils studied.

Soil Material	Sand (%)	Silt (%)	Clay (%)	Liquid Limit (%)	Plastic Limit (%)	Compacted Dry Density (kg/cm³)	Optimum Moisture Content[a] (%)	Saturated Hydraulic Conductivity (μm/s)
Drummer soil[b]								
0 to 30 cm	6	77.2	16.8	42.5	26.8	1520	21.2	0.0586
30 to 75 cm	6.3	80.5	13.2	54.7	29.2	1300	21.8	0.1
75 to 90 cm	6.9	82.6	10.5	48.9	32	1430	22.5	0.0694
Illinoian till[c]	62	20	18	22.2	14.7	1720	11.7	0.861
Lakeland fine sand[d]	98	2	0	NP	NP	1560	0.65[e]	41.1
Ottawa sand[d]								
0.50 to 0.05 mm	100	0	0	NP	NP	1700	0.50[e]	28.6
2 to 0.84 mm	100	0	0	NP	NP	1650	0.43[e]	37.2
Fayette-C subgrade[c]	7	75	18	32	23	1250	17.2	0.597
Concrete sand[d]	98.8	1.2	0	NP	NP	1640	0.61[e]	46.4
Beer Farm soil[f]	12.3	37.45	50.25	54.9	29.4	1020	24.3	2.48

Notes: 1 cm = 0.4 in; 1 kg = 2.2 lb; 1 cm³ = 0.06 in³.
NP indicates nonplastic.

[a] Gravimetric moisture content.
[b] AASHO A-7-6.
[c] AASHO A-4.
[d] AASHO A-3.
[e] Air-dry gravimetric moisture content.
[f] AASHO A-7.

Figure 1. Experimental and calculated hydraulic conductivities of Lakeland fine sand.

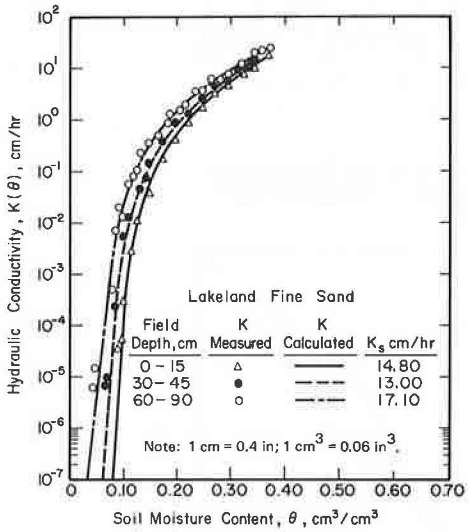


Figure 3. Experimental and calculated hydraulic conductivities of Botany sand.

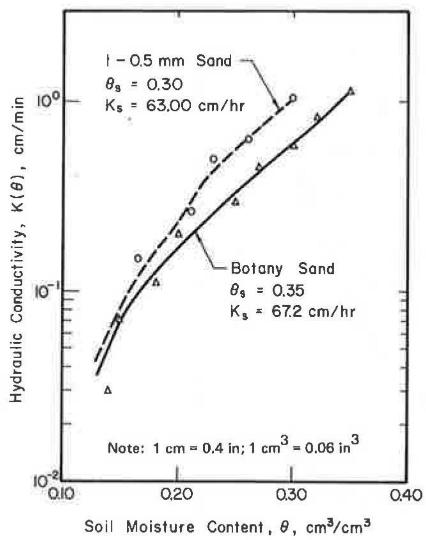


Figure 2. Experimental and calculated hydraulic conductivities of Dana and Guelph loam.

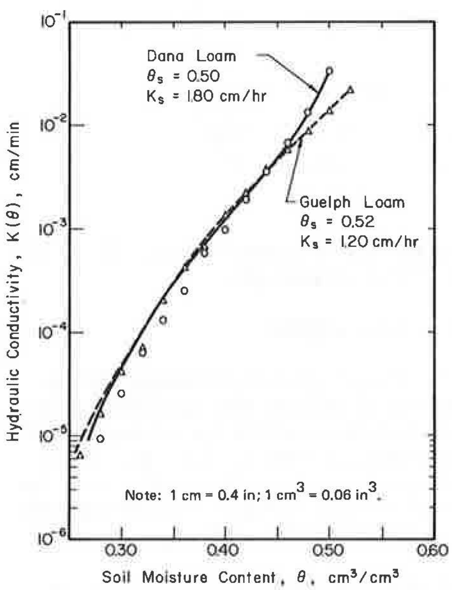


Table 2. Dry density and saturated hydraulic conductivity for three depths of Lakeland fine sand.

Soil Depth (cm)	Dry Density, ρ_s (g/cm³)	t	Saturated Hydraulic Conductivity, K_s (cm/h)	t
0 to 15	1.56	0.06	14.8	1.12
30 to 45	1.57	0.03	13	0.93
60 to 90	1.57	0.05	17.1	1.09

Notes: 1 cm = 0.4 in; 1 g/cm³ = 0.036 lb/in³.
t-distribution at 95 percent confidence level.

cesses of these soils.

It was felt that choosing an agricultural soil sample representative of Illinois soil might give a better idea of the validity of the model, especially when it is applied to a heavy clay soil. A surface soil sample was collected from the Beer Farm in Illinois, and its h(θ) function and K_s were obtained in the laboratory. The engineering properties of this sample are given in Table 1, and its experimental and calculated K(θ) are shown in Figure 8. The agreement between the model prediction and experimental values of the hydraulic conductivity is excel-

Figure 4. Soil moisture content-suction relations of Drummer soil, Illinoian till, and class X concrete sand.

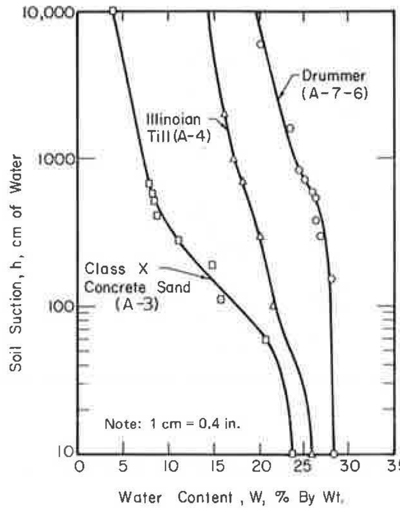


Figure 5. Experimental and calculated hydraulic conductivities of Drummer subgrade.

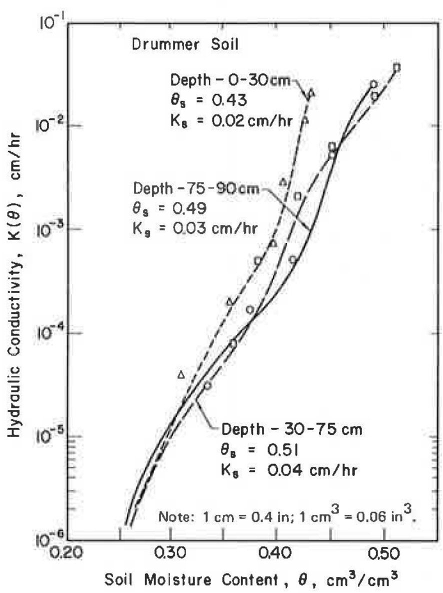


Figure 6. Experimental and calculated hydraulic conductivity of Illinoian till subgrade.

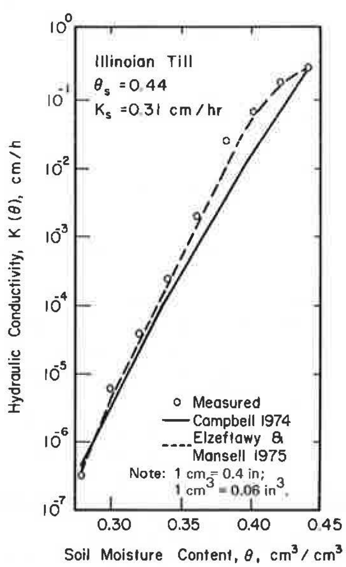


Figure 7. Experimental and calculated hydraulic conductivities of Ottawa sand and class X concrete sand.

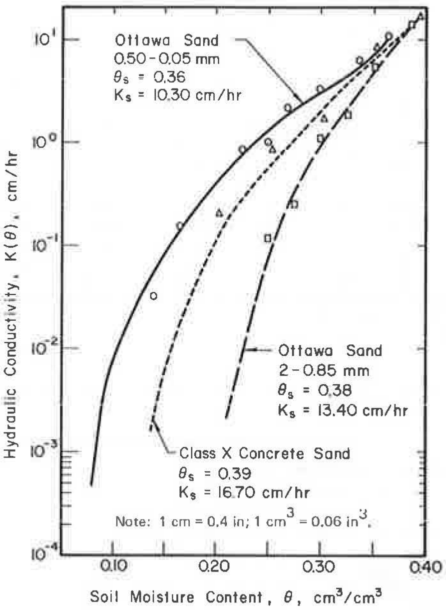
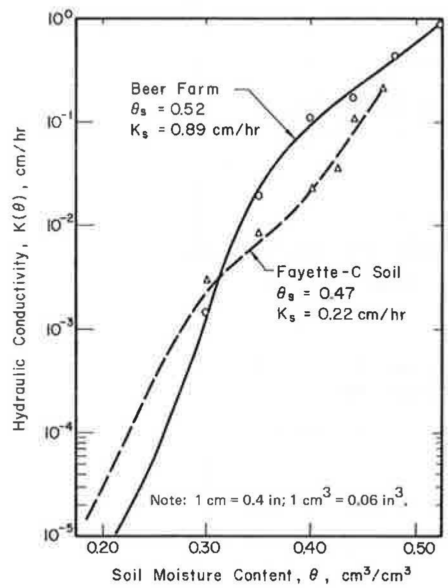


Figure 8. Experimental and calculated hydraulic conductivities of Fayette-C subgrade and Beer's Farm agricultural soil.



lent regardless of the heavy nature of this soil (50.25 percent clay and 37.45 percent silt).

SUMMARY AND CONCLUSIONS

The procedure discussed here for predicting the hydraulic conductivities of highway soil materials provides an economical and accurate method for determining the necessary hydraulic parameters for the study of unsaturated and saturated moisture flow in pavement materials and subgrades. The following conclusions can be drawn from the results of the study.

1. The model successfully predicts the hydraulic

conductivity of a wide range of subgrades and highway soils.

2. The simplified laboratory procedure proposed is reliable and can be easily used to determine the soil moisture-suction relations of highway soils.

3. Quicker and more economical evaluation of the unsaturated hydraulic conductivities of subgrade and highway soils can be done by using the proposed method.

ACKNOWLEDGMENTS

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The opinions, findings, and conclusions expressed in this report are ours and not necessarily those of the Illinois Department of Transportation.

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Abridgment

Physicochemical Considerations in Thermal Susceptibility of a Base-Course Material

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Thermal susceptibility in a granular base-course material indicates that the material will experience a volumetric contraction on freezing in a condition of constant moisture content. The measure of thermal susceptibility is the freeze coefficient of the material (1), which is the linear coefficient of thermal contraction for temperature changes below freezing (strain per degree centigrade).

Earlier data for six tested materials (2) show that a particle reorientation is the most probable mechanism to account for the noted change in the measured properties of suction and volume. Each freeze induces a volume contraction, and each freeze-thaw cycle produces a permanent volume change. The results of a scanning electron microscope study of particle structure with and without a freeze-thaw-cycle history are presented to verify the hypothesis of particle reorientation. Physicochemical measurements are shown to substantiate the clay-moisture interaction that causes the particle reorientation.

SCANNING ELECTRON MICROSCOPE STUDY

A material of intermediate activity was chosen for investigation. A set of samples were compacted at a single moisture content, slightly dry of optimum; this moisture condition would assure a volumetric contraction in all samples. The samples were then sealed for a time to allow moisture equilibrium. Half of the samples were run through a series of six freeze-thaw cycles; all of the samples were then prepared for the scanning electron microscope study.

Original Structure

The electron micrographs in Figure 1 show the compacted clay structure that had not undergone freeze-thaw cycling. These micrographs show that the clay minerals attapulgite and montmorillonite combine to form a clay skin that surrounds the larger silt particles. The attapulgite fibers further show a clay structure interconnecting the silt particles. The orientation of the attapulgite fibers is random, both in covering the silt particles and in interconnecting them.

Structure After Freeze-Thaw Cycling

The electron micrographs in Figure 2 show the compacted clay structure following freeze-thaw cycling. There is no longer a continuous clay skin interconnecting the silt-sized particles, particularly the attapulgite fibers. These fibers are much more oriented around the particles. The montmorillonite film is no longer continuous between the particles and appears as a torn, crumpled film where it lacks the support provided by the attapulgite fibers.

Reorientation

The clay particles maintain an intimate relation with the moisture that surrounds them. The strength with which this moisture is held by the clay particles depends on the size of the clay particle and the ions in the moisture and on the surface of the clay mineral.

When the temperature of the material drops below freezing, the water in the larger voids will freeze first. Further lowering of the temperature draws moisture away from the clay particles, primarily because of the temperature-energy gradient between the ice and the water. This drying process forces the clay particles to reduce their spacing and reorient themselves to use the remaining surface moisture more effectively. With the continuous clay skin shown in Figure 1, this clay particle reorientation will force the enmeshed silt particles to reorient also, producing the volume change noted. This is supported by the reorientation of the attapulgite fibers after freeze-thaw cycling. The more orderly parallel arrangement indicates that the fibers have been drawn together by the freezing process.

This behavior has been postulated for the structural realignment in gels under the effects of freeze drying, which shows a decrease in particle spacing. These phenomena are for rapid freezing in a saturated environment where the ice crystals that form are considered the primary force that pushes the clay particles closer together as the ice crystals grow. The particle reorientation validated in this study cannot use the force of ice crystals on the structure to produce an overall decrease in volume. The clay structure is actually dried by a freezing process that is limited to the larger void spaces in which there is a large amount of air space to absorb the expansion of any ice that forms. The reorientation in this study depends on the clay-moisture interaction.

PHYSICOCHEMICAL CONSIDERATIONS

The volume change for all samples is activated by a uniform decrease in temperature; thus a similar amount of work is done, externally, on all the samples and materials tested. The difference in the amount of volume change is the result of the difference in the interparticle forces in the structure of the sample. Structure differences result from different compaction methods, moisture contents, particle sizes, and ion concentrations in the tested materials.

Repulsive and Attractive Potential

Previous researchers have established theoretical relations for interparticle forces. These forces, which are related to the physicochemical properties of the clay particles, are represented by an attractive or repulsive potential that is controlled by the particle spacing.

Figure 3 shows the relation established for the repulsive potential and the influence of ion concentration. In the granular materials investigated in this study, the major ion present remains the same for all materials because the basic material is limestone. The ion concentration changes if the materials have different durability or solubility levels. A material that is more soluble and more easily broken during the compaction process produces a higher ion concentration.

The attractive potential is primarily an adsorptive force-field effect resulting from Van der Waal's forces. The condition of low moisture contents, which accentuates these attractive potentials, has previously been shown to exist for base-course material in west Texas. Figure 3 also shows the relation established for the attractive potential and the influence of particle size. Adsorptive properties are influenced primarily by the size, or specific surface area, of a material.

Interpretation

Ion concentration and specific surface area exist together in a material and not as separate quantities as shown in

Figure 1. Compacted clay structure without a freeze-thaw-cycle history.

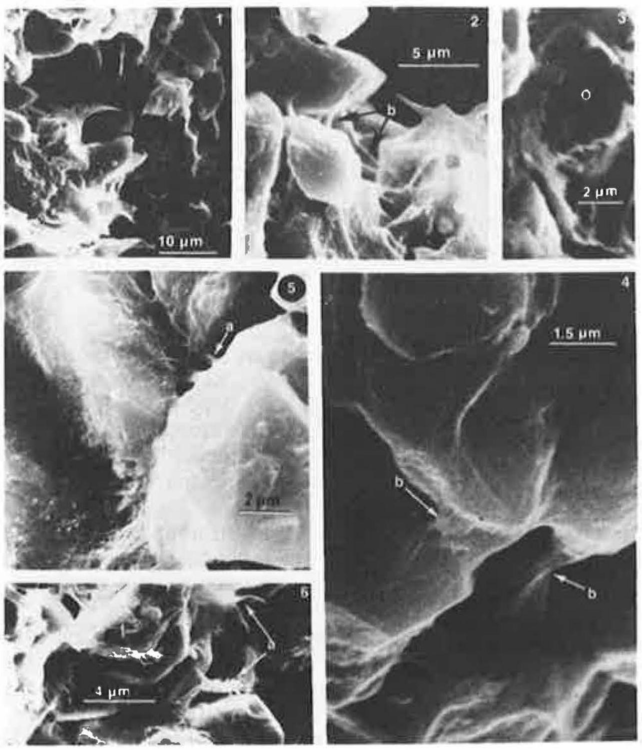

Figure 2. Compacted clay structure after freeze-thaw cycling.

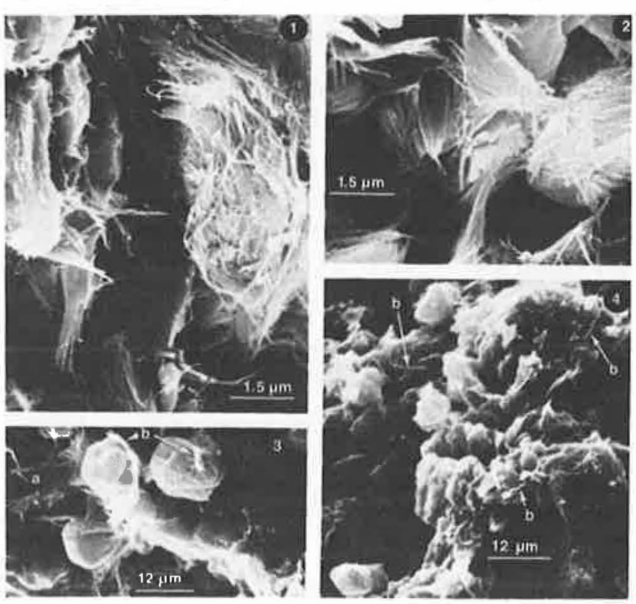

Figure 3. Attractive and repulsive potentials between clay particles as a function of particle spacing.

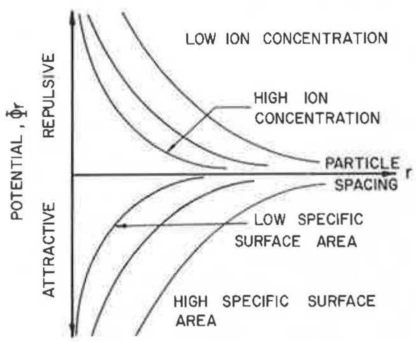

Figure 4. Composite curve formed by combining the effect of attractive and repulsive potentials.

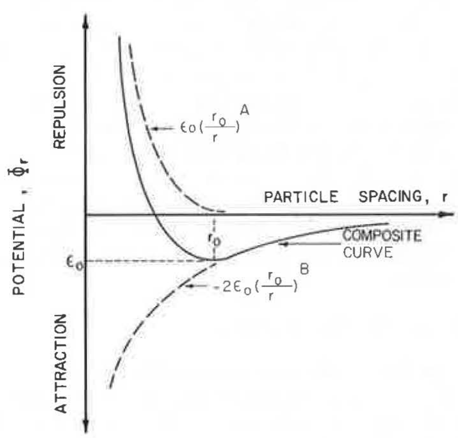

Figure 5. Ion-concentration exponent as a function of resistivity.

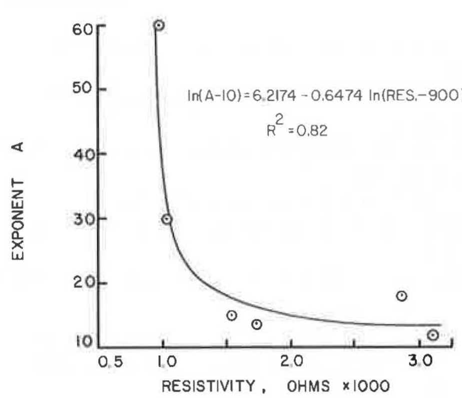

Figure 6. Specific-surface-area exponent as a function of specific surface area.

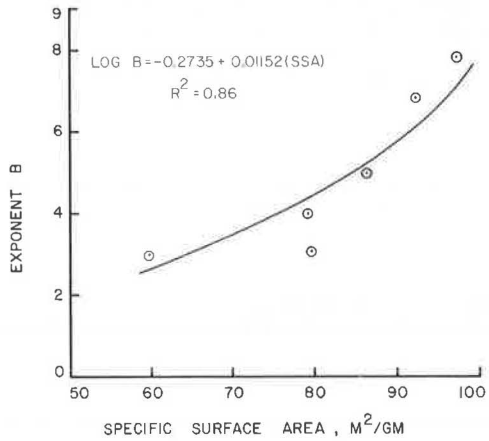

Figure 3. The combination of the separate curves in Figure 3 is shown in Figure 4. When the A exponent is set equal to 12 and the B exponent is set equal to 6, the resulting curve is the Lennard-Jones potential for intermolecular forces, developed in statistical mechanics. This curve is identical to the curve for freeze coefficient and suction given in the study by Carpenter, Lytton, and Epps (1), except that the freeze coefficient replaces the force potential and suction replaces particle spacing.

Because the energy change is similar for all samples, the resulting deformation depends on the existing interparticle forces and any forces activated by the freezing process. The freeze coefficient may thus be considered analogous to the force potential. Suction is related to particle spacing in that a dry sample has a flocculated structure with large center-to-center spacing and a high suction. A moister sample has a dispersed structure with a smaller center-to-center spacing and a low suction. A unique relation is not available although the trend for both quantities is the same and they may be considered analogous. Thus, the behavior of a sample during freezing is influenced by the ion concentration and the specific surface area of the material, as shown in Figure 4, and these two quantities may be considered as material properties.

MATERIAL PROPERTY RELATIONS

As demonstrated by the previous discussion, the interrelation of particle size and ion concentration will produce a freeze coefficient-suction curve. Data for this curve for the six tested materials (1) were regressed against the equation developed from Figure 4, which is

$$FC = FC_{max}(\log h_o/\log h)^A - 2(\log h_o/\log h)^B \quad (1)$$

where

- FC = freeze coefficient (strain per degree centigrade),
- FC_{max} = maximum freeze coefficient (strain per degree centigrade),
- h_o = suction of the sample with the maximum freeze coefficient (Pa),
- h = suction at which FC is desired (Pa),
- A = exponent denoting the effect of ion concentration, and
- B = exponent denoting the effect of specific surface area.

This regression analysis produced the exponents given in the following table. Test materials are those designated by Carpenter, Lytton, and Epps (1).

Test Material	Specific Surface Area	Ion Concentration
4	6.8	18
5	5	12
6B	4	30
6JD	8	14
7SA	3.5	15
6FS	3	60

The relation of the A exponent with the ion concentration is shown in Figure 5. Resistivity measurements taken on 1-cm-thick samples of base-course material mixed to a moisture content of 13 percent are used to represent the relative ion concentration of each material. The resistivity is inversely related to the ion concentration. A pore fluid with a high resistance to flow lacks ions to aid conduction; a pore fluid with a higher ion concentration will conduct electricity and have a low resistance. The proposed relation in Figure 3 is verified by Figure 5 in which the larger ion concentration (lower resistivity) has a larger A exponent.

The relation of the B exponent with the specific surface area of each material is shown in Figure 6. This relation clearly shows that a larger specific surface area produces a larger B exponent.

CONCLUSIONS

The importance of predicting the magnitude of the freeze coefficient in the relation of freeze contraction and pavement damage becomes evident as a base-course layer contracts during a freeze. This produces a buildup of tensile stress (1), which, when it exceeds the tensile strength, causes the base course to crack. Repeated freeze cycles will propagate the crack through the asphalt surface. The larger the freeze coefficient is the higher the stresses and the greater the damage will be.

The granular materials investigated in this study show contraction on freezing for the climatic area of west Texas and much of the Southwest. This contraction is controlled by the properties of the clay minerals and the unique, membranelike clay particle structure they form around the larger silt particles. The freezing process forces the clay particles to reorient, which produces the noted volume contraction shown in the scanning electron microscope study. The amount of reorientation, and thus of volume change, is controlled by the specific surface area and the ion concentration.

The specific surface area is a property of the clay fraction of the material. The ion concentration (resistivity) is a property of the granular portion of the material and represents the relative durability or solubility of the material. The ability of these two properties to model the freeze behavior is important because it shows how the coarse and fine-grained fractions of a material fit together and influence the environmental behavior of the material under freeze-thaw activity.

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Publication of this paper sponsored by Committee on Physicochemical Phenomena in Soils.

Climatic Materials Characterization of Fine-Grained Soils

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Characterization of the performance-related characteristics of fine-grained subgrade soils depends largely on the moisture and temperature regime in which they are found. This paper presents the results of a repeated-load testing program designed to produce some important materials properties for a variety of fine-grained subgrade soils. The materials properties characterized are compatible with a newly developed Federal Highway Administration computerized stress and distress analysis system, VESYS II, which represents flexible pavements as linearly viscoelastic layered media. Such characterization has not been done in previous studies. The materials characteristics presented in this study are resilient modulus, residual strain, and permanent deformation characteristics, all of which, as expected, vary with the number of load repetitions. The results, taken from repetitive load tests on three different soils having a range of clay contents of 20 to 70 percent, include the relation of the materials characteristics to mean stress, deviator stress, soil suction, clay content, and temperature. Because the equilibrium suction value of a subgrade soil beneath a pavement is related to the climatically controlled Thornthwaite Moisture Index, it is possible to infer under what conditions and in which parts of the United States special design considerations will be required for pavement structures that rest on the tested soils.

The performance of highway pavements is controlled by the traffic loading, the climatic conditions, and the mechanical properties of the materials in the pavement layers. The properties of subgrade soils that are most important in predicting the performance of pavements under load are its creep compliance and permanent deformation characteristics. These two properties are used as input to the VESYS II pavement-analysis system of the Federal Highway Administration (FHWA) (1, 2, 3). This paper presents the results of a repeated-load testing program at Texas A&M University that was designed to produce some of these important material properties for a variety of fine-grained subgrade soils. The experimental design of the testing program included various levels of temperature, soil suction, stress intensity, clay content, and load repetitions. The properties that were measured included the resilient modulus and the permanent strain properties as currently used in the VESYS II computer program.

Climate influences material properties by changing the temperature and the availability of moisture. This availability is measured by a climatic moisture index that indicates the relative balance between water entering the soil as rainfall and water leaving the soil as either evaporation or transpiration through plants. Russam and Coleman (4) found a reliable correlation between the Thornthwaite Moisture Index and the soil suction, which was measured at depths remote from the seasonal influences of moisture and temperature variations. That relation (Figure 1) shows that in any given climate the suction that is expected to develop beneath a pavement depends on the amount of fines present in the soil. Suction and temperature are thus measurable quantities that are directly related to the local climate and are important variables in the climatic design of pavements.

DEFINITIONS

Several of the terms used in this paper are defined below.

1. Resilient deformation or recoverable deformation is that portion of the total deformation that is recovered after the load is removed.
2. Residual deformation or plastic deformation is that portion of the total deformation that is not recovered before the next load application.
3. Resilient strain or elastic strain (ϵ_r) is the ratio of the resilient deformation to the sample length.
4. Residual strain or plastic strain (ϵ_p) is the ratio of the residual deformation to the sample length.
5. Resilient modulus (M_R) is the ratio of the deviator stress to resilient strain. The resilient modulus is analogous to the elastic modulus in static testing.
6. Soil suction is the energy with which water is attracted to soil and is measured by the work required to move this water from its existing state to a pressure-free, distilled state.

The total suction can be determined by measuring the vapor pressure in equilibrium with the soil water. The total suction can be quantitatively defined by the Kelvin equation, which expresses the total suction (h) in gram·centimeter/gram of water vapor (centimeters of water):

$$h = (RT/gm) \log_e (P/P_o) \qquad (1)$$

where

R = gas constant [8.314 J/°C mole (83 million ergs/°C mole)],
T = absolute temperature (°C),
g = gravitational force [981 cm/s^2 (0.39 in/s^2)],
m = molecular weight of water [18.02 g/mole (0.63 oz/mole)],
P = vapor pressure of soil water,
P_o = vapor pressure of free water, and
P/P_o = relative humidity (or relative vapor pressure).

Thus, the total suction is directly related to the relative humidity of the soil. Because the relative humidity is always 1.0 or less, its logarithm is always zero or negative and thus h is always negative. Consequently, the higher the relative humidity is, the more moisture the sample contains and the smaller the absolute value of the suction will be.

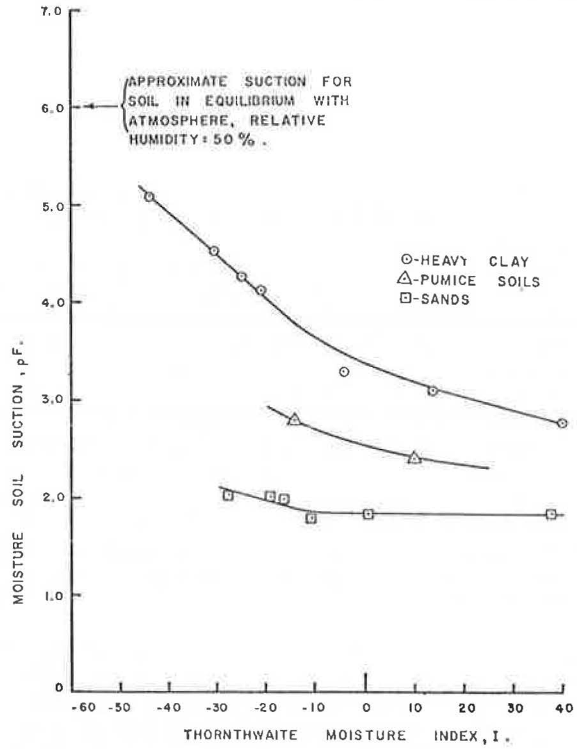
Although soil suction is defined as a negative quantity, its absolute value or positive magnitude is normally used for ease of discussion. Thus, a soil suction of -980 kPa (-142 lbf/in^2) is referred to as a suction of 980 kPa (142 lbf/in^2).

MATERIALS AND TEST EQUIPMENT

Materials

The three soils used in this test program are classified as CH, CL, and ML. For ease in identifying the different soils, each soil is named for the town near which it was obtained. The CH soil was obtained from Moscow, Texas, and consists of dark gray, plastic clay that has a high shrink-swell potential. The CL soil was obtained from Floydada, Texas, and consists of fine, textured clay with alkaline sediments from the high plains. The ML soil, which was obtained from Allenfarm, Texas, con-

Figure 1. Subgrade soil suction versus Thornthwaite Moisture Index.



sists of reddish, calcareous soils that make up the flood plains of the Brazos River; in this soil, therefore, a small percentage of clay is mixed with a large amount of silt. The physical properties of the three soils are given in the table below (1 kPa = 0.145 lbf/in^2).

	Soil		
Property	Moscow	Floydada	Allenfarm
Liquid limit, %	83	30	27
Plastic index, %	55	13	0
Shrinkage limit, %	14	14	23
Optimum moisture content			
(Harvard miniature, 138 kPa), %	31.5	18	16
Soil classification			
AASHO	A-7-6(57)	A-6(7)	A-4(0)
Unified	CH	CL	ML
Specific gravity	2.69	2.70	2.72
Thornthwaite index	+21	-17	0
Percent passing No. 200 sieve	91	71	72
Clay (2 μ), %	70	39	20

The distribution of the soil less than 0.2 mm (0.008 in) was determined by using a hydrometer analysis in accordance with ASTM D422-61T (5). The Moscow, Floydada, and Allenfarm soils have clay percentages of 70, 39, and 20 percent respectively.

Although soil density and soil structure are important factors in determining the dynamic properties of soils, they were not controlled in this study. Johnson and Sallberg (6) report that the kneading compaction method best represents the soil structure obtained in the field. For this reason, Harvard miniature samples were made by using the kneading compaction method with a compressive stress of 138 kPa (20 lbf/in^2), which approximates a compaction effort that produces 97 percent of AASHO T 180 density.

Test Equipment

In this program, the following were to be measured: (a) soil suction before, during, and after testing; (b) vertical deformation, both permanent and recoverable, at any time during the test; and (c) magnitude of the applied vertical load. The repetitive loading apparatus used in the study is a pneumatically operated testing machine that applies an axial load to a standard triaxial cell. The axial pressure pulse consists of 0.2 s with the load applied and 1.8 s with the load off. This frequency corresponds to a highway speed of 72.4 km/h (45 mph). A psychrometer was chosen to measure the suction of the soil samples because this instrument has a large range and could be incorporated into an end cap, thus measuring the soil suction during the test. By using the dew-point method of measurement, temperature corrections could be made easily; the results are accurate to within ±5 percent. A pair of induction coils were used to measure the axial deflections by measuring the change in the magnetic field caused by a change in the spacing of the coils. The accuracy of the deflection measurements is ±0.0127 mm (±0.0005 in).

Test Matrix

The following table gives the variables considered in the testing program [1 kPa = 0.145 lbf/in^2 and 1°C = (1°F - 32)/1.8]:

Variable	High	Medium	Low
Soil suction, kPa			
Moscow (CH)	1725	759	414
Floydada (CL)	1035	345	138
Allenfarm (ML)	966	193	69
Temperature, °C	0	22.2	38
Stress condition			
Axial pressure (σ_1), kPa	118.7	241.5	172.5
Confining pressure (σ_3), kPa	24.1	138	103.5
Mean stress (σ_m), kPa	55.9	172.5	126.3
Stress ratio [$(\sigma_1 - \sigma_3)/\sigma_m$]	1.69	0.60	0.55
Clay fraction (-2 μ)	0.70	0.39	0.20

Different suction levels were used on each soil, and the higher suctions were used on the soils having higher clay content. The midlevel of suction was set at about optimum moisture content.

Method of Analysis

The equations presented in this paper were developed by using the two-step regression method of the SELECT computer program (7, 8). The first step is a linear regression on the logarithms of the dependent and independent variables. When the antilog is taken, the coefficients obtained in this first step become powers of the independent variables. The second step is a linear regression of the independent variables raised to the powers determined in the first step. With this method, there is no preset power law or polynomial form of the equation, and experience has shown that this method consistently produces higher coefficients of determination (R^2).

RESILIENT MODULUS

Although the resilient modulus is not used in the VESYS II computer programs, it is used in other pavement systems analysis programs such as FPS-BISTRO (9) and PDMAP (10); it is included here to show how subgrade stiffness depends on the climatically controlled variables of temperature and suction. The equation developed in this study for the resilient modulus (M_R) at a constant

Table 1. Constants for resilient-modulus equation.

	Soil		
Constant	Moscow (CH)	Floydada (CL)	Allenfarm (ML)
b	0.084	0.145	0.081
c	3.6	3.3	1.4
d	-0.60	-0.60	-0.16
e	3.6	2.0	-0.26
f	-0.27	-0.23	0.063
g	-3.3	-2.25	-0.30
a_0	-4791.99	7980.89	-1827.72
a_1	-27 272.4	2981.64	171 705.0
a_2	-45.0169	64.397	0.6566
a_3	-3.733	-4.2008	-4.4849
a_4	1.706×10^{-7}	-2.002×10^{-3}	64.6522
a_5	-5.0763	-3.7228	-1.6108
a_6	-0.1288	-0.1639	-0.001 155
a_7	0.059 99	-0.1974	-14.8816
a_8	-5.8416	-4.2766	-1.5899
R^2	0.534	0.453	0.766
Standard error, kPa	45 000	27 973	10 771

Note: 1 kPa = 0.145 lbf/in².

temperature of 22.2°C (72°F) is as follows:

$$M_R = a_0 + a_1 \left[(h_f/h_i)^{0.20} N^b\right] \{1 + a_2 (1-n)^c \left[1 + a_3 (\sigma_1 - \sigma_3)^d\right] + a_4 (S)^e \left[1 + a_5 (\sigma_1 - \sigma_3)^d + a_6 \sigma_m^f\right] + a_7 (nS)^g \left[1 + a_8 (\sigma_1 - \sigma_3)^d\right]\} \quad (2)$$

where

h_f = final suction (kPa × 0.145);
h_i = initial suction (kPa × 0.145);
N = number of load cycles;
(1 - n) = volumetric soil content in decimal form;
$(\sigma_1 - \sigma_3)$ = deviator stress (kPa × 0.145);
S = saturation (percent);
σ_m = mean stress (kPa × 0.145); and
nS = volumetric moisture content in decimal form.

The constants for this equation are given in Table 1.

The final suction and the number of load cycles are directly related to the resilient modulus whereas the deviator stress is inversely related. The power of the suction ratio is constant in all the equations at about 0.20; the power of the number of load cycles varies between 0.081 and 0.145. The power of the deviator stress is negative and becomes smaller when the clay content decreases below 40 percent. The suction and the number of load cycles have a larger influence on the resilient modulus than does the deviator stress.

Several general observations can be made from the three equations. As the clay content decreases, the power of the volumetric soil content, the volumetric moisture content, and the saturation decreases. However, the decrease is not linear with decreasing clay content. The single most important term in the equations is the number of load cycles. As the clay content decreases, the equations are less dependent on the soil suction and more dependent on the volumetric moisture properties. From a comparison of the coefficients of determination it appears that the resilient modulus becomes more predictable with lower clay contents.

A temperature correction must be made to this equation for temperatures other than 22.2° C (72° F). The resilient modulus of Equation 2 is multiplied by the following correction factor:

$$f_{M_R} = a_0 - a_1 (D/D_0)^b + a_2 (h/h_0)^c + a_3 (T/T_0)^d \times \{1 - a_4 (h/h_0)^c (D/D_0)^b + a_5 (N/N_0)^e \left[1 - a_6 (h/h_0)^c + a_8 (h/h_0)^c (D/D_0)^b - a_7 (D/D_0)^b\right]\} \quad (3)$$

where

(D/D_0) = deviator-stress ratio [D_0 = 94.6 kPa (13.7 lbf/in²)];
(h/h_0) = soil-suction ratio [h_0 = 759, 345, and 193 kPa (110, 50, and 28 lbf/in²) for CH, CL, and ML soils respectively];
(T/T_0) = temperature ratio [T_0 = 22.2° C (72° F)];
(N/N_0) = ratio of number of load cycles (N_0 = 10 000);
b = -1.7013 + 6.2014(PL);
c = 0.0271 - 0.2873 log (clay);
d = 0.0697 - 0.9846 (clay);
e = 0.0582 - 0.002 26 (clay);
a_0 = -125.574(SL) - 2764.13(PL) + 21 234.1 (SL × PL);
a_1 = -465.052(SL) - 2890.01(PL) + 23 642.5 (SL × PL);
a_2 = -37.6644 + 279.813 (SL + PL)²;
a_3 = -15.0184 + 13 786.434 (SL × PL)²;
a_4 = 0.8088 + 0.3006 (clay);
a_5 = 30.8763 - 306.7167(LL)²;
a_6 = 7.5058(SL) - 6.0135(PL) + 41.1548 (SL × PL);
a_7 = 3.6476(PL) + 2.0336(LL) - 7.3402 (PL × LL);
a_8 = 4.370(SL) - 6.1516(PL) + 53.4137 (SL × PL);
LL = liquid limit;
PL = plastic limit;
SL = shrinkage limit; and
clay = clay content in decimal form.

The coefficients of determination for the power relations are all above 0.90. As with the deviator-stress ratio, the soil suction and the number of load-cycle-ratio changes are directly related to the changes in resilient modulus. Whereas the powers were generally related to the clay content, the coefficients are generally related to the Atterberg limits. The coefficients of determination for the coefficient relations are all above 0.90.

STRAIN RELATIONS

A fundamental change occurs in the behavior of fine-grained soils at a water content about 2 percent dry of optimum, as determined by the Harvard miniature compaction procedure. When the soil is wetter than this amount its properties change dramatically with a small change in water content. When the soil is drier than this amount its properties are much less dependent on water content and much more dependent on the level of suction in the soil. The soil suction at this threshold is related to the clay fraction in the soil by the following equation:

$$h = 21.481 + 181.14(c) \quad (4)$$

where

h = soil suction in kPa (1 kPa = 0.145 lbf/in²) and
c = clay fraction in the soil in decimal form.

This value of suction is henceforth referred to as the threshold suction.

Analysis of Strain Data

The residual strain was analyzed as an exponential function of the number of load repetitions (N):

$$\epsilon_p = I N^S \quad (5)$$

The constants (I) and (S) in this equation were then related to ratios of the other independent variables in the test series. The values of these independent variables are given in the following table [1 kPa = 0.145 lbf/in² and 1°C = (1°F - 32)/1.8]. (The strain equation was developed by using customary unit values.)

Variable	Value	Variable	Value
Soil suction (h_0), kPa		Temperature (T_0), °C	22.2
Moscow (CH)	759	Mean stress (m_0), kPa	55.9
Floydada (CL)	345	Stress ratio (s_{r0})	1.69
Allenfarm (ML)	193	Clay fraction (c_0)	0.4

Residual Strain

The large range of residual strain that occurred during the first few load cycles is attributed to seating error because the samples were not preloaded. To compensate for this the residual strain was set at zero at the one-hundredth load repetition. The differences in the residual strain are thus due to differences in the samples and not to differences caused by the seating error.

The constants (I) and (S) in the residual strain equation are expressed as follows:

$$I = -6.017 \times 10^{-4} + 3.28 \times 10^{-4}(h/h_0)^{-1.15} + 3.22 \times 10^{-5}(m/m_0)^{1.22} + 9.88 \times 10^{-6} \times (T/T_0)^{-4.30} + 1.13 \times 10^{-4}(c/c_0)^{-2.0} \quad (R^2 = 0.45) \tag{6}$$

$$S = -1.553 + 0.451(h/h_0)^{0.15} + 0.597(m/m_0)^{-0.275} + 0.737(T/T_0)^{0.87} + 0.442(c/c_0)^{0.33} \quad (R^2 = 0.39) \tag{7}$$

where

(h/h_0) = soil-suction ratio,
(m/m_0) = mean-stress ratio,
(T/T_0) = temperature ratio, and
(c/c_0) = clay-content ratio.

The intercept or I equation produces numbers around 10^{-4} to 10^{-7}. The intercept varies inversely with the soil-suction ratio, the temperature ratio, and the clay-content ratio but directly with the mean-stress ratio.

The residual strain increases as the number of load cycles increases; the slope or S equation will therefore be positive. The range of the slope is 0.1 to 1.4. In this equation the slope (S) varies directly with the suction ratio, the temperature ratio, and the clay-content ratio and inversely with the mean-stress ratio.

PERMANENT DEFORMATION RELATION

In predicting the rutting behavior of pavements the VESYS II computer program calculates the fractional increase of permanent strain that develops with each load that passes. The clearest explanation of this calculation appears to be that by Rauhut, O'Quin, and Hudson (11); the following has been extracted from their discussion.

The residual strain equation is $\epsilon_p = I\ N^S$ (Equation 5). The change of residual strain with each load is

$$d(\epsilon_p)/dN = IS\ N^{S-1} = \Delta\epsilon_p \tag{8}$$

The total strain at a given load cycle is the sum of the resilient strain and the incremental increase of permanent strain given above. Consequently, the fraction of the total strain that becomes permanent strain with each load cycle is

$$F(N) = \Delta\epsilon_p/(\epsilon_r + \Delta\epsilon_p) \approx ISN^{S-1}/\epsilon_r \tag{9}$$

The function [F(N)] must be specified in the input to VESYS II as

$$F(N) = \mu\ N^{-\alpha} \tag{10}$$

from which it is found that

$$\alpha = 1 - S \tag{11}$$

and

$$\mu \cong IS/\epsilon_r \tag{12}$$

both of which are related to the constants (I) and (S) in Equations 6 and 7.

Figures 2 and 3 show the dependence of μ and α respectively on soil suction and stress ratio at a constant temperature and number of load repetitions for the Allenfarm soil (ML). These figures show the striking change of behavior that occurs at the threshold suction value. The Allenfarm soil, a low-plastic silt, is similar to the subgrade soil of the AASHO Road Test. The values of μ and α to the wet side of the threshold suction are in the same range as those calculated from AASHO Road Test data by Rauhut, O'Quin, and Hudson (11) in which α varied from 0.63 to 1.0 and μ was around 0.1. For the other two soils tested, the peaks were not so sharp, the levels of μ were generally lower (0.001 to 0.01), and the levels of α were similarly lower (0.3 to 0.7).

The μ and α relations show several general characteristics. As the number of load repetitions increases, μ increases slightly and α remains nearly constant. Temperature is another important influence: As temperature increases both μ and α decrease and vice versa. Both of these soil properties are strongly dependent on temperature; α actually becomes negative for soils with higher clay contents, as shown in Figure 4. A negative value of α indicates a progressively increasing permanent strain with each additional load cycle.

IMPLICATIONS FOR CLIMATIC DESIGN OF PAVEMENTS

In addition to the more detailed effects to be derived from pavement analysis, at least two broad-scale climatic effects are implied by the results of this study. These effects concern (a) the threshold suction and (b) the dependence of α on temperature.

Threshold Suction

Because the Thornthwaite Moisture Index is related to the suction level in subgrade soils, it is possible to draw a climatic map of the United States (Figure 5) that delineates those regions where ML, CL, and CH soils must either be treated or protected by extra pavement thickness or stiffness from the likelihood of excessive rutting. The shaded areas in Figure 5 represent climatic areas where subgrade suction can be expected to be less than the threshold suction value. As the figure shows, silty soils will require special pavement-design considerations throughout most of the United States.

Negative α

When α becomes negative in a soil, that soil will suffer progressively increasing permanent strain ($\Delta\epsilon_p$) with each passing load. No part of the United States has temperatures higher than 35°C (95°F) during substantial portions of the year. The southern states, however, can have subgrades of high clay content whose temperatures range above this value for brief periods of time each day, usually toward evening. If this higher temperature period coincides with a period of heavy traffic, accelerated pavement rutting may be expected. In these instances, a thick pavement overlying the subgrade will (a) reduce the traffic stresses in the subgrade and (b) provide thermal insulation to keep the subgrade from reaching a temperature at which α will become negative.

CONCLUSIONS

The following conclusions can be drawn from the results of this study.

1. The dynamic properties of fine-grained subgrade soil depend strongly on factors of traffic, climate, and soil composition. The important climatically related factors are soil suction and temperature.
2. Resilient moduli, resilient strain, and residual strain may be predicted reliably from these factors.
3. Equations have been developed that relate stress, suction, temperature, and clay content to the permanent deformation factors (μ) and (α) currently used in the VESYS II pavement-analysis computer program of FHWA.
4. Climatic design of pavements will recognize the importance of the threshold suction value. Subgrades that have expected values of suction lower than the threshold value will require special consideration in terms of added thickness or stiffness or stabilization.
5. A negative α can develop under certain thermal conditions. At a temperature above 35°C (95°F), a subgrade soil that has a high clay content can suffer a progressively increasing permanent strain with each load cycle. Thus, thick pavements in the warmer climates have two functions: reduction of traffic stress and thermal insulation.

Figure 2. μ versus soil suction and stress ratio at 10 000 load repetitions and 22.2°C (Allenfarm soil).

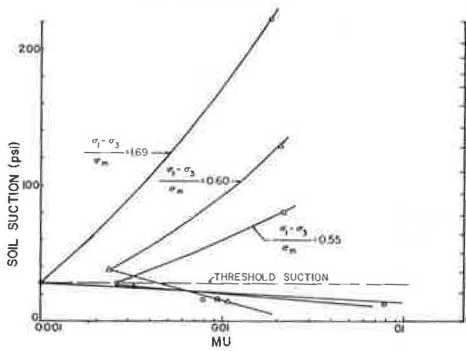


Figure 3. α versus soil suction and stress ratio at 10 000 load repetitions and 22.2°C (Allenfarm soil).

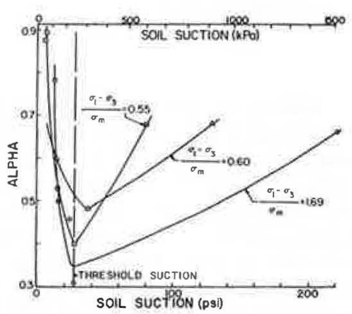


Figure 4. α and μ versus temperature and stress ratio for threshold suction at 10 000 load repetitions (Moscow soil).

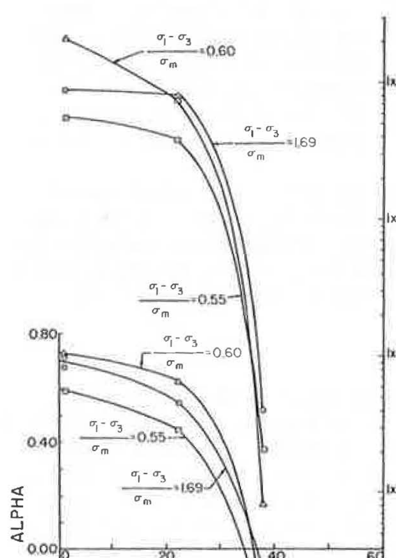
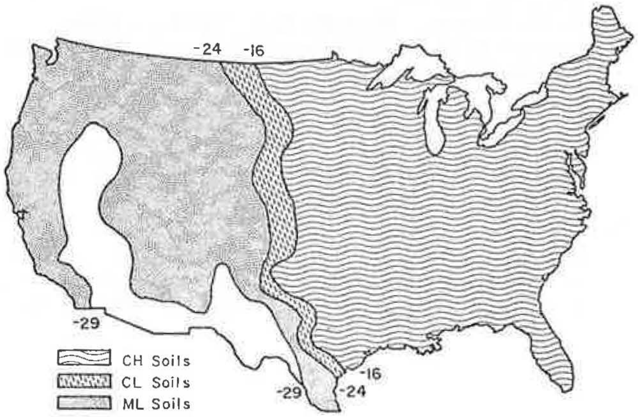


Figure 5. Climatic map corresponding to Thornthwaite Moisture Index.



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Desiccation of Soils Derived From Volcanic Ash

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Five volcanic-ash-derived soils from the island of Hawaii were studied to determine the relation of changing moisture content to engineering behavior. Two soils weathered on the leeward side of the island under relatively dry conditions; the other three developed on the windward side under high mean annual rainfalls. The dry soils show little change on desiccation whereas the desiccation of the wet soils is accompanied by an irreversible hardening that causes drastic changes in the index properties. Engineering behavior of the dry soils is similar to that of a sandy silt. The wet soils behave as plastic clays but, when they are dried out, their engineering characteristics change to those of a sand. Mercury porosimetry tests reveal that, in wet soils, volume changes between field moisture content and the oven-dry state are about 150 percent. The dry soils exhibit very small volumetric shrinkage. Drying tests under controlled relative humidity provide data on drying rates and critical moisture contents. The mineralogy of the soils was studied by using X-ray diffraction and fluorescence, differential thermal, and thermogravimetric analyses. The predominant minerals are gibbsite, iron oxides, and allophane. Mineralogical studies indicate that irreversible hardening is accompanied by an increase in gibbsite content. Mercury porosimetry results and mineralogical analysis indicate that a major portion of the shrinkage is due to contraction of the intermediate-size pores and that the extent of shrinkage is a function of allophane content.

The behavior of some soils derived from volcanic ash in very wet tropical areas has been of considerable interest to pedologists and soil engineers. Highway-construction experience with these soils in Hawaii has been discussed by Hirashima (7, 8), who pointed out problems associated with compaction at very high moisture contents. In general, ash soils are characterized by low density, high permeability, and high water-holding capacity (4, 7, 11, 15). Birrell (4), who worked with ash-derived soils from New Zealand, has reported that the preconsolidation pressure of the soils as determined in conventional consolidation tests is frequently greater than the overburden pressure but that once this preconsolidation pressure is exceeded the soils are highly compressible. Yamanouchi (16) has pointed out that the ash-derived soils of Japan are difficult to stabilize with conventional additives if the soils are high in organic content.

One of the most interesting properties of these soils is that they harden irreversibly when dried. This hardening is often accompanied by shrinkage. At field moisture contents the ash soils are plastic and claylike; if they are allowed to dry, however, sand- or silt-size aggregates form. Drying reduces liquid limits and decreases clay contents in these soils (3, 6, 7). If the soils are allowed to dry partially at relatively high moisture contents, they retain their plastic nature. No data were found to indicate the moisture content at which an ash-derived soil loses its plastic character. The component of ash soils that is responsible for irreversible hardening and for some other unique properties has been referred to variously as palagonite (7), amorphous clay (15), amorphous colloids (4), and allophane (6). Few quantitative data on the mineralogy of ash-derived soils are to be found in the literature. The confusion in terminology and the lack of quantitative data arise from the vague definition of the poorly crystalline components in these soils and from the resultant difficulties in making measurements.

The data presented in this paper may help to provide a better understanding of the desiccation process in ash soils and thus contribute to evaluating their potential for chemical stabilization, classifying them for engineering purposes, and predicting their behavior in the field.

SOILS STUDIED

Three ash-derived soils known to exhibit irreversible hardening when dried are the Kukaiau, Honokaa, and Hilo series from the windward side of the island of Hawaii. These soils were weathered from a volcanic ash known as the Pahala ash under very high mean annual rainfalls ranging from 178 to 457 cm. As a basis for comparison, two other soils were studied that weathered from the same parent material but do not exhibit irreversible hardening. These two soils, Waimea and Kilohana, developed under mean annual rainfalls ranging from 51 to

114 cm. Complete pedologic descriptions of the soil profiles can be found in the Hawaii soil survey report (10). A summary of the environmental conditions and the pedologic classifications of the five soils is given in Table 1.

Relatively undisturbed samples were collected from the B horizon of each soil series by means of thin-walled shelby tubes that were hydraulically pressed into the soil. The tubes were sealed to preserve field moisture contents and were air freighted to the mainland in specially constructed, rubber-foam-padded shipping crates.

TEST PROCEDURES AND RESULTS

Composite samples of each series were prepared by trimming about 100 g from every tube sample, mixing, and quartering. Some samples were air dried and passed through a 74-µm (No. 200) sieve prior to X-ray, thermogravimetric, and differential thermal analyses to determine mineral contents. Other samples in the field moisture state were also subjected to X-ray analysis.

Iron contents were determined by X-ray fluorescence. The method developed for this purpose was based on the comparison of X-ray fluorescent peak intensities of iron in the sample with intensities of iron peaks in specimens composed of the original sample plus known additional amounts of iron. The method and the derivation of equations can be found elsewhere (12). The fluorescent method is similar to the diffraction method described by Tuncer and others (13).

Gibbsite contents were determined by thermogravimetric analysis in which the weight loss corresponding to the most characteristic gibbsite thermal reaction of the soil sample is compared with that of a sample of pure gibbsite. The amount of gibbsite in the soil is calculated by simple proportioning (14).

Allophane is most difficult to determine quantitatively: It is amorphous to X-rays and isolating pure allophane for calibration of the thermogravimetric analysis is difficult. The allophane content in the test soils was estimated by selecting as the reference the Hilo soil, which contains the fewest mineral species, and assuming that the only minerals present were gibbsite, various iron oxides, and allophane. Once the iron oxides and gibbsite were measured, the allophane in the Hilo was calculated by simple subtraction. The allophane content in the other four soils was calculated by taking the weight loss for the allophane thermal reaction in Hilo and proportioning the weight loss in the other soils that corresponds to the same allophane reaction.

Organic carbon contents were measured by the dichromate method. The qualitative X-ray diffraction study reveals that the Kilohana soil has large amounts of plagioclase feldspar and some hydrated halloysite. The Waimea soil has even larger amounts of halloysite. No quantitative work was done on these minerals because these two soils do not exhibit irreversible hardening.

The chemical and mineral contents of the test soils are given in Table 2. Gibbsite is an important component of the soils that harden irreversibly (Kukaiau, Honokaa, and Hilo); allophane is present in all five soils but in greater amounts in the soils that harden. Iron oxide content increases from dry to wet soils, but organic carbon content does not show any systematic variations.

Mechanical analyses, Atterberg limit tests, and specific gravity tests were performed on composite samples of each of the soil series studied according to American Society for Testing and Materials (ASTM) procedures that require that the soils be air dried prior to testing. To evaluate the effect of irreversible hardening, additional gradation and Atterberg limit tests were conducted at field moisture contents (Tables 3 and 4). As expected there is little difference between the dry-state and moist-state index properties of the soils from the dry side of the island, but the soils that harden irreversibly show a marked decrease in clay and sand contents and a decrease in Atterberg limits after drying.

Densities and void ratios were determined by weighing the tube samples and measuring their bulk geometry. Eight to 10 tubes from each series were measured, and the data reported for each series (Table 5) are the averages. The soils that harden irreversibly exhibit extremely high void ratios and field moisture contents. The void ratios of the soils that do not harden irreversibly are somewhat lower.

The volume-change characteristics of the soils were investigated by shrinkage-limit tests and tests using mercury injection porosimetry. The shrinkage limit (Table 5) was determined for composite samples of each series according to ASTM procedures. Volumetric shrinkage was calculated by dividing the difference between the volumes of the soil at field moisture content and at the shrinkage limit by the volume of the soil at the shrinkage limit.

Mercury porosimetry tests were conducted on all five soils according to procedures described by Lohnes, Tuncer, and Demirel (9). Tests were run on air-dried samples as well as on samples that had been freeze dried at field moisture content. Freeze drying was done according to the method described by Erol, Lohnes, and Demirel (5). The change in pore volume from field moisture to oven-dry states was used to calculate the volumetric strain by dividing the change in pore volume by the pore volume at field moisture content. Shrinkage and hardening characteristics are given in Table 6.

To investigate the mode of volume change, the Hilo soil was subjected to controlled drying and samples from it were freeze dried at various moisture contents between field moisture content and the oven-dried state. The samples were then subjected to porosimetry tests. Pore-size-distribution curves at various stages in the drying history are shown in Figure 1. Figure 2 shows the variation in pores of various size ranges with changing moisture content. The greatest volume change occurs in the intermediate-size pores (10 to 0.01 µm), whereas the very large pores (>10 µm) and very small pores (<0.01 µm) are little affected by drying.

Undisturbed samples of each series were allowed to air dry in the laboratory at a relative humidity of 20 ± 3 percent. Moisture contents were taken periodically, and curves for moisture content versus time were plotted for all five series. The moisture content-time curves are shown in Figure 3. The initial linear portion of the drying curves is controlled by ambient conditions such as relative humidity and air velocity. During this constant-rate period of drying, the surface of the soil sample that is in contact with the air is completely wetted and the drying rate is independent of the characteristics of the solid and void space. The moisture content at which the curve deviates from linearity is the critical moisture content (Table 6) (2). The form of the drying curve at moisture contents below the critical moisture content depends on the structure and composition of the soil and the voids and on the mechanism by which the moisture moves within the soil (2). Drying curves for all soils are shown in Figure 3.

Slaking tests were performed at four stages in the drying history of the three soils that harden irreversibly. These tests were run in an attempt to define the moisture content at which the hardening would occur, i.e., the hardening limit of each soil. At moisture contents above this limit, the soils retain their plastic characteristics and slake when immersed. Below the hardening limit, the soils do not slake. Because the number of samples

Table 1. Pedologic classifications and environmental conditions of the soils studied.

Soil Series	7th Approximation Classification	Great Group	Range of Mean Annual Rainfall (cm)	Range of Slope Angles (%)
Kilohana	Mollic Vitrandept	Regosol	51 to 102	12 to 20
Waimea	Typic Eutrandept	Reddish Prairie	64 to 114	6 to 20
Kukaiau	Hydric Dystrandept	Humic Latosol	178 to 254	6 to 35
Honokaa	Typic Hydrandept	Hydrol Humic Latosol	254 to 381	10 to 35
Hilo	Typic Hydrandept	Hydrol Humic Latosol	305 to 457	0 to 35

Table 2. Chemical and mineral contents.

Soil Series	Allophane (% weight)	Gibbsite (% weight)	Iron Oxide (% weight)	Organic Carbon (% weight)	Relative Contents[a]		
					Quartz	Halloysite	Plagioclase
Kilohana	26	0	10	4.6	X	X	XX
Waimea	32	8	16.4	2.2	X	XX	0
Kukaiau	42	27	17.7	5.3	X	0	0
Honokaa	55	22	19.6	9.2	X	0	0
Hilo	42	32	26	4.2	X	0	0

[a] X indicates a small amount; XX indicates a large amount.

Table 3. Gradation data.

Soil Series	Sand (%)		Silt (%)		Clay (%)	
	Dry	Wet	Dry	Wet	Dry	Wet
Kilohana	69	68	24.8	28.8	6.2	3.2
Waimea	33	54	57.7	39	9.3	7
Kukaiau	89	59	10.4	32	0.6	9
Honokaa	89.5	42	9	33.5	1.5	24.5
Hilo	87.5	31	7.4	39.5	5.1	29.5

Table 4. Atterberg limits.

Soil Series	Liquid Limit (%)		Plastic Limit (%)		Plasticity Index (%)	
	Dry	Wet	Dry	Wet	Dry	Wet
Kilohana	NP	NP	NP	NP	NP	NP
Waimea	66.8	64	63	62.7	3.8	1.3
Kukaiau	93.3	164	88.6	162.4	4.7	1.6
Honokaa	NP	301	NP	279.9	NP	21.1
Hilo	61.4	206	NP	191.9	NP	14.1

Note: NP indicates nonplastic.

Table 5. Density data and shrinkage limits.

Soil Series	Field Moisture Content (%)	Void Ratio	Dry Density (g/cm^3)	Specific Gravity	Shrinkage Limit (%)
Kilohana	39.2	2.155	0.92	2.904	44.7
Waimea	45.79	2.802	0.81	3.084	35.0
Kukaiau	164.13	5.993	0.44	3.071	47.9
Honokaa	244.92	8.901	0.30	2.980	50.5
Hilo	234.90	7.130	0.35	2.842	56.3

was limited, it was not possible to monitor the behavior of the soils continuously throughout their drying history. Therefore, rather than precisely defining the hardening limit, the data given in Table 6 bracket the hardening limit between a higher moisture content at which the soil continues to slake and a lower moisture content at which the soil is observed to be irreversibly hardened. For the three soils that harden irreversibly, the upper and lower moisture contents that bracket the hardening limit also bracket the critical moisture content. These moisture contents also bracket the shrinkage limit (except in the case of the Honokaa soil where the shrinkage limit falls below the hardening limit).

DISCUSSION OF RESULTS

A comparison of the critical moisture contents in Table 6 with the shrinkage limits in Table 5 reveals that, although two of the three soils that harden have nearly equal shrinkage limits and critical moisture contents, the other three soils do not show this trend. A comparison of critical moisture content with the change in void ratio calculated from porosimetry data (Table 6) shows that there is a good correlation between the two parameters. Figure 4 shows a good correlation between the allophane content and the critical moisture content. These comparisons and correlations indicate that volumetric shrinkage is best predicted by the critical moisture content. Volume change as calculated by the shrinkage limit is based on tests on disturbed samples and is not representative of the shrinkage that can be expected from the desiccation of an undisturbed ash-derived soil. The correlations suggest that drying tests may be a valuable interpretive tool for a better understanding of soil structure and mineralogy.

The change in the pore-size distribution of the Hilo soil (Figure 2) that is caused by drying reveals that the major change occurs in pores between 10 and 0.01 μm in size, which covers the range of large, medium, and small pores defined earlier. A second observation is that, within this magnitude of pores, the 10 to 1-μm pores empty at the highest moisture range, i.e., 120 to 240 percent, and it is not until these pores empty that the pores in the 1 to 0.01-μm range begin to empty, as indicated in Figure 2. Although capillary tension is high in the very small pores (<0.01 μm), the structure of the soil around the pores is sufficiently strong that they do not collapse. The very large pores (>10 μm) do not show much change because the capillary tensions are lower in that size range. Thus the intermediate-size pores that combine the effects of a weak structure and moderately high capillary tensions are the pores most affected in the collapse. These observations result from the fact that the saturation pressure of the vapor, which is in equilibrium at the interface of the larger pores, must be reduced to the saturation pressure of the interface in the smaller pores before these pores can empty.

Previous researchers have indicated that allophane is responsible for the irreversible hardening and shrinkage of ash-derived soils. Figure 4 shows plots of the change in void ratio caused by drying versus allophane content and the initial void ratio versus allophane content, which tend to support this idea that soils with higher initial void ratio and soils that exhibit greater shrinkage all have higher allophane contents. However, allophane content alone cannot be responsible for the hardening of ash-derived soils because the two soils that do not harden irreversibly contain fairly large amounts of allophane. Even though the quantitative estimates of allophane can be questioned as absolute amounts, their relative contents should be fairly accurate. The Hilo soil, which exhibits large shrinkage and hardening and was used as the standard, contains only 10 to 14 percent more allophane than the two soils that do not harden. Gibbsite, however, is present in large amounts in soils that harden but in small quantities or not at all in soils that do not harden. Data in Table 2 are based on thermogravimetric analyses; the soils were dry at the time their mineral contents were determined. To further evaluate the role of gibbsite in irreversible hardening, X-ray diffraction patterns (using $Cu_{K\alpha}$ radiation) were obtained on all three of the soils that harden at both the field

Table 6. Shrinkage and hardening characteristics.

Soil Series	Volumetric Shrinkage From Shrinkage Limit	Void Ratio Decrease From Porosimetry	Volumetric Strain From Porosimetry (%)	Critical Moisture Content (%)	Hardening Limit
Kilohana	0[a]	0.110	5.1	27	–
Waimea	9.03	0.539	19.2	30	–
Kukaiau	104.49	5.156	86	50	32.5 to 51.2
Honokaa	139.63	8.057	90.5	80	63.8 to 170.4
Hilo	166.66	6.109	85.7	56	34.0 to 122.0

[a] Field moisture content is lower than shrinkage limit.

Figure 1. Pore-size-distribution curves for Hilo soil at various stages of drying.

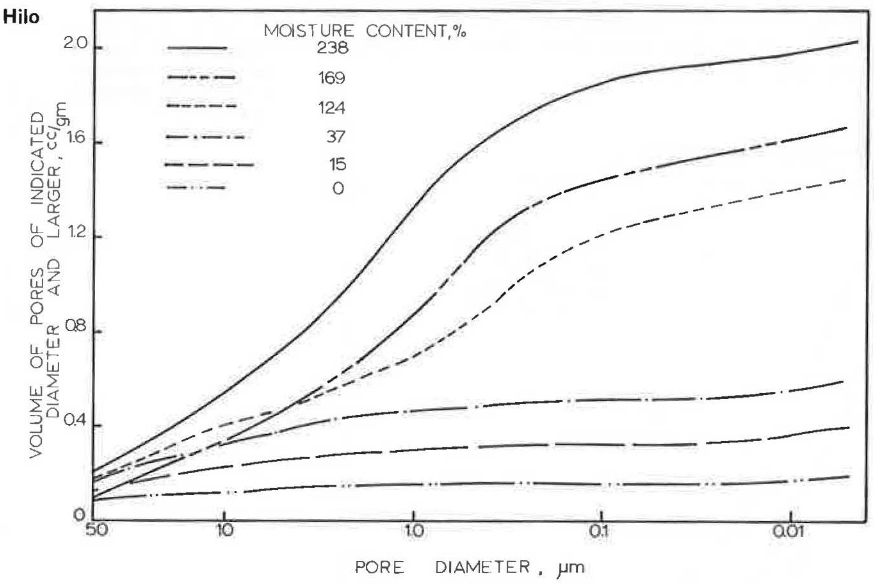
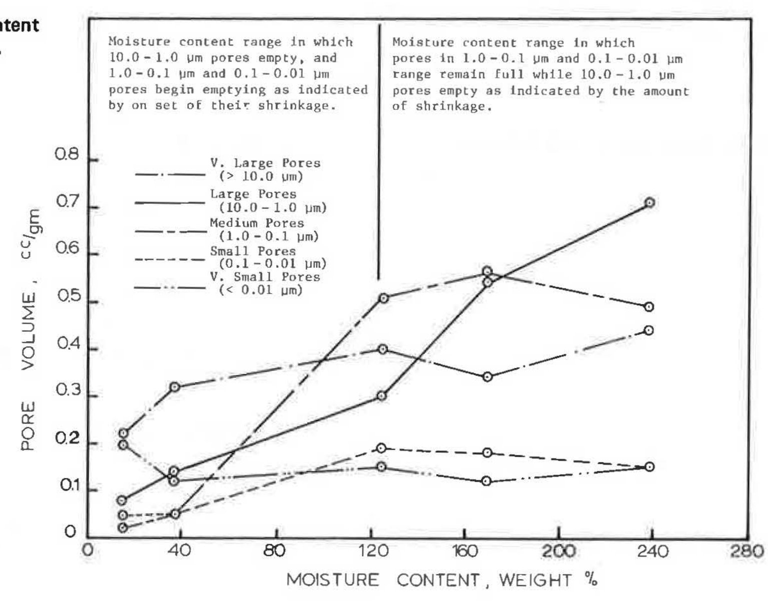


Figure 2. Pore volume versus moisture content for pores of various size ranges in Hilo soil.



moisture content and the oven-dry state. All three sets of X-ray diffraction tests gave results similar to those for the Hilo soil shown in Figure 5. The gibbsite peak is weak in all the soils at field moisture content but is more pronounced at oven dryness. The peak breadths are the same at both moisture contents as are the height and breadth of the quartz peaks. These observations lead to the conclusion that gibbsite is either synthesized or better crystallized in the drying process. No boehmite peaks nor other hydrated aluminum oxide peaks were observed in the diffractograms of the moist samples; therefore, if gibbsite is synthesized, the allophane must be the source material for it. Aomine (1) has suggested that allophane can be converted to gibbsite as part of the weathering process. It is possible therefore that allophane may be the source material in the drying process.

CONCLUSIONS

Based on data resulting from the study of Hawaiian volcanic-ash-derived soils, the following conclusions regarding the desiccation of soils may be drawn.

1. The drying process can more than double the sand content, reduce clay-size material as much as 12 times, and reduce the liquid limit as much as from over 300 percent to nonplastic behavior.

2. The moisture content at which the hardening process becomes irreversible is in the range of the shrinkage limit for two soils and in the range of the critical moisture content for all three soils that harden irreversibly.

3. The shrinkage of the soils is due mainly to the shrinkage of pores in the 10 to 0.01-µm-diameter range. Very large pores and very small pores do not enter into the shrinkage process because of low capillary tensions in the large pores and high structural strength around the small pores.

4. Although desiccation of allophane has been considered in the past to be the primary cause of hardening, in this study allophane was observed to occur in ash soils that do not harden. Gibbsite, on the other hand, is unique to ash soils that harden. X-ray evidence indicates that gibbsite is either synthesized or better crystallized in the hardening process.

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Figure 3. Drying curves for fine soil series.

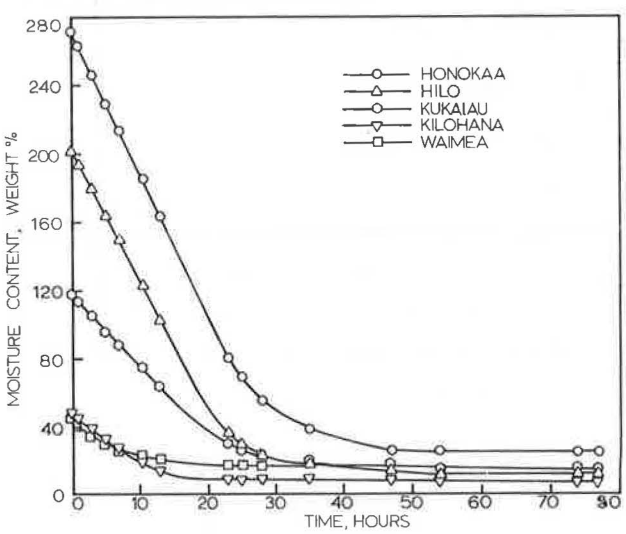


Figure 4. Allophane content versus void ratio, critical moisture content, and change in void ratio.

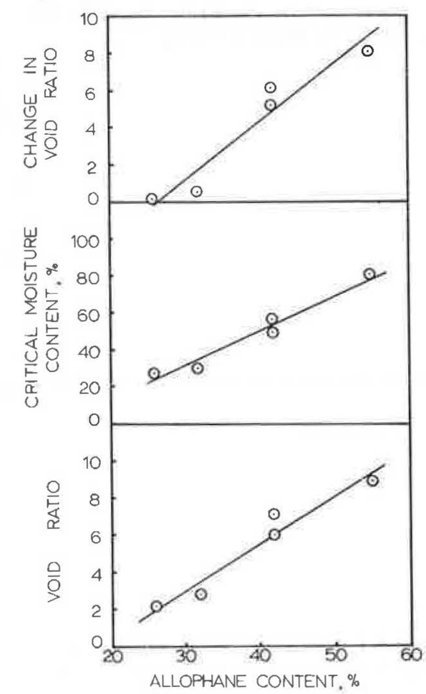
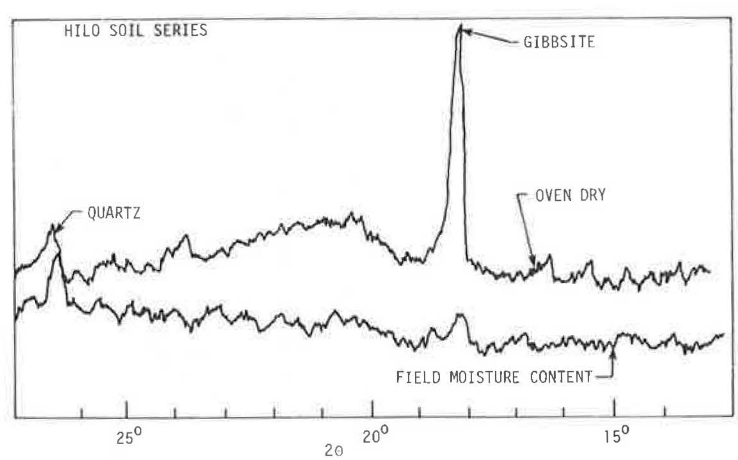


Figure 5. X-ray diffraction pattern of Hilo soil before and after oven drying.



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Clay Structure and Rate Process Theory

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An effort was made to incorporate structural variations into rate-process theory by defining a primitive or ideal clay that has a linear strain-time relation implicit in rate-process theory. The slope of the creep curve of the primitive clay is equal to the slope of the tertiary curve at its inflection point. The deviations of the tertiary curve from the straight line are a measure of the behavior of the real clay caused by the structural changes. The ratio of the strain of the real clay to the strain of the primitive clay can be calculated at any point in time. This ratio, defined as the mobilization ratio, is a measure of real-clay structure relative to primitive-clay structure, which remains constant during progressive creep deformations. The method of analysis proposed here reveals that equivalent mobilization ratios correspond to points of identical structure on creep curves. This hypothesis is supported by the experimental results. The analysis of undrained simple shear creep tests conducted on grundite-illite clay at various temperatures and shear stresses demonstrates that the rate process parameters—flow volume, activation enthalpy, and proportionality constant—are structure dependent. The structural changes that accompany creep deformations can be expressed in terms of variations in these parameters.

Although structure is accepted as one of the most important properties influencing the mechanistic behavior of soil, it is at best a descriptive concept manifest in terms such as single grained, massive, aggregated, dispersed, flocculent, and edge-to-face and face-to-face association. The following definitions taken from engineering and pedologic references briefly illustrate the current concepts of structure.

The U.S. Department of Agriculture (USDA) (10) defines soil structure as follows:

> Soil structure refers to the aggregation of primary soil particles into compound particles or clusters of primary particles, which are separated from adjoining aggregates by surfaces of weakness.

Although some researchers use the terms structure and fabric interchangeably, Mitchell (7) defines fabric as the arrangement of particles, particle groups, and pore spaces in a soil and states that "... structure is taken to have the broader meaning of the combined effects of fabric, composition, and interparticle forces." Implicit in the USDA definition (10) is that the aggregates are visible to the unaided eye. Mitchell (7) on the other hand clearly states that his emphasis in soil mechanics is at the microfabric level, which requires at least an optical microscope for study, but that macrofabric is also of great importance.

According to Yong and Warkentin (12),

> We define soil structure as that property of soil which provides the integrity of the system and which is responsible for response to externally applied and internally induced sets of forces and fluxes. Soil structure, as a property, includes the gradation and arrangement of soil particles, porosity and pore-size distribution, bonding agents and the specific interactions developed between particles through associated electrical forces.

Hillel (5) states:

> Soil structure is generally defined as the mutual arrangement, orientation, and organization of the particles in the soil. The term is also used sometimes with reference to the geometry of the pore spaces. Since the arrangement of soil particles is generally too complex to permit any simple geometric characterization, there is no practical way to measure soil structure directly. Therefore, the concept of soil structure is used in a qualitative sense.

From these references it can be seen that Mitchell (7) and Yong and Warkentin (13) consider that fabric is one aspect of structure whereas Hillel (5) and USDA (10) make no such distinction. Hillel (5) points out the complexity involved in measuring soil structure and that methods for quantitative characterization of structure, such as pore-size distribution, are indirect methods. He further points out that structure is dynamic and changes in response to changes in environment. The very complex geometry of the individual primary particles of clays, the complex geometry of the aggregates, and the changes in structure resulting from changes in stress make the problem of relating the structure of clay-water systems to mechanistic behavior even more formidable.

APPROACH TO THE PROBLEM

Soil structure may be defined, for application in soil mechanics, as the size, the shape, and the arrangement of primary soil particles to form aggregates. The size of the primary particles is referred to as texture; the arrangement of the primary particles may be referred to in granular soils as packing and in clay soils as fabric. In most soils, at stresses commonly encountered in engineering problems, the structure changes that occur in response to changes in stress are changes in fabric. At extremely high stresses, in soils of very low density or high moisture content, or in soils containing easily deformed primary particles, all three aspects of structure may be influenced by changes in stress.

A major difficulty in the quantitative characterization of structure is the lack of a reference state. In this study, therefore, a unique point in the stress-strain history of a soil was selected that could be used to compare other points, each of which represents a different degree of deformation or structure.

Rate-process theory, which is the fundamental theory adopted for the study of the relation of clay-water structure to its mechanistic behavior, has been tested in soil studies for nearly two decades (1, 6, 8, 9). The theory, as adopted by Noble and Demirel (9), states that

$$\dot{\gamma} = Ae^{-\Delta H^*/kT}e^{\beta\tau} \qquad (1)$$

where

$\dot{\gamma}$ = shear strain rate,
A = a constant that includes the activation entropy,
ΔH^* = activation enthalpy or bond energy,
β = flow volume that characterizes the mechnical motion of the building blocks of the clay-water system, and
τ = applied shear stress.

This equation does not explicitly include a term that reflects the structure of the material; however, during deformation a rearrangement of either the primary particles or the aggregates is expected to occur. This rearrangement reaction should result in an increase in strength of the bonds (essentially Van der Waal's bonds), the primary particle size, and the order of the system. An increase in flow volume and activation enthalpy and a decrease in activation entropy may therefore be expected. It is obvious that, as a particulate system such as clay-water deforms, there is the potential for change in any or all of these parameters.

Equation 1 implies (a) a linear relation between shear strain (γ) and time (t) and (b) that at constant shear stress (τ) and temperature (T) the flow volume, activation entropy, and activation enthalpy of the system are constant. Many experiments indicate that the shear strain-time curves of soils and clay-water systems are not linear but that strain rate decreases with time (primary or terminal creep) or decreases to an inflection point and then begins to increase (tertiary creep). This behavior suggests that, at constant shear stress, the activation entropy, the activation enthalpy, or the flow volume or any combination of the three may vary.

Equation 1 states that the shear strain rate is proportional to the number of bonding units that have energies equal to or greater than the activation energy. Previous studies have focused on obtaining a single set of thermodynamic parameters characterizing the activated state of clay-water or soil systems; however, in order to determine flow volumes and activation enthalpies, shear strain rates must be compared at points of identical structure. Because the creep curves are not linear, the problem of locating points of identical structure has been approached in two different ways. Some researchers (6, 8) have said that identical soil structure is attained at equivalent time of shear. Noble and Demirel (9) and others maintain that the structure is equivalent at inflection points on the tertiary creep curves.

To incorporate structural variations into rate-process theory, a primitive or ideal clay-water system may be defined by a linear strain-time relation implicit in Equation 1. Figure 1 shows that the slope for the primitive clay is equal to the slope of the tertiary creep curve at its inflection point. Thus, at the point where the second derivative with respect to time is zero, the first derivative is obtained and a straight line at that slope is drawn through the inflection point. This straight line then defines the strain-time behavior of the primitive clay according to the definition. The deviations of the real-clay strain-time curve from that of the straight line (Figure 1) are a measure of the structural changes that accompany the deformation of the real clay. The structure of the real clay at the inflection point is thus the reference structure for the real clay and is equivalent to the structure of the primitive clay, which is constant throughout its deformation history.

The ratio of the strain of the real clay (γ_r) to the strain of the primitive clay (γ_p) can be calculated at any point in time on the strain-time curve of the real clay. This ratio, defined as the mobilization ratio (M), is a structure parameter that measures the departure in the behavior of the real clay from that of the primitive clay.

To compare the strain-time curves of clay samples at various shear stresses, one must be able to assume that the structures of the samples are the same at equivalent mobilization ratios. It is possible, then, to use the mobilization ratio to study the influence of shear stress on the strain-time behavior of clay-water systems at various temperatures; it is also possible to study the variations in flow volumes, activation enthalpies, and activation entropies as shear stress varies.

At a constant shear stress, the mobilization ratio will be fractional at the beginning of a test and increase to a value of one at the inflection point. In the accelerating portion of the tertiary strain-time curve, the mobilization ratio will continue to increase until the soil fails (i.e., the shear stress is relieved).

EXPERIMENTS AND RESULTS

Grundite collected from Morris, Illinois, was used for the study. Raw clay was first sieved through a 74-μm (No. 200) sieve, and the fraction passing was used in the experiments. This clay, which is mainly illite with minor amounts of kaolinite, has the following properties: liquid limit, 58.6 percent; plastic limit, 28.4 percent; and percent finer than 2 μm, 72.2 percent.

The creep experiments were conducted by using a simple shear apparatus developed by Erol and Hartwell (2, 4). Mechanical details of the apparatus are shown in Figure 2. The simple shear box was designed to test 12.7 × 63.5 × 63.5-mm^3 (0.5 × 2.5 × 2.5-in^3) specimens enclosed in teflon-coated metal walls. Teflon coating was found to be satisfactory in providing lubrication for the specimen-shear box boundaries to minimize load loss in friction. Because there is no change in the area of the specimens as they strain, simple shear testing appears to be most appropriate for correct and simultaneous measurements of stresses and strains. A double-layered, insulated, asbestos housing unit; heating elements; and a solid-state temperature controller [accurate within ±0.5°C (±33°F)] were used to control the temperature of the air surrounding the shear box.

Clay pastes were molded into the shear box by hand and seated by static pressure of 104 kPa (15 lbf/in^2). Normal pressure was kept constant at 41.2 kPa (6 lbf/in^2) throughout the experiments. Moisture content and temperature of the specimens were varied between 33 and 52 percent and 10 and 65°C (50 and 150°F) respectively. Undrained creep experiments were conducted at different levels of shear stresses. The shear deformations and vertical deflections were continuously recorded on strip-chart recorders having a chart speed range of 610 to 152 mm/min (24 to 0.06 in/min). Typical time deformation curves are shown in Figure 3.

Shear strain-time curves were plotted, and the strain

Figure 1. Strain versus time behavior of real clay-water system at constant shear stress and temperature and behavior of ideal or primitive clay.

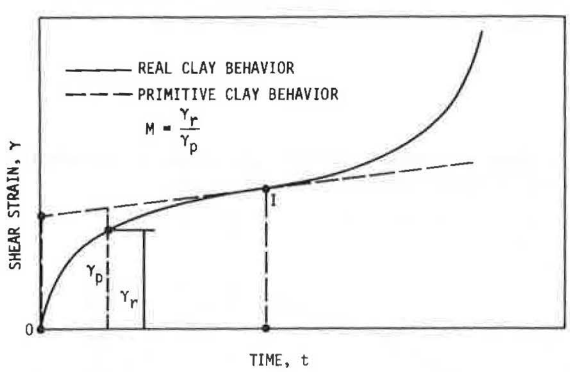


Figure 2. Simple shear apparatus.

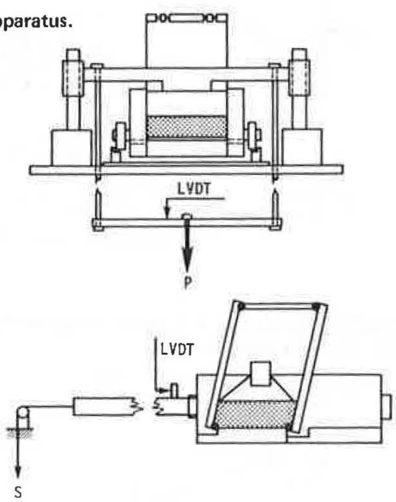
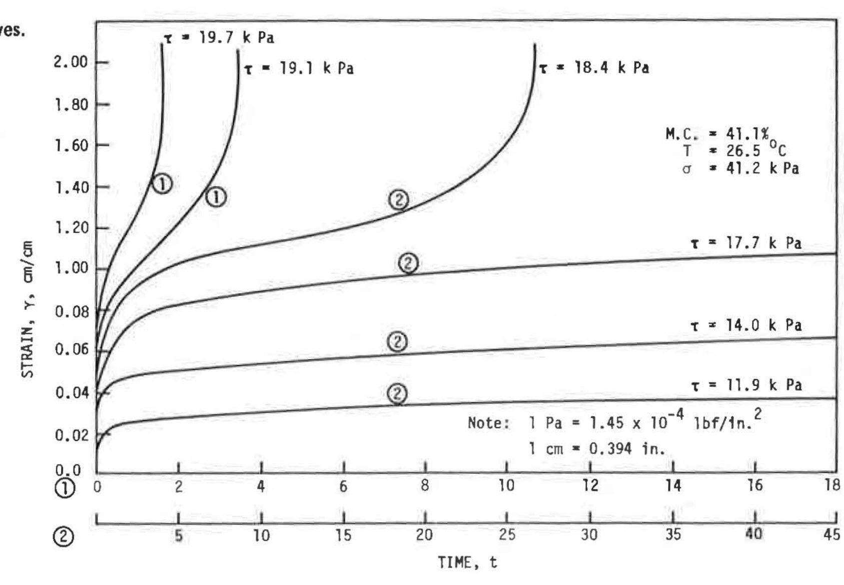
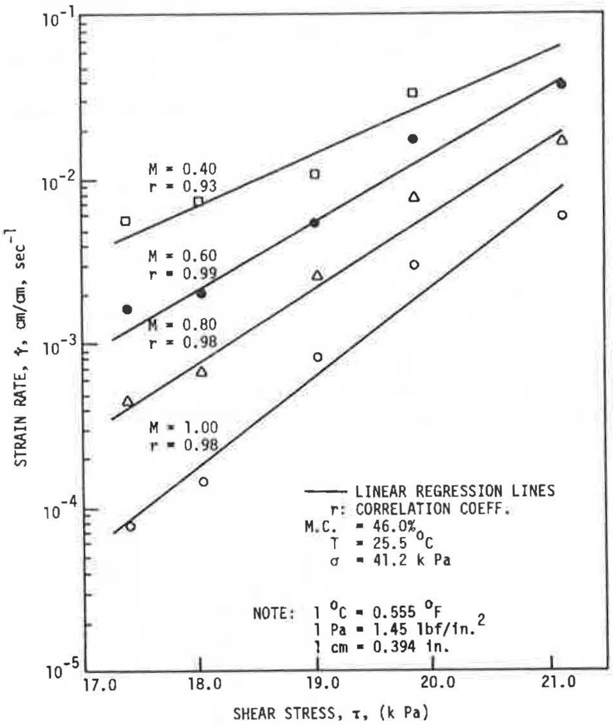


Figure 3. Typical strain versus time curves.



rates ($\dot{\gamma}$) at equal mobilization ratios (M) were determined. The log of strain rates was plotted versus shear stress and the reciprocal of temperature, as shown in Figures 4 and 5 respectively. [The slopes of the lines in Figure 4 give flow volumes (β). In Figure 5, the slopes of the lines give activation energies (ΔH^*) and the numerical values correspond to $°K^{-1}$.] The linearity of the plots in these figures supports the validity of the concept of points of equal mobilization ratio being points of equivalent structure.

Figure 4. Shear stress versus strain rate at various mobilization ratios.



Flow volumes, activation enthalpies, and the proportionality constants that reflect the activation entropy were computed from the slopes and intercepts of Figures 4 and 5 at various mobilization ratios. Figure 6 shows the resulting variation of each of these parameters. The trends in Figure 6 show an increase in flow volume and activation enthalpy and a decrease in the activation entropy up to the mobilization ratio of one (inflection point of the creep curve). The variations in rate-process parameters follow reverse trends in the tertiary region of the creep curves. The parameters thus reach their maximum and minimum values at the inflection point. An increase in flow volume (β) and activation enthalpy (ΔH^*) implies that larger structural units and stronger bonds are formed during the primary (strain-hardening) portion of the creep curves. In the same region, the orderliness of the system increases as indicated by the decrease in the proportionality constant (A). This agrees with direct observations of shear-induced fabrics (3, 11), which showed increasing particle orientations in the shear direction at different stages of shear. The occurrence at the inflection point of the highest values of β and ΔH^* and the lowest value of log A can be interpreted as indicating that the structure achieves its coarsest texture and most strongly bonded and most orderly particle arrangement at the inflection point. The opposite behavior in the tertiary creep zone indicates disintegration of the structural units into smaller units, loosened particle association, and decrease in degree of orderliness of the structure, as implied by the decrease in β and ΔH^* and the increase in log A respectively.

Figure 5. Reciprocal of absolute temperature versus strain rate at various mobilization ratios.

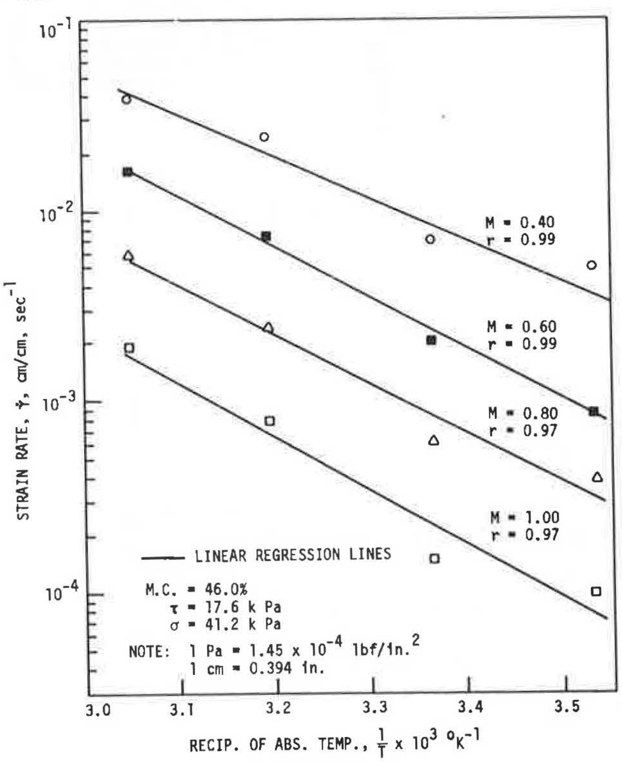
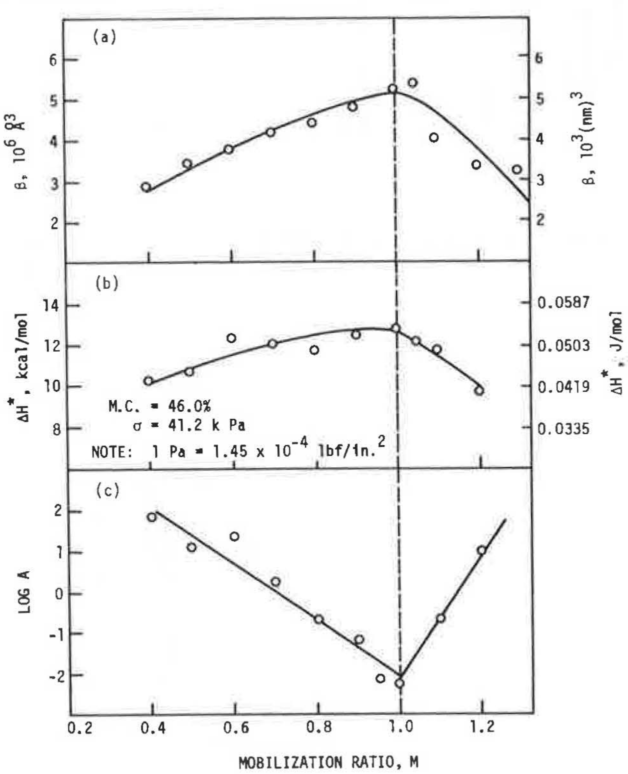


Figure 6. Mobilization ratio and rupture ratio versus (a) flow volume, (b) activation enthalpy, and (c) log of coefficient A.



CONCLUSIONS

To incorporate structural variations into rate-process theory, a primitive or ideal clay-water system is defined by a linear strain-time relation implicit in the theory. The deviations of the real-clay strain-time curve from ideal behavior are attributed to the structural changes that accompany the deformation of real clay. To quantify the structural variations a strain ratio, called the mobilization ratio, is defined. When creep curves of clay specimens at various shear stresses or temperatures are compared, the structures of the specimens are identical at equivalent mobilization ratios.

The method of analysis reveals that the rate-process parameters (β), (ΔH^*), and (A) are structure dependent. Because these parameters vary with creep deformations they can be treated as structural parameters to characterize the structural variations. The test results indicate that strain hardening is associated with a rearrangement of particles that tends toward a more ordered system and with a tendency in the primary particles to be welded into larger particles with stronger bonds. The structure attains its coarsest texture and most strongly bonded and most orderly particle association at the inflection point of the creep curves, as indicated by maximum values of β and ΔH^* and minimum value of A.

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Sampling a Glacial Silty Clay

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Over a period of 10 years a total of 42 borings were made in a glaciolacustrine deposit on the western boundary of Detroit, Michigan. The soil profile consisted of yellow-brown mottled silty clay underlain by gray silty clay. The undrained shear strength, moisture content, and dry density of 329 soil specimens of the gray silty clay are statistically analyzed. The variables are randomly distributed in both the vertical and the lateral directions. The lognormal distribution is the most likely fit for the data but, on engineering grounds, the normal distribution is preferred. Statistical estimation theory indicates that as few as 5 borings arranged in an X pattern and containing at least 30 specimens could adequately estimate the values for design at this site.

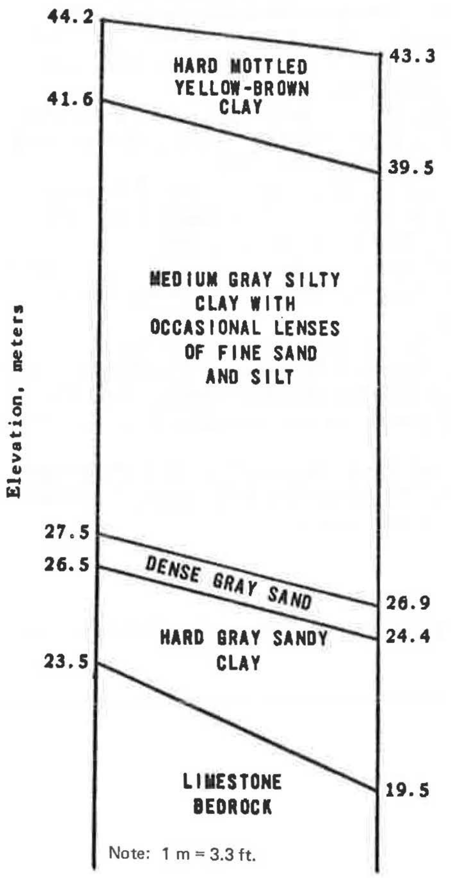
Any program to determine the properties of a natural soil deposit requires answering the following questions:

1. How many borings should be made?
2. Where should the borings be located?
3. How many field tests or laboratory tests or both should be performed?

Once these questions are answered, usually somewhat arbitrarily, it is still necessary to adopt a method for calculating the value of the design parameter. For example, a procedure that has been recommended for analysis of bearing capacity in clays is to take several borings in the area of the footings, average the values in each boring within the significant depth, and take the minimum boring average divided by the factor of safety for design (4). Although this procedure is generally effective, the actual factor of safety is not known. Because the various properties of natural soil deposits behave like random variables, their variations can be analyzed by statistical methods. Such methods make it possible to answer the above questions systematically.

The most important objection to the use of statistical methods of calculation is that they require obtaining more data than are generally considered economical on most soils engineering projects. Examining this need for excessive amounts of data reveals that it is generated by requirements for selecting a suitable probability distribution function to model the distribution of values of random variables, e.g., the undrained shear strength. There may be a way out of this dilemma. Experience and published data suggest that soil deposits that result from similar geological processes and that have similar composition have similar engineering properties. It seems reasonable then to hypothesize that corresponding properties of such deposits might be adequately modeled by the same probability distribution function. In that case, it becomes a matter of identifying the soil type in each stratum and taking sufficient samples to estimate the distribution parameters to the desired confidence level.

Figure 1. Composite soil profile.



SOIL DATA

The soil deposit studied here is a water-worked glacial silty clay formed by the Erie-Huron ice lobe during the glaciation of the Great Lakes. The surface features were formed during the Wisconsin stage of the Pleistocene glaciation (3).

The design of an interchange at the Jeffries and Southfield freeways on the west side of Detroit was changed several times over a 10-year period. Each time the design was changed, additional subsurface information was obtained. A total of 42 borings were made in a 59 458-m^2 (14-acre) area. The main structures were finally supported on point bearing piles to rock.

Figure 1 shows a composite profile of the soil in which the borings were made. The soil is composed of an upper layer of hard yellow-brown mottled clay with a mean thickness of 4.27 m (14 ft) and a standard deviation of 2.13 m (7 ft) underlain by a layer of medium gray silty clay with a mean thickness of 10.67 m (35 ft) and a standard deviation of 2.44 m (8 ft). The next layers are a dense gray sand, a hard gray sandy clay, and then limestone bedrock. All borings and laboratory tests were made by personnel of the Michigan Department of State Highways and Transportation in accordance with procedures described in the department's Field Manual of Soil Engineering (2).

TEST PROCEDURES AND RESULTS

Soil samples were obtained by pressing the sampler hydraulically into the soil or by levering; the sampler was never driven. The sampler was a 76-cm-long (25.8-in) steel tube equipped with a cutting tip that had a 4.44-cm (1.5-in) outside diameter and was fitted with a series of liners that took a soil cylinder of 3.49-cm (1.2-in) diameter and 25.4-cm (8.6-in) length. The

Table 1. Results of soil classification test.

		Sieve		Sample 1		Sample 2		Sample 3	
Test	AASHTO Soil Classification	Size	Opening (mm)	Cumulative Percent Passing	Percent Retained	Cumulative Percent Passing	Percent Retained	Cumulative Percent Passing	Percent Retained
Sieve analysis	Gravel	3/4 in.	19.1						
		1/2 in.	12.7						
		3/8 in.	9.52						
		No. 4	4.76						
		No. 8	2.38						
		No. 10	2	100		100		100	
	Coarse sand	No. 18	1	97		97		98	
		No. 20	0.84	96		96		97	
		No. 35	0.5	94		94		95	
		No. 40	0.425	94	6	93	7	95	5
	Fine sand	No. 50	0.297						
		No. 60	0.25	91		90		92	
		No. 100	0.149						
		No. 140	0.105	84		82		86	
		No. 200	0.075	82	12	80	13	84	11
Hydrometer	Silt		0.05	78		74		79	
			0.005	46	36	43	37	49	35
	Clay		0.001		46		43		49

Note: 1 mm = 0.039 in.

liners were taken to the laboratory where the samples were tested for unconfined compression strength, moisture content, and natural unit weight in accordance with recommended AASHO standards. Gradation analyses, Atterberg limits, and specific gravity tests were also performed on three of the specimens (Table 1). The following table gives the resulting soil constants for three samples.

Soil Constant	Sample 1	2	3
Liquid limit, %	28	29	32
Plasticity index, %	11	13	14
Specific gravity	2.68	2.68	2.67
Shrinkage limit, % by weight	15	15.2	15.4
Shrinkage ratio	1.90	1.9	1.88

A total of 329 specimens of the gray silty clay were obtained from the 42 borings and tested. The results are presented in Table 2 in terms of

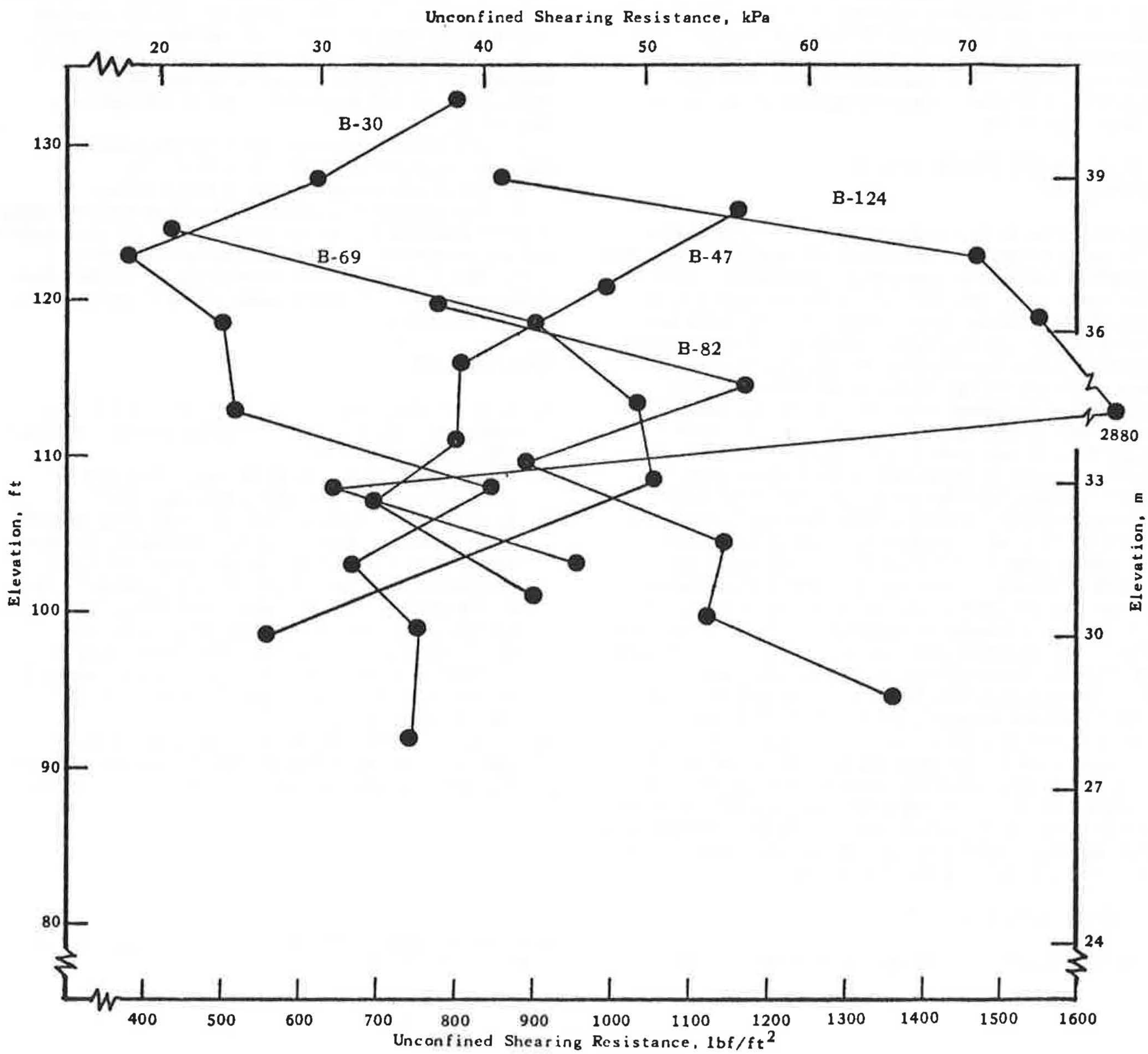
$$\bar{x} = 1/N\sum_{i=1}^{N} x_i \qquad (1)$$

Table 2. Statistical properties of gray silty clay.

Statistic	Undrained Shear Strength[a] (kPa)	Unit Weight of Dry Soil[b] (g/cm³)	Moisture Content[c] (% dry weight)
Median value	36.38	1.679	22
Mean value	38.64	1.668	22.7
Standard deviation	15.79	0.120	4.7

Note: 1 kPa = 20 lb/ft^2; 1 g/cm^3 = 0.036 lb/in^3.
[a] Coefficient of variation is 0.408.
[b] Coefficient of variation is 0.072.
[c] Coefficient of variation is 0.207.

Figure 2. Strength profile of gray silty clay layer.



$$S = \left[1/(N-1) \sum_{i=1}^{N} (x_i - \bar{x})^2 \right]^{1/2} \quad (2)$$

$$V = S/\bar{x} \quad (3)$$

where

$\bar{x}$ = sample mean value,
S = sample standard deviation,
V = sample coefficient of variation,
N = number of specimens, and
x_i = ith value of the random variable.

The median value is x_i, for which 50 percent of the values are larger (or smaller).

Examination of the values in Table 2 reveals that the coefficient of variation for the undrained shear strength of this glacial silty clay is 0.408. This agrees with previously published data on similar glacial silty clay strata from the same geological region, which recommend the value of 0.40 (6).

Linear regression analyses in which elevation was used as the independent variable were performed to determine whether vertical or horizontal spatial correlations existed. The largest correlation coefficient found was 0.20, which indicated that no such useful correlation existed. The strength profile shown in Figure 2 is typical.

PROBABILITY DISTRIBUTION FUNCTIONS

Undrained shear strength and moisture content were plotted on normal and lognormal probability paper. For moisture content the lognormal distribution is clearly the best model. The results for the undrained shear strength are not as clear because the lognormal distribution best fits the higher strength tail but the lower strength tail is best fitted by the normal density function. The chi-square goodness-of-fit test (1) was applied to the strength data for both the normal and the lognormal distribution models for cases in which (a) all data were grouped into 20 equally likely intervals, (b) the 10 percent of the data of the highest strength were "lumped," and (c) the 2.5 percent of the data having the highest strength were truncated. For each of the three cases considered, a pair of chi-square statistics were obtained and the best fit was determined by the value most likely to occur in a random process described by the chi-square distribution. On this basis the lognormal statistic is closer to the mean than is the Gaussian statistic in every case except that in which the lower 97.5 percent of the data are used. This is consistent with the work of Wu and Kraft (5). The lognormal is clearly the more probable fit of the two if all the data are used, and it would be the one selected if the choice were based only on statistical considerations. However, because the Gaussian distribution fits the lower strength tail very well and this tail is more critical to prediction of failure probabilities than the higher strength one, the Gaussian statistic would be a better empirical selection.

BORINGS AND SPECIMENS

In exploring a site of the size used in this research, it is typical practice to begin with five borings arranged in an X pattern. This allows the construction of two intersecting soil profiles that indicate the gross characteristics of the soil stratigraphy. Extensive analysis of the data show that, if the five borings contain a minimum of 30 specimens, that number is sufficient to calculate a value of strength for use in design. It was found that the strength corresponding to the lower bound of the 99 percent confidence interval on the mean is conservative, but not unduly so, and it is consistent with that produced by the ad hoc procedures currently used by experienced geotechnical engineers. The analysis also shows that it is not conservative to use the average specimen strength for the design value. Using the minimum of the individual boring averages, however, is too conservative.

CONCLUSIONS

For a gray, water-worked, glacial silty clay of low plasticity,

1. On the basis of the most probable chi-square statistic, the lognormal distribution function models undrained shear strength, moisture content, and unit weight better than the normal (Gaussian) distribution;
2. On the basis of engineering needs, the normal distribution is a better model for undrained shear strength because it predicts the low strengths more accurately;
3. The coefficient of variation for the undrained shear strength, for 329 specimens is 0.408;
4. There are no useful spatial correlations;
5. Five borings arranged in an X pattern and containing at least a total of 30 specimens are sufficient to calculate a design value for the undrained shear strength; and
6. The best design undrained shear strength is that corresponding to the lower bound of the 99 percent confidence interval.

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Rainfall Factors That Affect Erosion

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Soil erosion from highway construction sites should be considered a significant environmental factor in the design of highway drainage systems. Although the problem of predicting soil erosion has been studied rather extensively over the past 40 years, there is still no consensus as to which predictive method is superior. Many causal factors contribute to soil erosion, some of them misunderstood and some mistreated in application. This paper isolates the most significant factor, rainfall, and demonstrates how that factor has evolved as the needs of researchers have changed. Some of the literature on the subject is reviewed, from the first studies performed to the present time. Three distinct rainfall parameters—30-min maximum rainfall intensity, rainfall energy, and direct runoff—have proved to be good indicators of soil erosion from land surfaces, and the time distribution of rainfall has recently proved to be of relative significance in predicting sediment yield.

Research on the various causal factors of soil erosion has been studied since the early 1920s. For the most part, this research has been concerned with agricultural soil erosion. Not until the mid-1960s was the problem of soil erosion from construction areas addressed.

Excessive soil loss reduces crop productivity and is naturally of major concern to farm owners and operators. However, although soil loss from construction sites is often many times greater than that from comparable farm lands, land developers and construction contractors have had less incentive for control. Consequently, soil erosion from construction sites has not been effectively checked and, in rapidly developing locations such as the eastern United States, it is creating serious environmental problems.

In September 1972 the Pennsylvania Department of Environmental Resources adopted rules and regulations for the control of soil erosion to protect the state's natural water resources. Because of similar environmental and ecological constraints imposed by other federal, state, and local authorities, engineers must now be able to predict the sediment yield from a proposed highway construction project. Although many causal factors of soil erosion and sediment yield have been studied, this paper focuses only on the rainfall parameters that are significant in the erosion process.

In the development of methods for predicting erosion, rainfall has always been considered, and usually verified, to be the most significant single index of erosion. Simple expressions were used in the early predictive methods, but as research techniques improved more complex factors evolved. Today, thanks to sophisticated high-speed computers and statistical analysis, complex parameters pose no real difficulty in computation.

Essentially, there are three rainfall parameters that are important in determining soil erosion and sediment yield: rainfall intensity, rainfall energy, and direct runoff. The time distributions of these parameters may also be significant.

RAINFALL INTENSITIES

Intense storms possess high kinetic energy. A high-intensity storm contains a greater percentage of energy than one of moderate to low intensity and is the principal cause of soil erosion.

Initial research dealt with artificial rainfall on well-calibrated soil plots. These initial investigations found raindrop size and amount, storm duration, and velocity of raindrops to be important parameters in predicting soil erosion. However, as further studies (1, 2, 3) showed, rainfall intensity was the most dominant rainfall factor.

Smith and others (4) studied 5, 15, and 30-min maximum rainfall intensities to determine which intensity was the most important in producing maximum rate of runoff for 79 storms over an 8-year period. Their research, which took into account antecedent soil moisture, found that the 30-min maximum rainfall intensity had the greatest effect on the maximum rate of runoff. In the late 1940s and early 1950s, more detailed studies evolved. Musgrave (5) developed an erosion-prediction method based on rainfall, flow characteristics, soil characteristics, and vegetal cover. In studying erosion from agricultural lands, Musgrave found rainfall to be the primary causal factor of erosion. Hays (6) also found in his studies that a very good relation existed between the maximum amount of rainfall occurring within any 30-min period and the amount of soil that was eroded during the duration of the storm. Other factors being equal, erosion was found to be approximately proportional to $P_{30}^{1.75}$, where P_{30} represents the maximum amount of rainfall (in inches) occurring in any 30-min period. (The data presented here were calculated in U.S. customary units only; therefore, values are not given in SI units.)

A statistical analysis performed by Foster (7) used nine indices of rainfall intensity: four simple, frequently used indexes and five compound indexes. The four common measures were the 5, 15, and 30-min intensities and the average intensity, which was defined as the total rainfall (in inches) divided by the elapsed time (in seconds). Foster (7)—like Hays and others (6) and Smith and others (4)—found that the maximum 30-min rainfall was the most significant rainfall factor.

A sample of 244 storms that occurred at six highway construction sites in Pennsylvania were analyzed to determine the level of significance of different rainfall intensities. The table below summarizes the statistics for P_{TOT} (total precipitation) and P_{15}, P_{30}, P_{60}, and P_{180} (15, 30, 60, and 180-min maximum rainfall intensities in inches per hour respectively). The table ranks the correlation coefficients of each measure of precipitation to sediment yield divided by the correlation coefficient for P_{180} (1 in = 25.4 mm).

	Correlation Coefficient	
Precipitation (in/h)	Total Sediment	Mean Sediment Concentration
15	1.73	2.37
30	1.41	2.11
60	1.07	1.61
180	1	1
Total	0.17	0.08

The data in the table show that shorter duration rainfall intensities are more correlated to sediment yield than are greater intensities. However, as other studies (4, 6, 7) have shown, maximum 30-min rainfall is as good, for all practical purposes, as any other single rainfall parameter.

Table 1. Kinetic energy of natural rainfall.

Intensity (in/h)	Energy[a]	Intensity (in/h)	Energy[a]	Intensity (in/h)	Energy[a]	Intensity (in/h)	Energy[a]	Intensity (in/h)	Energy[a]
0.00	0	0.40	784	0.80	884	3.0	1074	7.0	1196
0.01	254	0.41	788	0.81	886	3.1	1079	7.1	1198
0.02	354	0.42	791	0.82	887	3.2	1083	7.2	1200
0.03	412	0.43	795	0.83	889	3.3	1088	7.3	1202
0.04	453	0.44	798	0.84	891	3.4	1092	7.4	1204
0.05	485	0.45	801	0.85	893	3.5	1096	7.5	1206
0.06	512	0.46	804	0.86	894	3.6	1100	7.6	1208
0.07	534	0.47	807	0.87	896	3.7	1104	7.7	1209
0.08	553	0.48	810	0.88	898	3.8	1108	7.8	1211
0.09	570	0.49	814	0.89	899	3.9	1112	7.9	1213
0.10	585	0.50	816	0.90	901	4.0	1115	8.0	1215
0.11	599	0.51	819	0.91	902	4.1	1119	8.1	1217
0.12	611	0.52	822	0.92	904	4.2	1122	8.2	1218
0.13	623	0.53	825	0.93	906	4.3	1126	8.3	1220
0.14	633	0.54	827	0.94	907	4.4	1129	8.4	1222
0.15	643	0.55	830	0.95	909	4.5	1132	8.5	1224
0.16	653	0.56	833	0.96	910	4.6	1135	8.6	1225
0.17	661	0.57	835	0.97	912	4.7	1138	8.7	1227
0.18	669	0.58	838	0.98	913	4.8	1141	8.8	1229
0.19	677	0.59	840	0.99	915	4.9	1144	8.9	1230
0.20	685	0.60	843	1.0	916	5.0	1147	9.0	1232
0.21	692	0.61	845	1.1	930	5.1	1150	9.1	1233
0.22	698	0.62	847	1.2	942	5.2	1153	9.2	1235
0.23	705	0.63	850	1.3	954	5.3	1156	9.3	1237
0.24	711	0.64	852	1.4	964	5.4	1158	9.4	1238
0.25	717	0.65	854	1.5	974	5.5	1161	9.5	1240
0.26	722	0.66	856	1.6	984	5.6	1164	9.6	1241
0.27	728	0.67	858	1.7	992	5.7	1166	9.7	1243
0.28	733	0.68	861	1.8	1000	5.8	1169	9.8	1244
0.29	738	0.69	863	1.9	1008	5.9	1171	9.9	1246
0.30	743	0.70	865	2.0	1016	6.0	1174		
0.31	748	0.71	867	2.1	1023	6.1	1176		
0.32	752	0.72	869	2.2	1029	6.2	1178		
0.33	757	0.73	871	2.3	1036	6.3	1181		
0.34	761	0.74	873	2.4	1042	6.4	1183		
0.35	765	0.75	875	2.5	1048	6.5	1185		
0.36	769	0.76	877	2.6	1053	6.6	1187		
0.37	773	0.77	878	2.7	1059	6.7	1189		
0.38	777	0.78	880	2.8	1064	6.8	1192		
0.39	781	0.79	882	2.9	1069	6.9	1194		

Note: 1 in = 25.4 mm; 1 ft-tonf = 2.7 MJ; 1 acre = 0.4 hm^2.

[a] Measured in foot-ton-force per acre per time unit for 1 in of rain.

Table 2. Procedure for determining total energy of a rainstorm.

Time (min)	Accumulated Rainfall (in)	Incremental Rainfall (in)	Intensity (in/h)	Energy[a]	Total Energy of Storm (ft-tonf/acre/in of rain)
0					
10	0.04	0.04	0.25	717	28.7
20	0.21	0.17	1.00	916	155.7
30	0.29	0.08	0.50	816	65.3
40	0.37	0.08	0.50	816	65.3
50	0.41	0.04	0.25	717	28.7
60	0.43	0.02	0.12	611	12.2
					355.9

Note: 1 in = 25.4 mm; 1 ft-tonf = 2.7 MJ; 1 acre = 0.4 hm^2.

[a] Measured in foot-ton-force per acre per time unit for 1 in of rain (from Table 1).

RAINFALL ENERGY

In the early 1950s, because of an increased interest in land-use practices, new impetus was generated to develop more precise techniques for predicting soil erosion. Rainfall intensity by itself was no longer a valid representation of the rainfall factor used in many of the soil-erosion equations of that period. For the first time, a concentrated effort was focused on the mechanics of the soil-erosion process. In an early study, Ellison (8, 9, 10, 11) showed that the impact of raindrops on the soil surface starts erosion by detaching the soil particles, which are then transported by overland flow. In 1954 the Soil and Water Conservation Research Division of the Agricultural Research Service initiated a program to summarize for further analysis all available runoff and soil-loss data on a national basis. Studies conducted under that program pointed out that greater accuracy could be achieved in soil-loss prediction equations applied to individual storms if a measure of rainfall energy were included as a variable. Both the efficiency and the simplicity of such equations were further improved by using terms that measure the interaction effects among variables.

In an attempt to improve soil-loss prediction, Wischmeier and Smith (12) related rainfall energy to soil erosion. Using a concept of rainfall energy that is based on studies such as that of Laws and Parsons (14), which relates drop size to rainfall intensity, they developed a relatively simple procedure for computing the approximate rainfall energy of a storm. If rainfall energy is to be used as the rainfall parameter in estimating soil erosion, then the kinetic energy of a rainstorm is the appropriate factor. Kinetic energies in foot-ton-force per acre per time unit for 1 in of rain, for natural rainfall at various intensities, are given in Table 1. Wischmeier developed the following regression equation from which the values in Table 1 were derived:

$$Y = 916 + 331 \log_{10} X \qquad (1)$$

where

Y = kinetic energy (in foot-ton-force per acre per time unit for 1 in of rain) and
X = rainfall intensity (in inches per hour).

To compute Wischmeier's energy value for a rainstorm, Table 1 is used in conjunction with recorded rain-gauge data. Given the time and accumulated rainfall values from a recording rain gauge, the energy of a storm can be obtained as follows:

1. Determine the rainfall, in inches, for each time increment.
2. Determine the rainfall intensity, in inches per hour, for each time increment.
3. Determine the kinetic energy, in foot-ton-force per acre per time unit for 1 in of rain, by using Table 2.
4. Multiply the values for accumulated rainfall by the energy values and add the resulting values to determine the total energy of the storm, in foot-ton-force per acre for 1 in of rain.

Table 2 gives an example of the use of this procedure.

Two rainstorms of equal volume falling on the same field often produce different amounts of soil loss. To analyze and solve soil-erosion problems of this kind it is necessary to know which rainfall characteristics are responsible for such differences. Wischmeier approached this problem primarily on a mathematical basis by using multiple regression theory. Combinations of rainfall characteristics, interaction effects, antecedent soil-moisture conditions, and soil-compaction terms were investigated in exploratory studies. The most significant variable found for predicting soil loss from cultivated fallow soil was the product of the total kinetic energy of a storm times its maximum 30-min intensity. This product, called the erosion index (or EI variable), measures the interaction effect of the two most prominent rainfall characteristics. Because it is used by so many researchers as the rainfall parameter for predicting soil erosion, the index is well documented in the literature and is a good measure of the erosion-producing capacity of a soil.

DIRECT RUNOFF

Rainfall intensity, the parameter initially used in determining soil loss, is highly correlated with soil erosion but it oversimplifies the problem. The ability to predict soil loss was substantially improved when Wischmeier and Smith published their universal soil-loss equation (13). In this equation they combined rainfall energy with 30-min maximum rainfall intensity as the significant rainfall parameter. The intended application of the equation was to predict potential soil loss from agricultural fields.

Although rainfall energy is generally highly correlated with runoff, it is not affected by antecedent soil moisture. Therefore, if soil moisture is low, high-energy rainstorms may produce little or no runoff. With no runoff there can be no sediment yield.

To design sediment-control devices the highway engineer must know how much sediment is transported to the drainage system. Wischmeier and Smith's equation predicts potential soil loss but not the amount of sediment at a particular location in the drainage area; the equation therefore needs to be modified by a delivery ratio (15, 16). Because the delivery ratio is a complex function of watershed characteristics, such as drainage area, stream slope, watershed shape, and runoff, how and why it varies have not been well documented in the literature. Because of the unknown variability and sensitivity of the delivery ratio and the fact that the soil-erosion process may not be the same for fallowed agricultural lands as it is for highly compacted soil conditions at highway construction sites, researchers have continued to investigate new rainfall parameters.

Many recent studies have used multiple regression analysis to develop parametric equations. The most significant rainfall parameter currently being studied is the runoff factor (17). Williams and others (18) found a runoff factor that proved to be superior to rainfall for predicting sediment concentrations from five small watersheds in the Texas Blacklands. In 1972 Williams and Berndt (19) modified the universal soil-loss equation for watershed application by replacing the rainfall factor of Wischmeier with a runoff factor. Williams had shown in an earlier study that runoff is more highly correlated to sediment loss than is rainfall.

The Hydraulics Division Committee on Sedimentation of the American Society of Civil Engineers (ASCE) has stated that runoff is the best single parameter in predicting soil erosion (20). The use of runoff rate for determining sediment yield is also appealing because many short-term runoff records for watersheds throughout the country can be extended by applying an assumed rainfall-runoff relation to long-term rainfall records. According to the ASCE committee, it is reasonable to assume that the best rainfall parameter would only approach a factor that expresses runoff rates or volumes because runoff represents the integrated effect of all rainfall and antecedent soil-moisture conditions.

TIME DISTRIBUTION OF STORM RAINFALL

The time distribution of rainfall parameters may be an important variable in the prediction of sediment erosion. The characteristics of a design storm must include the amount, the duration, the season of the year, and the time-distribution pattern of rainfall. Figure 1 shows time-distribution curves for three types of storms. Figure 2 shows the difference between the time-distribution curves produced by an early-peaking storm (type 1) and a late-peaking storm (type 3) for one of the watersheds currently being studied.

Because a designer may be interested in synthesizing a flood hydrograph, the time distribution of rainfall can be important. In addition, because runoff is affected by the pattern of rainfall distribution, sediment yield may also be affected by rainfall distribution even though energy is independent of storm type. For the 244 storms studied, runoff is the rainfall parameter most highly correlated to sediment erosion.

In his research Wischmeier expected the relation of the EI value to soil loss to be influenced by the sequence of rainfall intensities within a storm. In 1958, Wischmeier and Smith (12) classified storms according to type as advanced (early peaking), intermediate (mean), and delayed (late peaking), depending on the relative time of occurrence of the period of greatest storm intensity. They found no correlation between the type of storm and the unexplained residuals of soil losses in the data and concluded that storm type did not influence the relation of soil loss to EI.

Our study, however, has found the type of storm to be significant at the 85 percent confidence level when storms are observed on an individual basis. Late-peaking storms appear to be more erosive than average and early-peaking storms. Because late-peaking storms generally yield more runoff with higher peaks, this further reinforces the fact that runoff is a critical predictor of sediment yield.

The data given in Table 3 illustrate the importance of the relative time of occurrence of the period of greatest storm intensity. Both storms have the same characteristics, the same kinetic energy, and the same EI, but they are distributed differently. The late-peaking storm will yield more runoff and ultimately produce a higher sediment yield. Maximum 30-min intensity for the early-peaking and late-peaking storms in Table 3 is determined as follows:

$$I_{30_{EP}} = 0.385 \text{ in}/0.5 \text{ h} = 0.77 \text{ in/h} \quad (2)$$

$$I_{30_{LP}} = (0.4 - 0.015)/0.5\ \text{h} = 0.77\ \text{in/h} \tag{3}$$

$$EI_{EP} = 366.57(0.77) = 282.26 \tag{4}$$

$$EI_{LP} = 366.57(0.77) = 282.26 \tag{5}$$

The relative increase of sediment yield from a late-peaking storm relative to that from an early-peaking storm is shown in Figure 3. (Because the relation is still being developed, this figure should be used only as a guide.) Figure 3 shows the significance of selecting a late-peaking storm over other distributions. If a design storm is used that has a high frequency of occurrence, the increase in sediment yield will be substantial if a late-peaking distribution is selected.

Figure 1. Time-distribution curves for rainfall for three types of storms.

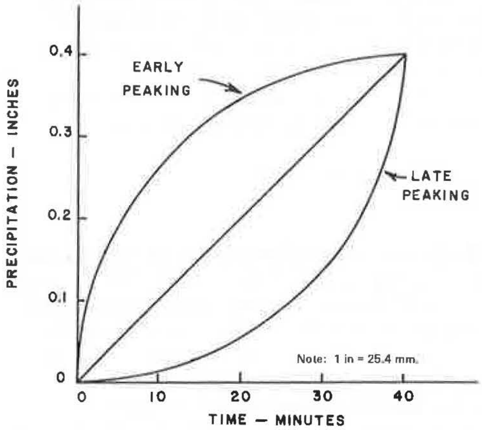
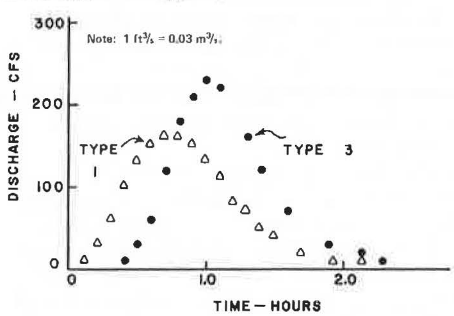


Figure 2. Hydrographs for early-peaking (type 1) and late-peaking (type 3) storm distributions.



CONCLUSIONS

The three rainfall factors predominantly used to predict soil erosion are 30-min maximum rainfall intensity, rainfall energy, and runoff factor. The 30-min rainfall intensity is the simplest factor to use. The rainfall energy factor developed by Wischmeier and Smith (12) has proved to be an excellent parameter for predicting soil erosion from agricultural lands. However, recent studies have shown that runoff may be the most significant factor for predicting erosion from highway construction sites. If runoff is to be used and if a design hydrograph is needed to size the appropriate erosion-control device, then the time distribution of the design rainfall may also be important.

Figure 3. Percentage increase of sediment yield from late-peaking storm over sediment yield from early-peaking storm.

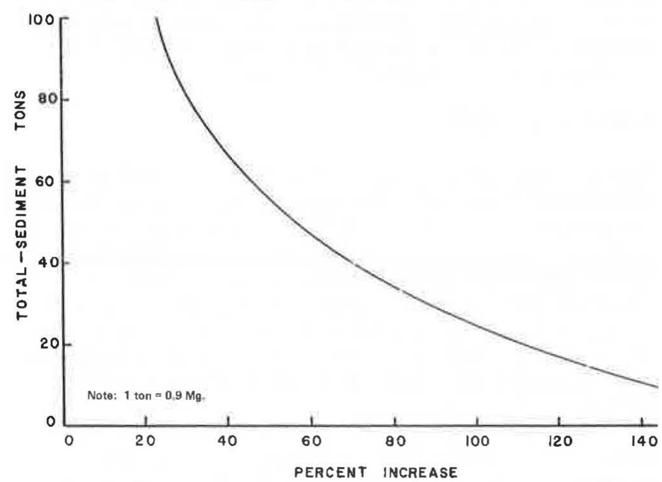


Table 3. Total storm energy of late-peaking and early-peaking storms.

Storm Type	Time (min)	Accumulated Rainfall (in)	Incremental Rainfall (in)	Intensity (in/h)	Energy[a]	Total Energy of Storm (ft-tonf/acre/in of rain)
Late-peaking	0					
	5	0.005	0.005	0.06	512	2.56
	10	0.015	0.010	0.12	611	6.11
	15	0.030	0.015	0.18	669	10.04
	20	0.055	0.025	0.30	743	18.58
	25	0.09	0.035	0.42	791	27.69
	30	0.135	0.045	0.54	827	37.22
	35	0.205	0.070	0.84	891	62.37
	40	0.400	0.195	2.34	1036	202.02
						366.57
Early-peaking	0					
	5	0.195	0.195	2.34	1036	202.02
	10	0.265	0.070	0.84	891	62.37
	15	0.310	0.045	0.54	827	37.22
	20	0.345	0.035	0.42	791	27.69
	25	0.370	0.025	0.30	743	18.58
	30	0.385	0.015	0.18	669	10.04
	35	0.395	0.010	0.12	611	6.11
	40	0.400	0.005	0.06	512	2.56
						366.57

Note: 1 in = 25.4 mm; 1 ft-tonf = 2.7 MJ; 1 acre = 0.4 hm^2.

[a] Measured in foot-ton-force per acre per time unit for 1 in of rain (from Table 1).

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Factors That Affect Water Erosion From Construction Areas

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The various factors that affect water erosion from agricultural lands are reviewed. Methods for predicting soil loss from agricultural lands appear to be well established and can be generally applied to farmlands. A review of the conditions existing on construction sites, however, indicates that they bear only a limited similarity to conditions on agricultural lands. The need to develop new means for predicting sediment yield from construction areas is evident. The factors that determine soil loss from a construction site are likely to be quite different from those used in determining soil loss from agricultural lands. Methods for controlling water erosion from construction areas are briefly discussed. The major factor is control of runoff water during the construction period. Current work to define the factors involved in erosion-control measures and the relative efficiencies of such measures are discussed.

Erosion is a naturally occurring part of the weathering process. Without natural erosion the landforms we know would not exist. Thus, only the elimination of excessive erosion caused by the activities of man, and not the complete elimination of erosion, is desirable. The two common erosion-producing factors are flowing water and wind. This paper deals only with water erosion.

In nature the rate at which water erosion occurs is controlled by gentle slopes and vegetative cover; many of the fertile agricultural areas are formed in this way. Human agricultural and construction activities expose the bare soil and thus accelerate erosion, causing downstream damage and loss of agricultural lands. Control of this accelerated rate of erosion is essential to the preservation of our way of life. Although agricultural activities are now generally conducted so as to minimize accelerated erosion, concern has recently arisen about accelerated erosion from construction activities. That concern has resulted in a need to predict where and how much erosion will occur in construction areas for the purpose of designing protective measures.

This paper examines (a) the factors that affect water erosion from construction areas for the purpose of predicting the amount of such erosion and (b) the factors that should be considered in the design of erosion-control devices.

PREDICTIVE METHODS

When the Soil Conservation Service was established in 1935, research on predicting soil erosion from farmlands was accelerated. Until that time only casual research had been conducted on the factors causing erosion. The result of 20 years of research by the Soil Conservation Service is the now widely recognized universal soil-loss equation (1). The following table lists the factors included in the soil-loss equation and the categories of erosion activity in which they may be grouped:

Category	Factor
Climate	Rainfall
Site conditions	Slope gradient
	Slope length
	Soil erodibility
Human activity	Crop management
	Erosion control

The equation predicts average expected soil loss per unit of area per year on a given farmland cultivated in continuous fallow. Since 1965 many researchers have attempted to modify the universal soil-loss equation (2, 3, 4), mostly by attempting to modify one of the terms—generally the rainfall factor. All of the equations developed include the same three categories. None of these other equations, however, has found widespread use and acceptance.

The development of the computer made possible studies that model the erosion process. Most of these studies are incomplete and currently put to only limited use. Because of the wide variation in climatic and site conditions, an extremely complex computer model will probably be required that, because of its complexity, will not be widely used.

Recent concern about preventing erosion from construction areas resulted in widespread use of the universal soil-loss equation or some modification of this equation. It soon became evident, however, that the equation did not apply to construction sites. Limited attempts were then made to develop equations from data obtained from construction sites (4). The same three categories—climate, site conditions, and human activity—were considered, and the factors considered in the universal soil-loss equation were generally included in some modified form. This approach has resulted in equations of only limited usefulness.

CLIMATE

Rainfall Factor

Naturally, water erosion cannot occur unless water is present, usually in the form of rainfall or flowing water. A measure of the ability of a rainstorm to detach and transport the soil particles—the rainfall erosion index—was developed by Wischmeier and Smith (1). Many other investigators, working over a 20-year period, contributed to the development of the concept (5, 6, 7). There is thus a large amount of data to substantiate its use.

The rainfall erosion index (EI) is the product of two rainstorm characteristics: the total kinetic energy of a storm times its maximum 30-min intensity. The data used in the development of this concept were obtained from cultivated farmland in continuous fallow. Under these conditions the soil is in a loose, porous state and it is reasonable to expect the energy and intensity of rainfall to be an index of the ability of a storm to detach the soil particles.

The process by which soil particles are detached and transported by the action of rainfall can be described as follows for farmland conditions. First, the soil of a farmland in continuous fallow is in a very loose condition with a high water-retention capacity. The cohesion between soil particles is poor. When rainfall starts, the water is rapidly absorbed into the soil. Generally the first 0.62 to 1.25 cm (0.25 to 0.5 in) of rainfall is absorbed. A layer of soil whose moisture content is above the liquid limit is formed on the surface. When a raindrop hits this soft, saturated soil the amount of soil detached is a function of the energy of the raindrop. As rainfall continues small puddles of water form in the rough surface of the soil. Runoff does not occur until the soil is saturated and all depressions are filled with water. As further rainfall occurs, rills are formed by the flowing water and further soil detachment is caused by the velocity of the flowing water. The rills then collect to form gullies, and the flowing water detaches and transports larger soil particles.

Under construction-site conditions, it is not reasonable to expect rainfall energy and intensity to be the controlling factors in soil erosion. At a construction site, compacting of fills and earth placement are normally done simultaneously. The area is also bladed relatively smooth to facilitate movement of earth-moving equipment. Thus, the rain falls on a smooth, compacted soil surface that has good soil cohesion and a very low infiltration rate. When rainfall begins, very little of it [0.25 to 0.62 cm (0.1 to 0.25 in)] penetrates the soil surface. Because of the relatively smooth condition of the surface, sheet flow forms and the raindrops expend their energy on a water surface and not on the soil surface. The water does collect in rills and later in gullies, as in farmland flow, but provision is made on most construction projects for collecting the water in controlled waterways so that gullies do not form. Rainfall impinging on the cut-and-fill slopes is proportional to the projected slope areas, which are generally small compared to flat areas. Control of the water by intercepter trenches and staged seeding and mulching greatly reduce erosion from these slopes.

In recent years the author has witnessed erosion on several construction projects. Examining the saturated soil scraped off the compacted fill after a rainfall revealed that the water only penetrated 0.2 cm (0.12 in) or less compared to a penetration of 2.5 to 5 cm (1 to 2 in) on adjacent farmland. Sheet flow was generally observed to occur in construction areas (8); little or no sheet flow was observed on adjacent farmlands. In construction areas only a few rills were seen to form, and these generally in wheel tracks and poorly graded areas. Generally many rills formed on the agricultural land. On one construction project, gullies were observed where uncontrolled runoff was allowed to flow over the side of an embankment. Although usually heavy rainstorms occurred on the farmlands, only a few gullies were observed because of the use of good farming practices. The action of the rain on cut slopes was minor in most cases. The use of intercepter ditches prevented concentrated flow over the face of the cut. On a well-dressed slope that was seeded and mulched, only minor rills formed; the same was observed on embankment slopes.

Because of recent concern about stream pollution from construction sites, an effort was made to predict soil loss at such sites by means of the universal soil-loss equation. Researchers (2, 3, 4) soon realized that storm energy and intensity were not the controlling factors at construction sites. Studies of various rainfall parameters indicated that runoff rates were correlated with sediment yield from construction sites. The runoff factor now appears to be gaining acceptance as a simplified approach to the problem.

Studies on sediment yield from construction sites conducted by the Pennsylvania District of the U.S. Geological Survey have indicated that this may be an oversimplification. It appears that the surface dust on construction sites is rapidly carried to streams by runoff and that, as further water flow occurs, a much reduced sediment yield occurs. The hydrograph in Figure 1 shows the effect of two consecutive rainstorms on sediment yield. The first storm occurred after 7 d of construction operation and produced 12.6 kg (27.74 lb) of sediment/93 m^2 (1000 ft^2) of exposed area. The second storm occurred 2 d later and produced 3.1 kg (6.84 lb) of sediment/93 m^2 (1000 ft^2) of exposed area. As a result, such factors as days between storms, contractor operations, and season of the year are being included in the joint study by the Pennsylvania office of the U.S. Geological Survey and Pennsylvania State University.

The time period between storm events and the season of the year appear to have a major influence on sediment yield but are difficult to include in a predictive equation. These factors may explain the poor correlation reported between direct runoff and sediment yield.

Freezing Areas

An important climatic factor in the snow regions is ground freezing and thawing. When the ground is frozen there is a very small loss (or no loss) of soil by erosion. This is also true for snowmelt conditions as long as the soil remains frozen. When the soil thaws, however, it is in a saturated, soft condition and water from snowmelt or rainfall then results in excessive sedimentation. Spring thaw periods may thus produce sediment yields many times those produced by storms during the summer months. This is important in the design of erosion-control measures at construction sites because such measures must be completed before the winter shutdown.

Storm Events

It is important to remember that the universal soil-loss equation was developed for gross annual soil loss and thus the yearly EI summation is used. It may be modified for use on an individual-storm basis, which would be especially applicable in estimating construction sediment yields for design purposes. But what is the typical design storm in erosion control? For economic reasons erosion-control measures should not be designed for a storm that would not normally be expected to occur during the short life of the project. The joint study conducted by the U.S. Geological Survey and Pennsylvania State University is expected to provide a guide to the storm frequency that should be used. That frequency should be based on the anticipated number of years the construction project will be exposed to erosion conditions.

SITE CONDITIONS

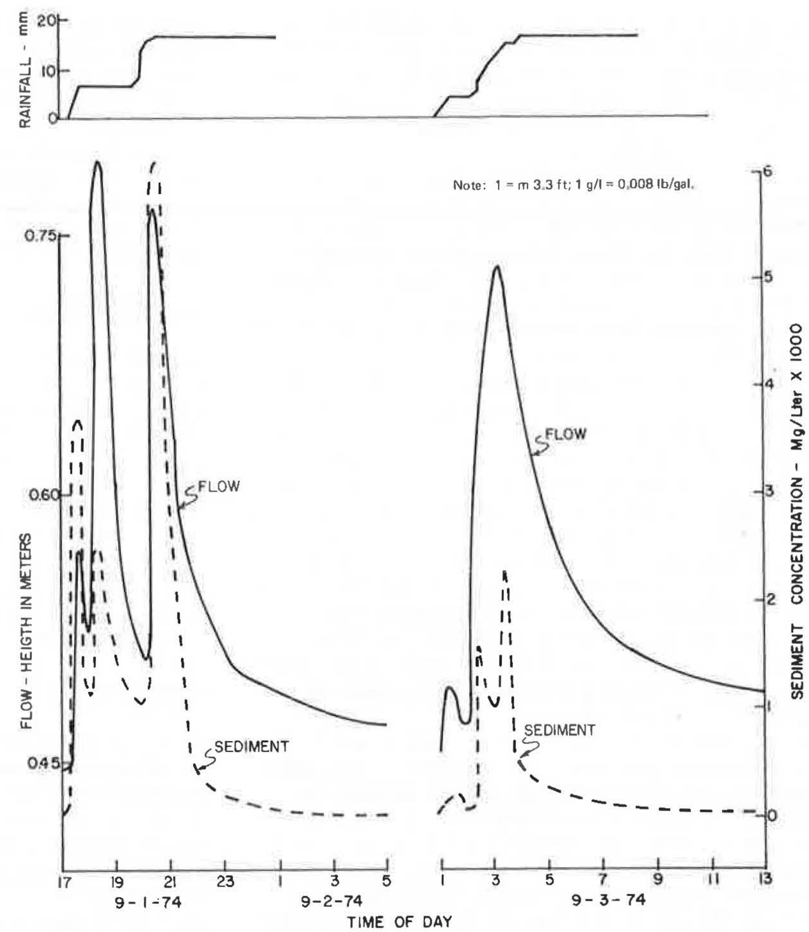
Slope Gradient

The slope of the land generally determines the velocity with which water flows across the slope. Such items as vegetative cover have a large effect on the velocity of runoff water. In sheet flow, rill flow, and gully flow, the velocity of water flow determines how much sediment the water will transport and causes the detachment of soil particles from the soil mass. Thus both detachment and transport of soil particles are functions of the slope of the soil surface.

To isolate the slope effect in developing the universal soil-loss equation, a 9 percent slope was adopted as standard. A standard roughness condition existed for land cultivated in continuous fallow. A slope effect was obtained by standardizing other factors, and this was applied as a factor to the 9 percent standard slope. Other researchers have since studied the effect of slopes on sediment yield, but the universal soil-loss concept is generally used.

Construction projects are usually characterized by cut-and-fill slopes and relatively flat work areas. The cut-and-fill slopes are steep and originally produced considerable sediment yield. Because of the practice of controlling the surface water so that it does not run

Figure 1. Effect of consecutive storm events on sediment yield.



over the top and down the slope, erosion has been greatly reduced. The standard practice of using intercepter trenches, dikes, and down drains has been very effective. Rain falling directly on the slope results in runoff, which produces a sediment yield. Continual fine grading of the slope and staged seeding and mulching have been observed to result in a sheet flow with minor sediment yield. Thus, good construction practices appear to be preventing the high sediment yields expected from slopes.

Work areas tend to be relatively flat with slopes that seldom exceed 5 percent. Studies in Pennsylvania have indicated that work areas are the principal source of sediment yield at construction sites [yields are of the magnitude of 45.4 kg (100 lb) of sediment/186 m^2 (2000 ft^2) of exposed area] (8). This would indicate that about 0.025 cm (0.01 in) of soil is removed from the work area, or about the thickness of the dust layer. During normal construction operations, little can be done to prevent erosion from work areas except to attempt to remove the sediment from the water before it flows from the site.

Researchers now tend to eliminate the slope factor from erosion-prediction equations for construction areas (4). Because of somewhat uniform slope conditions in construction operations, this factor is likely to remain constant as long as good construction practices are followed.

Slope Length

In erosion from cultivated farmland, sediment yield has been found to be a function of slope length (1). [A standard slope length of 22 m (72.6 ft) was used in developing the universal soil-loss equation.] Rills form rapidly in cultivated farmland; sediment yield can be expected to be a function of the length of the rill because the length of the flow path of water determines the amount of soil that is detached and, thus, the sediment yield. This is a reasonable assumption in soft, saturated soil conditions such as those on cultivated farmlands. In construction areas with compacted soils, however, the length of the flow path may not determine the sediment yield because the rainfall washes the loose surface dust off the compacted soil.

Researchers have found that slope gradient and slope length, as defined by the universal soil-loss equation, do not appear to relate to sediment yield from construction areas (2, 3, 4). Attempts are being made to combine other drainage-basin parameters into one factor so that these basin characteristics can be estimated based on sediment yield. There does not appear to be any uniformity in the results currently being obtained. When soil conditions are considered, there is no reason to expect the sediment yield from construction areas to be similar to that from agricultural land. In addition, flow paths in construction areas are short because of the practice of providing for the collection and control of surface runoff.

Efforts have been made to determine the sediment yield produced by sheet, rill, and gully flows (8). Table 1 gives construction-site data for the composition of suspended solids in runoff water. The sheet and rill flows are from an embankment surface, and the gully flow is from an embankment slope where the water flowed freely down the slope. The data show no relation between

Table 1. Percentage composition of suspended solids in runoff water.

Condition	Suspended Solids (mg/L)	Composition (%)			
		Gravel	Sand	Silt	Clay
Native soil		3	26	41	30
Sheet flow	3690	0	3	47	50
Rill flow	4270	0	5	47	48
Gully flow	6030	2	10	41	47

Note: 1 g/L = 0.008 lb/gal.

the composition of the native soil and that of the transported solids. The percentage composition of the transported materials is similar for the sheet, rill, and gully flows. Similar results have been obtained by the author on other construction projects. The relatively uniform slopes and short length of flows in construction areas seem to produce somewhat uniform results. Slope gradient and slope length are expected to become constants for construction areas and to be included in the constants for predictive equations.

Soil Erodibility

The wide variation in the erodibility of various soils under similar conditions is attributable to the variation in chemical, physical, and in situ soil properties. Soil erodibility has been defined as the inherent susceptibility of soil particles to detachment and transport by raindrops and runoff. Thus, erodibility is, by definition, a property of each soil.

Soil erodibility has generally been determined by holding other factors constant or by controlling their variation and measuring the quantity of soil removed. The factors are then calculated by using various soil properties. [This is how the K-factor was determined for the universal soil-loss equation (1).] The K-factor is obtained for the A horizon in standard cultivated condition, generally by use of a nomograph. Roth and others (9) prepared such a nomograph for subsoils such as those encountered in construction and, for conditions existing in their tests, the erodibility factors are all valid. Care and judgment must be used, however, when these factors are applied to predicting sediment yield from construction sites.

The following table lists in three broad categories some of the many factors used by researchers to study soil erodibility.

Chemical	Physical	In Situ
Organic	Mechanical analysis (sand, silt, clay, colloids)	Density
Sesquioxide	Plasticity	Percolation rate (permeability)
pH	Specific gravity	Moisture content
Exchangeable base	Moisture equivalent	Cohesion
Fe_2O_3, Al_2O_3, S_1O_2, %	Percentage suspension (dispersibility)	Soil structure
Ionic dispersion	Partial surface area	Aggregation
Lime content		Shrinkage and swelling
		Depth of A, B, and C horizons
		Artificial channels

Some researchers have used ratios of two or more of these factors to express various soil properties, but only the basic factors are discussed here.

The chemical category defines the ability of water to detach the soil particles and retain them in suspension; it is not generally practical to use this category for routine determination of a soil-erodibility factor. The erodibility of subsoils has been defined as a function of the percentage of sand and the oxides of iron, aluminum, and silica in the soil. A well-equipped laboratory can easily determine the percentage of these oxides. But, although they frequently define some of the physical properties of the soil, it is hard to understand how they can define the significant in situ properties. In view of the fact that in construction operations the in situ properties often determine the sediment yield, it is questionable if chemical properties can be used in predicting sediment yield from construction areas.

Because the physical properties of soils can readily be determined in a soils laboratory, they have been widely used in estimating soil erodibility. But they do not define the in situ properties; thus, some in situ properties are often included, as they are in the universal soil-loss equation. The physical properties give an indication of the ability of water to detach soil particles and a reasonable approximation of the ability of soil particles to remain in suspension. Physical properties will probably continue to be widely used in some form in predicting sediment yield.

The in situ properties of soils can be approximated with some degree of accuracy before construction. Information on in situ properties for farmlands can be obtained from U.S. Department of Agriculture maps. In situ properties primarily indicate how easily the soil particles may be detached from the soil mass. Some in situ properties such as soil structure relate to the ability of the soil particles to remain in suspension, but these are of minor importance. In situ properties are of major importance in predicting sediment yield from construction areas. The difference between the in situ properties of soils from agricultural and construction sites is probably the major reason why an agricultural soil-erodibility factor should be used with such care for construction sites.

Soil-erodibility factors have been determined by means of test plots and are only valid for the existing test conditions. Erodibility factors are expressed by either equations or nomographs. To the author's knowledge no erodibility factor has ever been determined for construction conditions. In their joint study, the U.S. Geological Survey and Pennsylvania State University will conduct limited research in this area, using watersheds as test plots.

The differences in the erodibility of soils from agricultural lands and soils from construction sites are basically caused by (a) in situ properties resulting from the physical processing of the earth and (b) major use of subsoils and rock in earthwork construction. In situ properties probably cause the principal differences in the erodibility factor. If the major difference at construction sites is the previously mentioned washing action of rainfall, then the contractor's operations will have a major influence on sediment yield; that is, if there are no construction operations in an area, only minor sediment yield will result after the first storm. To evaluate this factor, data are being collected in the joint study by the U.S. Geological Survey and Pennsylvania State University.

In recent years attempts have been made to determine the erodibility of soils by means of laboratory tests. To be useful, a laboratory test must duplicate field conditions for the detachment and transport of soil particles. At the present time there appears to be no test that accomplishes this for conditions at construction sites. The existing tests are basically meant to provide solutions to specific problem areas. It may be necessary to develop a soil-erodibility test for earth used in construction.

HUMAN ACTIVITY

Crop Management

Vegetation is used in nature for erosion control. Vegetative cover absorbs the energy of raindrops. The organic residue from vegetation covers the ground and further absorbs the energy in raindrops and also provides storage for the water. When runoff occurs the vegetative material acts as a filter to reduce the sediment yield. Thus nature uses vegetation to control the rate at which erosion occurs. This is the natural process in humid regions. In semiarid areas, although the vegetative cover is sparse and major erosion occurs with heavy rainfall, the soils are frequently pervious and runoff is greatly reduced.

Man removes vegetative cover to produce food and shelter, accelerating erosion by exposing the soil directly to rainfall and runoff. The vegetative cover is then partially restored by agricultural crops. The management of crops has a major effect on the rate at which erosion occurs. Agricultural erosion-prediction equations such as the universal soil-loss equation contain factors that account for crop management (1). In construction activities the restorative approach is also used at the completion of a project: Vegetative cover is established in areas not protected by structures so that natural conditions are restored. During construction, however, the ground surface is bare to the effects of erosion, and this has become an area of concern.

Although crop management refers to agricultural practices, it is also applicable to construction sites. Good crop-management practices eliminate uncontrolled erosion and improve the appearance of the facility being constructed. This has been standard practice for many years and is not discussed further here.

Erosion Control

Erosion control may be defined as the use of various measures to reduce the rate of accelerated erosion. Engineers have recently attempted to prevent all sediment yield from leaving the construction site, but is this reasonable or desirable? It can only be done at great effort and expense. Preventing accelerated erosion during the construction process is the desirable approach. When water at the site would normally be clear, no sediment yield should be produced by the construction activities; when the water is normally muddy, no water leaving the construction site should contain a greater than normal amount of sediment. These results can be achieved by use of good construction practices and erosion-control techniques.

The two basic processes in erosion control are (a) preventing the detachment of soil particles and (b) removing the sediment that is being transported by the water. The usual way to prevent detachment is to cover the ground surface. Reed (8) has reported that vegetation at a construction site will reduce the sediment yield from the planted area by as much as 90 percent. This approach is of limited value, however, during major earthwork operations because only completed areas can be seeded and mulched. During construction operations, surface water is normally collected and then removed by means of controlled paths that may vary from closed pipes to open ditches. Among many methods used to protect the exposed soil are jute matting or plastic sheeting, sod placement, and fiberglass matting (10). Grasses are established as rapidly as possible to complete the protection of the soil. Where high water velocities will occur, materials such as rock, cemented soil, and concrete are used to line the channel and reduce the detachment of soil particles. Where the soil cannot be protected from the flowing water, it may be desirable to reduce soil detachment by reducing the velocity of the water. This can be done by using straw bales, rock dams, and ponds. One frequently overlooked method of protecting the soil from the flowing water is placing the base on roadways, parking areas, and other areas to be paved. Reed (8) has reported that placing the base on a roadway project reduced sediment yield from the covered area by 90 percent.

The second area of concern is the transport of soil by moving water. The principal method of removing the soil particles from the water is to allow them to settle under the force of gravity, which requires reducing the velocity of the water to zero or near zero. This is generally done by forming a pond of some type (11). It has been shown (8) that the efficiency of various ponding devices ranges from 5 to 85 percent depending on the size of the suspended soil particles, the ratio of rainfall and area of erosion to pond size, and other factors. These interrelations are complicated, and all the factors have not been fully investigated. They must be considered, however, whenever suspended sediment is removed from flowing water.

Solids can also be removed from water by the use of chemical flocculants. This method, which can be very effective and produces nearly clear water, should only be used in special situations. Care must be taken that the chemical used does not result in downstream pollution of water-supply systems.

The velocity factor is frequently overlooked in removing sediment from flowing water. The velocity of the water determines the maximum particle size that the water will move downstream. The piles of sand and gravel often observed at the downstream portion of a gully on a slope are the result of a reduction in the velocity of the water. Small dams, enlarged areas, and other methods of velocity reduction in a channel will also remove sands and gravels from flowing water. However, to remove silt and clay-size particles from the water, the velocity must in effect be reduced to zero. Days may then be required for the removal of the fine soil particles from the water, and extensive ponding would be required. Researchers are currently working to evaluate some of the factors involved in removing suspended solids from ponded water.

In any erosion-control plan it is desirable to prevent the water from forming its own flow path by providing flow paths in which its velocity can be controlled. The detachment of soil particles can thus be reduced and suspended solids removed as the water flows to the main waterway. Methods for reducing the sediment yield can then be used to reduce the amount of sediment leaving the construction site. This implies a degree of control over the contractor's operations, which contrasts with the present method of noninterference in the contractor's performance of the work. If any erosion-control plan is to be successful, such control is necessary and must be provided for in the specifications. The necessary sequence of operations must be detailed so that the contractor can bid intelligently on the project. The location and the design of the erosion-control devices must be shown, and descriptive information must be given on when these control devices are required to be operational. A well-designed erosion-control plan will enable the contractor to construct the project efficiently, without major problems, and to control the flow of water at all times.

Energy dissipators have been widely used for many years to reduce the velocity of water leaving the boundaries of construction areas. The use of conduits to carry water from the upstream to the downstream limits of a construction project usually results in an increase in velocity, which can cause extensive erosion of the stream channel downstream of the project. For this reason, energy dissipators are used at the exit ends of culvert pipes. Similar situations can exist in culverts or open channels within the project limits. In these cases, simple rock dams, roughened channel linings, or hydraulic jumps can be used to dissipate the energy of the water. The use of energy dissipators should be considered in any erosion-control plan. Failure to provide for energy dissipation can result in major erosion damage during construction or after completion of a project.

On almost all construction projects, waterways are crossed by the construction. If bridges are used, only minor work should have to be done in the channel. However, if conduits or pipes are used to channel the water across the project, major sediment yields may occur. If work is performed in the channel, sediment yields result even without rainfall and a normally clear water flow can become dirty. No work should be allowed in the channel except the construction of temporary crossings for the construction equipment. All conduits and pipes must be placed outside the normal water channel, and the downstream and upstream connections to the channel must be constructed so as to minimize the production of sediment. The use of good construction practices will result in the production of only minor sediment loads.

The Pennsylvania District of the U.S. Geological Survey has done an outstanding study of the efficiency of various erosion-control techniques (8). Their findings indicate that engineers will need to use imagination and basic engineering principles to solve many of the problems in erosion control. The key word appears to be control—that is, keeping the flow of runoff water under control at all times. If this is done, erosion-control measures will perform as anticipated for any rainfall up to the design-storm level. It will then be possible to use some type of efficiency factor in the predictive equations and to estimate the sediment yield.

CONCLUSIONS

The factors that affect sediment yield from agricultural lands are not the same as those at construction sites. The concept of rainfall intensity times energy that is used in agricultural soil-loss predictions does not appear to be a reasonable approach to estimating soil loss from construction sites because of drastically different soil conditions. The slope and length factors used in agricultural soil-loss predictions do not appear to be major factors in construction areas. A new approach to the prediction of sediment yield from construction areas is needed, and it is anticipated that new predictive techniques will soon be developed.

Reducing the rate of accelerated erosion from construction areas is currently of major concern. The rate of erosion can be greatly reduced by careful use of existing erosion-control measures. The results of existing studies on the effectiveness of erosion-control measures indicate that many existing concepts need to be revised. The time required to remove clay-size particles from water makes ponding methods of questionable value. Wherever possible greater emphasis should be placed on the prevention of erosion during construction.

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Soil Properties That Affect Erosion

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It is well known that some soils erode more easily than others. The erodibility of soils has been related to such physical and chemical soil properties as texture, structure, organic content, pH, and permeability and to such engineering properties as the dispersion and surface-aggregation ratios. This paper reviews the pertinent literature on soil erosion, concludes that the nomograph model developed by Wischmeier and others gives the best estimate of soil-erodibility values for most soils, and suggests that the nomograph developed by Roth and others be used to predict erodibility values for appropriate subsoils.

It is well known that some soils erode easily whereas others, under the same conditions of climate, vegetation, and topography, erode very little. This phenomenon is directly attributed to basic differences in the physical and chemical properties of soils. The erodibility of a soil is usually determined on the basis of soil characteristics alone.

Kibler and Busby (1) defined soil erodibility as the inherent susceptibility of soil particles to detachment and transport by raindrops and runoff. The erodibility of soils has been related to such physical and chemical soil properties as texture, structure, organic content, pH, and permeability and to such engineering properties as dispersion and surface-aggregation ratios. These are only a few of the parameters with which engineers and scientists have tried to quantify erodibility.

Because the farmer was the first to be concerned with soil loss, earlier studies of erodibility involved agricultural lands. The higher the erodibility of a farm soil was, the greater was the potential loss of productivity and therefore of profits. Today, because of increased environmental awareness of stream pollution, studies are being initiated that deal with lands affected by construction activities. Stringent laws now limit the amounts of sediment pollution permitted in streams that border construction sites; erosion-control methods and measures are thus essential. Sometimes the costs of these control measures make up a sizable amount of the budget for a project. Adequate estimation of erodibility values can help cut these costs by increasing the accuracy of the erosion-prediction equations often used to design control structures, thus helping to eliminate excessive overdesign. The purpose of this paper is to review some of the pertinent literature on soil erosion and to conclude from the literature what is the best parameter to use in representing potential soil erodibility.

In 1930, Middleton (2) made one of the earliest attempts to analyze the properties of soil that influence soil erosion. He indicated that the dispersion ratio, the ratio of colloid to moisture equivalent, the erosion ratio, and the silica-sesquioxide ratio were the most significant soil parameters influencing erosion.

The dispersion ratio is the suspension percentage divided by the total silt plus clay and is a measure of the stability of soil aggregates when they are acted on by moving water. The suspension percentage is a function of the dry weight of the silts and clays and is obtained by pipetting a suspension of soil sample in water [the suspension and pipetting methods are explained by Middleton (2)]. Total silt plus clay is determined by standard mechanical analysis of the soil sample. The erosion ratio, which gives an indication of the erodibility of soils under similar field conditions, is the value obtained by dividing the dispersion ratio by the ratio of colloid (obtained by the water-vapor-absorption method) to moisture equivalent. Middleton gave dispersion ratio as the most valuable single criterion in distinguishing between erodible and nonerodible soils. Higher dispersion ratios corresponded to erodible soils and lower ratios to nonerodible soils.

Middleton pointed out other soil characteristics of some value: angle of repose, which was much greater for a nonerodible soil in a saturated condition than for an easily eroded soil; plasticity number, which was of more significance than the liquid lower limit; percolation rate; quantity of organic matter; total exchangeable bases (in both quantity and character); and determination of slaking value (Middleton suggested that some modification was needed in the determination method used).

In 1932 and 1934, Middleton, Slater, and Byers published reports on the determination of the physical and chemical properties of soils from the then-existing agricultural erosion experiment stations (3, 4). The percolation ratio, which was given as the ratio between the suspension percentage and the colloid to moisture equivalent value, gave an indication of permeability and depended on the fact that in the more easily dispersed soils the muddy percolation waters more effectively closed the naturally occurring water passageways with silt and colloid. The percolation ratio is applicable only in the comparison of surface soils. Other parameters cited for further study in relation to erosion were shrinkage and swelling characteristics, the acid contents of soils, and soil structure.

A 1933 study by Baver (5) stated that two factors affecting runoff and erosion were the capacity of the soil to absorb water (the rate being more important than the amount) and the permeability of the soil profile (the degree of permeability of the subsurface horizons being of great importance). Both of these parameters were related to the structure and texture of soil as well as to the amount of lime and organic matter in the soil, the presence of which leads to increased granulation.

Baver also proposed other factors that influence soil erosion: the ease of dispersion and the size of the soil particles and the degree of aggregation of the soil. The size of the soil particles and the aggregation of smaller particles into larger units affected the ease of dispersion, i.e., the ease with which soil particles can be suspended in runoff water. The degree of aggregation of the soil was the single most important parameter because all of the other factors mentioned were related to it in some way. An increase in the degree of aggregation increased porosity and, consequently, the rates of water absorption and percolation. It also decreased the ease of dispersion and increased the size of the particles.

In 1935, Lutz (6) indicated that the amount of soil erosion depended partly on the amount and the velocity of the runoff water and partly on the soil properties. Iredell sandy clay loam and Davidson clay were selected for a study of the physical soil properties that influence erosion. Field observations showed that the Iredell loam was an erodible soil and the Davidson clay a comparatively nonerosive one. A laboratory study of the physical properties of the two soils under the same environmental conditions showed that the difference in their erodibility resulted primarily from the degree of aggregation of the finer fraction. Because of this, and because of the results of further analysis, it was concluded that flocculation, hydration, and permeability of the Iredell and Davidson colloids at least partially explained the differences in their erodibility. The erodibility of the Iredell loam resulted from its ease of dispersion (in which hydration was an important factor) and the dense, impervious nature of the B horizon. The nonerodible nature of the Davidson clay was the result of its nonhydrated condition and the high degree of flocculation of the colloid fraction into large, porous, and stable aggregates.

In a preliminary investigation of the relation of the physical properties of Cecil sandy loam, Cecil clay loam, and Madison clay loam to their respective erodibilities, Peele (7) reported in 1937 that the rate at which water percolates through a soil is a much more accurate index of the susceptibility of a soil to erosion than is the water-holding capacity of that soil. He also indicated that Middleton's suspension percentage and dispersion ratio appeared to give a good index of relative erodibility. Peele suggested that other factors that should be taken into consideration in evaluating erodibility are the compactness of the soil, the presence of artificial channels (as a result of plant and animal life), and the thickness of the various soil horizons.

In 1945, after conducting various experiments, Peele, Latham, and Beale (8) concluded that no single value determination or ratio could be found that would adequately characterize the erodibility of all soils. They stressed that too many variables affected the relation of the physical properties of soil to erodibility for all of them to be expressed by a single value. The authors suggested that a workable, systematic soil classification based on erodibility might be developed by grouping soils according to their internal permeability and forming subgroups based on the mechanical composition of the surface soil. The soils in the subgroups would be further differentiated on the basis of the physical properties of the A horizon, such as the degree and stability of aggregation of the clays and silts and the degree of flocculation of the colloidal material.

In 1954, Anderson (9) found three soil variables to be of value in a study relating watershed characteristics to sediment discharge in Oregon. In arriving at the three variables, Anderson employed an analysis of variance technique to test the significance of differences, among soil types, in some physical characteristics expected to be related to erodibility. The physical characteristics used in the analysis, in decreasing order of significance, were the surface area of the particles coarser than 0.05 mm in diameter, aggregated silt plus clay, Middleton's dispersion ratio, ultimate silt clay (Middleton's total silt plus clay), and Middleton's suspension percentage.

Anderson singled out two processes in relating suspended sediment to soil characteristics: the supply process and the binding process. The supply process is represented by that component in the soil that produces the fraction of erosion that is caught and measured as suspended sediment (sediment yield). The ultimate silt plus clay was taken as an index of the supply process. The binding process is represented by the fraction of the soil that tends to bind the soil together versus the amount of soil surface in the nonbinding fraction that requires binding. The surface area of particles coarser than 0.05 mm in diameter divided by the aggregated silt plus clay was taken as an index of how effectively the soil was bound. This new parameter was called the surface-aggregation ratio.

Anderson called the third soil variable in his study soil erosibility. This factor is the product of the dispersion ratio multiplied by the suspension percentage, which is multiplied by the ultimate silt plus clay, and then divided by 100 times the aggregated silt plus clay. Anderson also indicated the importance of parent material as a soil characteristic affecting erosion.

In 1963, Wischmeier and Olson (10) approximated absolute soil-erodibility factors for 20 agricultural soils by using the universal soil-loss equation of Wischmeier and Smith (11), which was originally determined for agricultural lands (the equation was formulated for U.S. customary units; therefore, values are not given in SI units):

$$A = RKLSCP \tag{1}$$

where A = estimated soil loss in tons per acre; R = rainfall erosion index (EI) (rainfall energy in hundreds of foot-tons force per acre per time unit for 1 in of rain times maximum 30-min intensity in inches per hour); K = soil loss in tons per acre per unit of rainfall erosion index (the soil-erodibility factor); L and S = length (in feet) and percent of slope parameters (both part of a dimensionless term); and C and P = ground cover and conservation practices. Wischmeier and Olson reported that, by using the equation in a transposed form (evaluating the equation for K), the effects of the inherent differences in erodibility of soils could be separated from the effects of differences in rainfall and management practices.

The accuracy with which the 20 soil-erodibility values could be approximated was dependent on the accuracy with which the other soil-loss data could be evaluated. Of the 20 soils studied, the 2 with the lowest K values were characterized as having a high percentage of coarse material on the surface. The remaining 18 soils fell roughly into a pattern in which the coarse-textured soils were the least erodible and the fine-textured soils were less erodible than the medium-textured soils.

In 1966, Bubenzer, Meyer, and Monke (12) evaluated the effect of particle roughness on erosion and sediment transport in a laboratory investigation. They used smooth sand, angular sand, and crushed glass cullet to simulate soil particles of different roughnesses. Major particle properties were size, shape (roughness), and specific gravity. In the investigation, particles of one size and roughness were studied at various combinations of slope length and steepness. It was found that particle roughness had little effect on the erosion rate of the larger particles but that the erosion rate for small particles increased as particle roughness increased. In addition, the erosion rate for all particles generally increased as the particle size decreased. Interestingly, on short, gentle slopes the larger particles for all degrees of roughness eroded more rapidly than the smaller particles. This reversal of expected erodibility due to particle size decreased as particle angularity increased.

In 1969, Wischmeier and Mannering (13) derived an empirical equation for calculating the soil-erodibility factor (K) (as found in the universal soil-loss equation) by applying multiple-regression analysis to specific soil properties. Properties that contributed significantly to soil-loss variances included percentages of sand, silt, clay, and organic matter; pH, structure, and bulk density of the plow layer and subsoil; steepness and concavity or convexity of slope; pore space filled by air; residual effects of sod crops; aggregation; parent material; and various interactions of these variables. Fifty-five widely differing corn-belt soils, most of which can be classified as medium-textured, were analyzed for specific physical and chemical properties. The resulting empirical equation is

$$K = 0.013(18.82 + 0.62X_1 + 0.043X_2 - 0.07X_3 + 0.0082X_4 - 0.10X_5 - 0.214X_6 + 1.73X_7 - 0.0062X_8 - 0.26X_9 - 2.42X_{10} + 0.30X_{11} - 0.024X_{12} - 21.5X_{13} - 0.18X_{14} + 1.0X_{15} + 5.4X_{16} + 4.4X_{17} + 0.65X_{18} - 0.39X_{19} + 0.043X_{20} - 2.82X_{21} + 3.3X_{22} + 3.29X_{23} - 1.38X_{24}) \quad (2)$$

The corresponding independent X-variables are given in Table 1. The equation combines the effects of primary and interaction terms and accounts for about 98 percent of the variability in the K-values of the 55 soils. Although Middleton's suspension percentage appeared to be the single variable most highly correlated with erodibility, the computer deleted it from the multiple-regression model because it was a function of other variables in the equation that, in the overall combination, had a greater capacity to decrease the error of estimation. The K-values calculated by using the equation were compared to 11 previously established benchmark K-values. This comparison indicated a high degree of technical accuracy in the equation.

Table 1. Variables used in calculating soil-erodibility factor.

Variable	Definition	r[a]	F-Ratio[b]
X_1	Percentage silt × 1/percentage organic matter	0.66	48
X_2	Percentage silt × reaction[c]	0.53	13
X_3	Percentage silt × structure strength[c]	0.06	5.9
X_4	Percentage silt × percentage sand	-0.22	29.3
X_5	Percentage sand × percentage organic matter	-0.63	38
X_6	Percentage sand × aggregation index	-0.54	6.2
X_7	Clay ratio	-0.37	24.7
X_8	Clay ratio × percentage silt	0.0006	2.4
X_9	Clay ratio × percentage organic matter	-0.46	34.2
X_{10}	Clay ratio × 1/percentage organic matter	0.002	88.3
X_{11}	Clay ratio × aggregation	-0.44	4.3
X_{12}	Clay ratio × 1/aggregation index	0.15	7.4
X_{13}	Aggregation index	-0.37	17.5
X_{14}	Antecedent soil moisture	-0.02	2.8
X_{15}	Increase in acidity below plow zone[c]	0.52	18.2
X_{16}	Structure[c]	0.05	19.9
X_{17}	Structure strength	-0.03	6.9
X_{18}	Structure change below plow layer	0.13	12.7
X_{19}	Thickness of granular material	0.13	6.7
X_{20}	Depth from friable to firm	0.05	1.8
X_{21}	Loess = 1, other = 0	0.36	14.3
X_{22}	Over calcareous base = 1, other = 0	-0.30	21.6
X_{23}	Percentage organic matter × aggregation index	-0.49	6.7
X_{24}	Reaction × structure	0.05	22.6

[a] Coefficient of partial correlation.
[b] Significance according to a statistical F-distribution.
[c] Numerically coded from profile descriptions.

Standard soil-profile descriptions provided all the information needed for the erodibility model except specific data on particle-size distribution, organic matter content, and aggregation in the plow layer.

In 1971, Wischmeier, Johnson, and Cross (14) discovered a new statistical parameter that successfully reflected the influence of particle-size interrelations. This made possible a soil-erodibility model presented in the form of a nomograph (Figure 1). The new parameter, designated M, is the product of the percentage of silt and the percentage of silt and sand.

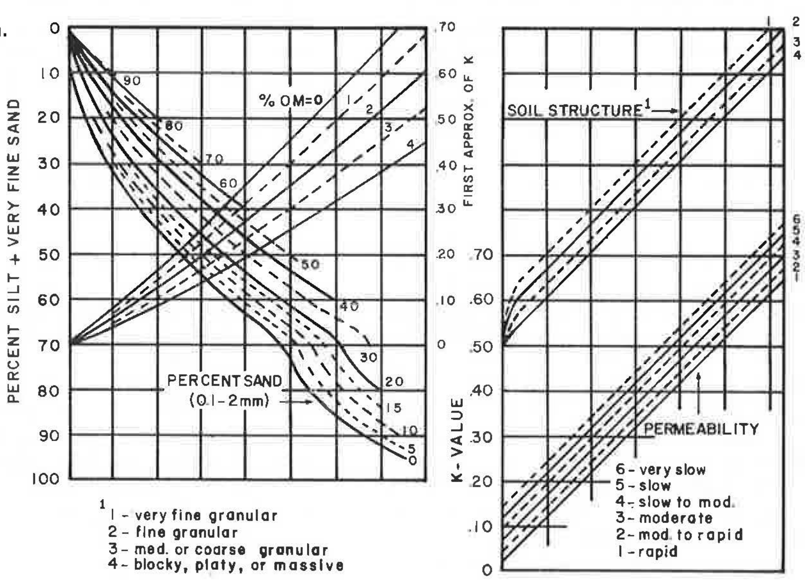
Wischmeier, Johnson, and Cross began their study by redefining the standard silt and sand classifications. The new silt classification included very fine sand (0.05 to 0.10 mm) because data showed conclusively that very fine sand behaved more like silt than like larger sand. Sand was therefore redefined as particles ranging from 0.10 to 2 mm in diameter. Use of the new classifications for silt and sand resulted in the M-value accounting for 85 percent of the variation in the observed K-values for 55 rainulator-tested soils.

Examination of the M-value showed that it was quite descriptive. For soils with a low or medium silt fraction, the M-factor increase for each additional percentage of silt increase depended very much on the sand-to-clay ratio of the soil. As the sand content got higher, the silt content decreased and the M-factor declined in value but remained a function of the silt-to-clay ratio. When the clay content was high, the M-factor assumed a low value that was a function of the sand-to-silt ratio.

Although the M-value is not directly identified on the nomograph in Figure 1, the left-hand portion of the graph is based on the relation of M to K. This relation changes when the silt content approaches 70 percent; the percent sand curves are therefore "bent" near the 70 percent silt line.

The five parameters needed to read numerical soil-erodibility values directly from the nomograph were obtained from routine laboratory determinations and standard soil-profile descriptions. These five parameters are percentage of silt plus very fine sand, percentage of sand greater than 0.1 mm, organic matter content,

Figure 1. Soil-erodibility nomograph.



Procedure: With appropriate data, enter scale at left and proceed to points representing the soils % sand (0.10-2.0mm), % organic matter, structure and permeability, in that sequence. Interpolate between plotted curves.

structure, and permeability. The soil-structure parameter refers to structure type and size as coded from a standard soil profile. The permeability factor refers to the soil profile as a whole and is classified according to the U.S. Department of Agriculture Soil Survey Manual (15). Whether the soil is original topsoil or "scalped" subsoil, all factors except permeability are taken from the upper 15 to 18 cm (6 to 7 in). One soil parameter that could be significant—percentage of coarse fragments—was not included in the nomograph. Limited data indicated that the K-value read from the scale may be reduced by 10 percent for soils with stratified subsoils that include layers of small stones or gravel that do not have a seriously impeding layer above them.

Comparison of the soil-erodibility values of benchmark soils to K-values obtained for these soils from the nomograph indicated the high accuracy of this study. The nomograph can be applied to agricultural lands as well as to lands affected by construction.

In 1973, in a state-of-the-art report on the causes and mechanisms of cohesive soil erosion, Paaswell (16) presented a number of soil parameters that are used in evaluating the erosion of cohesive soils. These parameters, which were placed in four categories, are listed in the table below.

Category	Parameter
Physical properties	Soil type (clay mineral)
	Percentage of clay
	Liquid and plastic limits and activity
	Specific gravity
Physicochemical properties	Base exchange capacity
	Sodium absorption ratio
	Pore-fluid quality
	Pore-fluid environment
Mechanical properties	Shear strength (surface and body)
	Cohesion and thixotropy
	Swelling and shrinkage properties
Environmental conditions	Weathering (wetness and dryness)
	Freezing and thawing
	Prestress history

Paaswell also included a good summary of selected studies on cohesive soil erosion.

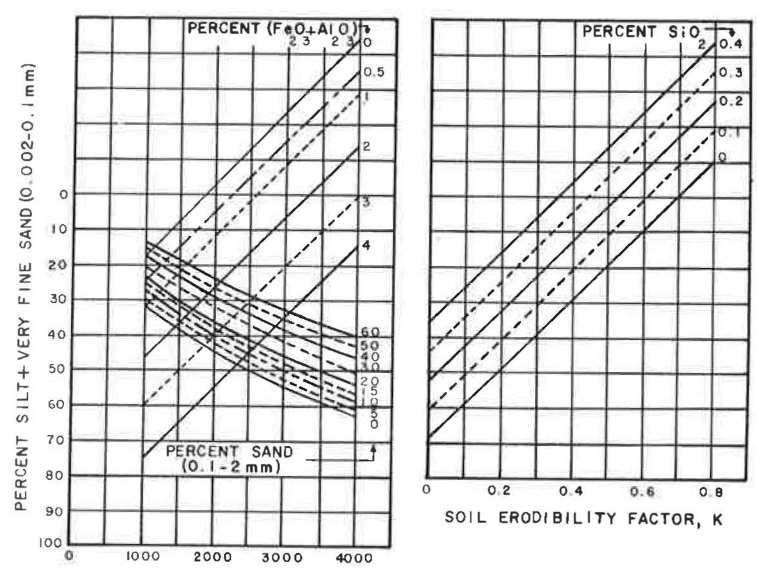
In 1974, Roth, Nelson, and Romkens (17) used multiple-regression techniques to determine a model of subsoil erodibility. Using the nomograph model of Wischmeier, Johnson, and Cross (14) as a starting point, the authors set out to (a) test the model on specific subsoils; (b) determine various chemical, physical, and mineralogical characteristics of both surface soils and subsoils and relate these to the soil-erodibility factor (K); and (c) improve the existing model, if necessary, so that subsoils would be included.

Six midwestern subsoils, with clay contents varying from 33.9 to 66.5 percent, were chosen to test the model. The existing erodibilities of these soils were measured for each of three land treatments: scalped soil, tilled soil, and semicompacted fill. Comparison of the erodibility values to those obtained by using Wischmeier's nomograph indicated that the nomograph was inadequate for estimating soil erodibilities for subsoils with high clay contents. As a result, and in fulfillment of the second objective of the study, various physical, chemical, and mineralogical parameters were determined for 46 surface soils (43 of which were used by Wischmeier, Johnson, and Cross in deriving their nomograph) and for 7 subsoils so that a better soil-erodibility model might be found. Some of the parameters used as independent X-variables in the multiple-regression analyses were the same as those used by Wischmeier and Mannering (13), and some of the terms used were new. Evaluating the independent factors for the surface soils only, by a backward elimination technique, resulted in the derivation of the following predictive equation:

$$K_{PRED} = 0.1357 + (6.710)(10^{-5})\,X_{12} + 0.034\,48\,X_{13} + 0.038\,47\,X_{14} - 0.1732\,X_{16} \qquad (3)$$

where K_{PRED} = predicted K-value, X_{12} = M-value (14), X_{13} = soil structure, X_{14} = permeability, and X_{16} = percentage C-Na pyrophosphate. (Similar results were obtained by using a forward selection technique.) According to the authors, the four most significant variables in their equation were essentially the same four variables

Figure 2. Subsoil-erodibility nomograph.



Procedure: With appropriate data, enter scale at left and proceed to points representing the soils % sand (0.1-2mm), % (Fe_2O_3+Al_2O_3) content and % (SiO_2) content, in that sequence. Interpolate between plotted curves.

with which Wischmeier, Johnson, and Cross constructed their 1971 nomograph for predicting K-factors. The only difference was that sodium pyrophosphate extractable carbon was found in the new equation instead of the organic matter percentage. With a correlation coefficient of 0.866, however, the two parameters are highly correlated.

A weighted regression analysis had to be used in establishing a model for the prediction of subsoil erodibilities because there were only seven sets of subsoil data available. Therefore, each of the 46 surface soils was weighted $1/46$ and each of the 7 subsoils was weighted $1/7$ to increase the amount of data. The equation obtained for the prediction of soil erodibilities for subsoils with high clay contents (such as those considered in the study) was then

$$K_{PRED} = 0.321\,14 + (20.167)(10^{-5})X_{12} - 0.144\,40\,X_{31} - 0.836\,86\,X_{21} \quad (4)$$

where

X_{31} = sum of the Fe_2O_3 and Al_2O_3 contents and
X_{21} = SiO_2 content.

This equation was found to be statistically significant at the 0.05 level. To further facilitate the use of this model, a nomograph was constructed from the equation (Figure 2). The layout of the nomograph is similar to that of the nomograph of Wischmeier, Johnson, and Cross (14).

CONCLUSIONS

As a result of an intensive literature review conducted to determine an adequate soil-erodibility factor, the authors have concluded that the nomograph model developed by Wischmeier, Johnson, and Cross (14) gives the best estimate of soil-erodibility factors. The nomograph of Roth, Nelson, and Rumkens (17) should be used to predict erodibility values for subsoils with blocky or massive structure, very low permeability, and high clay content. The nomograph of Wischmeier, Johnson, and Cross is well documented and appears to be far superior to all other parameters and methods reported in the literature for predicting soil-erodibility values.

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Relation Between Resilient Modulus and Stress Conditions for Cohesive Subgrade Soils

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The relation between stress conditions and resilient modulus, which is a necessary input parameter in fatigue design of asphalt concrete pavements, is established. For a cohesive subgrade soil there is a relation between resilient modulus and deviator stress, confining pressure, and matrix suction. A proposed constitutive relation was experimentally checked by using samples of compacted glacial till from the Qu'Appelle Moraine in Saskatchewan, Canada. Four series of repeated triaxial tests were performed on the repeated-load triaxial system developed at the University of Saskatchewan. Matrix suctions were measured on a pressure-plate device immediately after each repeated-load test. Experimental data indicate a good correlation between the resilient modulus and the stress variables. The stress variables of most significance with respect to changes in resilient modulus are deviator stress and matrix suction. An equation is proposed by which the resilient modulus of a compacted subgrade soil can be linked to these stress variables.

The necessity of developing a complete fatigue design program for asphalt concrete pavements has become increasingly evident in recent years. One of the important input parameters to such a design program is the resilient modulus of the subgrade. Because fatigue prediction is highly sensitive to changes in subgrade resilient modulus, it is not enough to assume one resilient-modulus value for the year; a relation must be established between stress conditions and resilient modulus (1). Previous attempts to develop realistic fatigue simulation may have failed because of inadequate characterization of the subgrade soils.

The research presented here includes a theory that establishes the relation between stress conditions and resilient modulus. Results of laboratory tests on a subgrade soil are also presented to compliment the developed theory.

THEORY

Previous research has shown typical relations between the volume and weight, the method of sample preparation, the deviator stress, and the resilient modulus of compacted soils (7). However, the authors are not aware of any unique relations having been established among these variables. Establishing a relation between the resilient modulus and the stress conditions in a soil is imperative in the fatigue design of asphalt concrete pavements.

Fredlund, Bergan, and Sauer (5) showed from a stress analysis standpoint that the resilient modulus is a function of three stress variables.

$$M_R = f[(\sigma_3 - u_a), (\sigma_1 - \sigma_3), (u_a - u_w)] \quad (1)$$

where

M_R = resilient modulus,
σ_3 = confining pressure,
σ_1 = major (vertical) principal stress during the application of the repeated load,
u_a = pore air pressure (approximately atmospheric),
u_w = pore water pressure,
$(\sigma_3 - u_a)$ = net confining pressure,
$(\sigma_1 - \sigma_3)$ = deviator stress, and
$(u_a - u_w)$ = matrix suction.

In other words, if the above three stress variables were known during a repeated-load test, it would be reasonable to attempt to relate resilient modulus to them. Unfortunately, there are serious technical problems associated with measuring air and water pressure under dynamic loading conditions. Relating the resilient modulus to the stresses before or after the repeated-load test may be sufficient.

Under repeated-load conditions, the first 100 repetitions of load have been found to be sufficient to ensure proper seating of the sample in the testing apparatus (2, 3, 6). Continuing to load the sample up to 100 000 repetitions produces a further change in resilient modulus, and this change is probably related to changes in the stress variables. However, because the stresses cannot readily be monitored, it is proposed that the number of repetitions (N) be designated as a further state variable. This paper considers only the effect of the first 100 repetitions.

Figure 1 shows the anticipated linear relation between resilient modulus and confining pressure for samples compacted at various water contents. The normal range of confining pressure of interest in the field is approximately 20.7 to 41.4 kPa (3 to 6 lbf/in^2) and linearity is anticipated in this range (8). At water contents above optimum (i.e., low matrix suction), the voids are largely filled with water and an increase in confining pressure produces little change in the resilient modulus. At low water contents (i.e., high matrix suction), confining-pressure increases produce more substantial increases in resilient modulus.

Figure 2 shows typical variations in resilient modulus for various deviator stresses. Dry of optimum, the resilient modulus does not vary as much with deviator stress as it does when wet of optimum water content. The results from previous investigations show relations that are curved. At high deviator stresses an increase in resilient modulus has sometimes been observed. The practical range of deviator stress is 0 to 83 kPa (0 to 12 lbf/in^2). In Figure 3 the relation between resilient modulus and deviator stress is linearized over the above stress range by plotting resilient modulus on a logarithm scale.

In extending the log resilient modulus versus deviator stress back to a deviator stress of zero, two variables can be used to define each line: the slope of the line on the semilogplot (m_{1d}) and the intercept on the ordinate (c_{1d}). Each line is therefore described by

$$\log M_R = c_{1d} - m_{1d}(\sigma_1 - \sigma_3) \quad (2)$$

where c_{1d} and m_{1d} are functions of matrix suction. In this way, the resilient modulus is also related to the third stress variable $(u_a - u_w)$.

Because resilient modulus is expected to be more highly affected by deviator stress and matrix suction than by net confining pressure, the effect of confining pressure could either be ignored or a correction could be applied for confinement. The correction equation would take the following form (Figure 1):

$$\Delta M_R = m_c \times \Delta(\sigma_3 - u_a) \qquad (3)$$

where

ΔM_R = change in resilient modulus,
m_c = slope of the plot for confining pressure versus resilient modulus, and
$\Delta(\sigma_3 - u_a)$ = change in confining pressure from that used to define the plot for resilient modulus versus deviator stress.

The relation between c_{1d} and m_{1d} and matrix suction must be experimentally determined. The form is not yet definite but should become better established with further testing. The degree of uniqueness of the proposed equations must be established experimentally by subjecting samples to varying stress paths or methods of sample preparation and comparing the results by using the proposed equation. The relation between resilient modulus and matrix suction (for a particular deviator stress) can also be obtained by cross-plotting for resilient modulus versus water content and matrix suction versus water content (5).

Figure 1. Anticipated relation between resilient modulus and confining pressure.

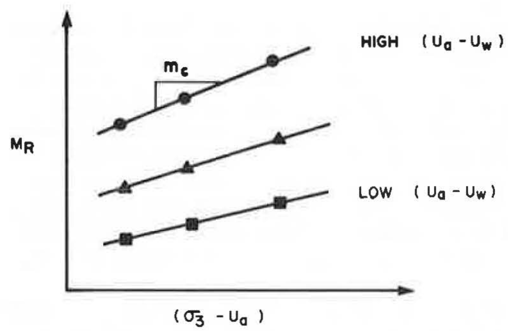


Figure 2. Anticipated resilient modulus versus deviator stress.

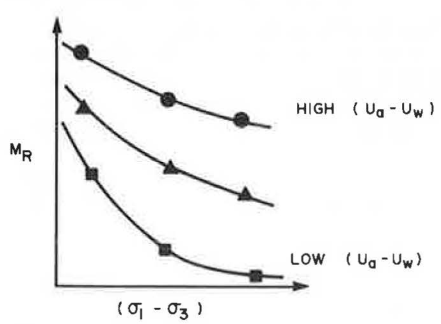
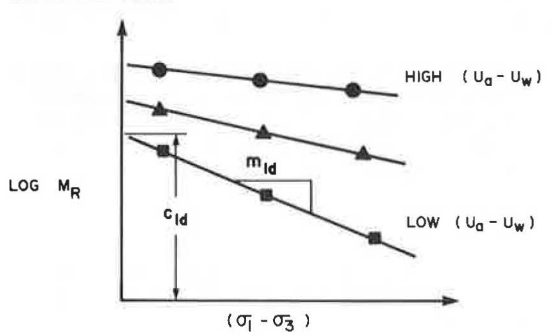


Figure 3. Linearization of relation between resilient modulus and deviator stress.



LABORATORY EQUIPMENT

The repeated-load apparatus (Figure 4) consists of a reinforced triaxial cell with a bellofram operated on compressed air to apply the deviator load. The cell was filled with air. The loading frequency was 20 repetitions/min with a load duration of 0.1 s. The load applied to the sample was measured by a load cell in the base plate of the triaxial cell. The vertical and lateral displacements of the sample were measured by linear variable differential transducers. The matrix suctions were measured by placing the samples on a high-air-entry disc [i.e., either 0.5 or 1.5 MPa (5 or 15 bars)] and using the axis-translation procedure to nullify the negative water pressures.

SOIL SAMPLES

The soil used in the study was a glacial till obtained from the Qu'Appelle Moraine in Saskatchewan. Its properties are summarized below (1 kg/m^3 = 0.06 lb/ft^3):

Property	Measurement
Liquid limit, %	33.9
Plastic limit, %	17.0
Sand, %	31.8
Silt, %	38.5
Clay, %	29.7
Specific gravity	2.77
Maximum standard density, kg/m^3	1767
Optimum water content, %	16.5
Modified AASHO density, kg/m^3	1967
Optimum AASHO water content, %	11.9

The soil samples were prepared by air drying, pulverizing, sorting on a 2-mm (No. 10) sieve, and then mixing with the appropriate amount of distilled water. The wet soil was placed in a plastic bag and stored in a high-humidity room for 24 h. The specimens were 15.2 cm (6 in) in length and 7.1 cm (2.8 in) in diameter and were formed by static compaction in three layers. The specimens were wrapped in plastic, waxed, and stored for at least 7 d before testing.

TEST PROGRAM

The test program was designed to evaluate the relation between resilient modulus (M_R) and deviator stress ($\sigma_1 - \sigma_3$), confining pressure ($\sigma_3 - u_a$), and matrix suction ($u_a - u_w$). The resilient modulus was calculated after 100 load repetitions; the effect of larger numbers of repetitions was not evaluated.

The test program consisted of four test series; data for dry density (γ_d) and water content are given in Table 1 and shown in Figure 5 (9). For all specimens, an attempt was made to measure the matrix suction at the top, middle, and bottom of the specimen (in some cases only two measurements were possible).

Series 1 samples were prepared at maximum standard density and water contents ranging from 7 to 19 percent. Each specimen was tested for deviator stresses (σ_d) of 20.6, 48.2, 82.7, and 103.4 kPa (3, 7, 12, and 15 lbf/in^2).

The confining pressure (σ_3 - u_a) was kept at 20.7 kPa (3 lbf/in^2) in all cases. The results from series 1 allowed a study of the resilient modulus versus deviator stress and matrix-suction relations when dry density is kept constant.

Series 2 was the same as the first series except that the dry density varied with water content in accordance with the standard compaction curve. The results allow a study of the resilient modulus (M_R) versus deviator stress and matrix-suction relation when dry density varies.

Figure 4. Repeated-load triaxial system.

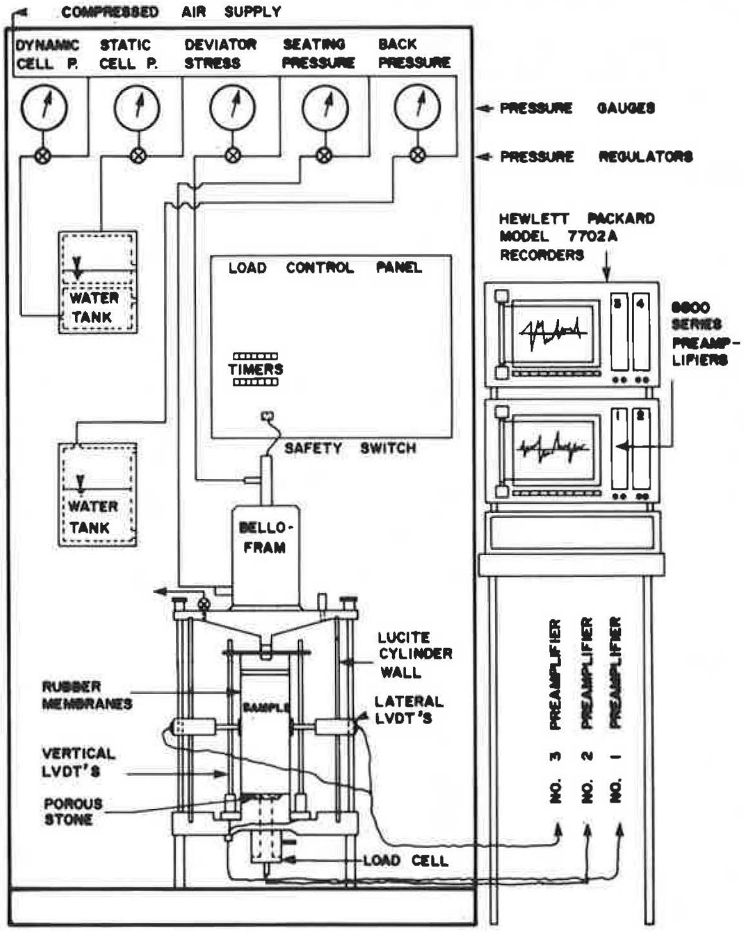
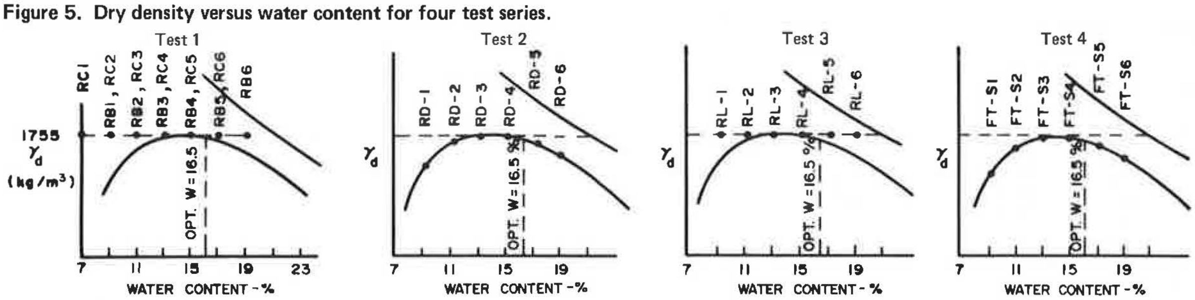


Table 1. Dry densities and water contents for four test series.

Test 1			Test 2			Test 3			Test 4		
Sample	Water Content (%)	γ_d (kg/m^3)	Sample	Water Content (%)	γ_d (kg/m^3)	Sample	Water Content (%)	γ_d (kg/m^3)	Sample	Water Content (%)	γ_d (kg/m^3)
RC-1	7	109.6	RD-1	9	90.0	RL-1	9	109.6	FT-S1	9	90.0
RB-1 and RC-2	9	109.6	RD-2	11	97.2	RL-2	11	109.6	FT-S2	11	97.2
RB-2 and RC-3	11	109.6	RD-3	13	102.8	RL-3	13	109.6	FT-S3	13	102.8
RB-3 and RC-4	13	109.6	RD-4	15	108.0	RL-4	15	109.6	FT-S4	15	108.0
RB-4 and RC-5	15	109.6	RD-5	17	109.4	RL-5	17	109.6	FT-S5	17	109.4
RB-5 and RC-6	17	109.6	RD-6	19	104.4	RL-6	19	109.6	FT-S6	19	104.4
RB-6	19	109.6									

Note: 1 kg/m^3 = 0.06 lb/ft^3.

Figure 5. Dry density versus water content for four test series.



Note: 1 kg/m^3 = 0.06 lb/ft^3

Series 3 samples were prepared at maximum standard density. Tests were run at deviator stresses of 48 and 69 kPa (7 and 10 lbf/in^2). The confining pressures on each specimen were 20.7, 68.9, 137.9, and 275.8 kPa (3, 10, 20, and 40 lbf/in^2). Each confining pressure was allowed 8 h for equalization. The results allow a study of the resilient modulus versus confining pressure and matrix-suction relations.

Series 4 samples were prepared at a constant dry density and varying water contents and then subjected to three freeze-thaw cycles. The purpose of freeze-thaw cycles was to check the consistency of the resilient modulus versus stress-variable relations when the soil structure was modified or disturbed. The confining pressure was 21 kPa (3 lbf/in^2) and the deviator stresses were 20.7, 34.5, 48.3, and 82.7 kPa (3, 5, 7, and 12 lbf/in^2).

PRESENTATION AND DISCUSSION OF DATA

The resilient-modulus values for series 1, 2, 3, and 4 are summarized in Tables 2, 3, 4, and 5 respectively.

Table 2. Results of test series 1.

Sample	Water Content (%)	γ_d (kg/m^3)	S^a (%)	$(\sigma_3 - u_a)$ (kPa)	$(u_a - u_w)^b$ (kPa)	M_R (kPa) σ_d = 20.6 kPa	σ_d = 48.2 kPa	σ_d = 82.7 kPa	σ_d = 103.4 kPa
RB-1	11.4	1751	55.4	20.7	469	32 476	28 476	25 443	23 443
RB-2	13.5	1752	65.5	20.7	345	61 021	43 301	22 616	28 270
RB-3	15.2	1772	76	20.7	269	52 057	47 713	33 027	28 339
RB-4	17.7	1749	85.6	20.7	207	61 917	39 991	15 376	6 619
RB-5	20.8	1703	93.2	20.7	186	41 715	12 066	10 687	5 902
RB-6	21.9	1740	104.5	20.7	172	3 068	3 254	3 652	—
RC-1	9	1693	40	20.7	896	124 041	109 424	100 391	89 635
RC-2	11	1664	46.6	20.7	558	99 564	129 626	90 531	93 358
RC-3	13.1	1732	61.6	20.7	355	54 677	39 026	34 958	32 131
RC-4	15.3	1700	68.5	20.7	293	80 465	46 472	28 683	19 720
RC-5	17	1728	79.4	20.7	217	32 613	18 134	7 495	6 268
RC-6	19.4	1703	87.1	20.7	205	31 579	8 481	6 019	6 392

Note: 1 kg/m^3 = 0.06 lb/ft^3; 1 kPa = 0.145 lbf/in^2.
[a]Degree of saturation. [b]Values estimated from matrix suction versus water content plot.

Table 3. Results of test series 2.

Sample	Water Content (%)	γ_d (kg/m^3)	S^a (%)	$(\sigma_3 - u_a)$ (kPa)	$(u_a - u_w)$ (kPa)	M_R (kPa) σ_d = 20.7 kPa	σ_d = 48.3 kPa	σ_d = 82.7 kPa	σ_d = 103.4 kPa
RD-1	11.3	1414	33.1	20.7	751	37 785	—	—	—
RD-2	13.1	1530	45.7	20.7	530	46 334	36 337	23 167	—
RD-3	15	1586	56.5	20.7	262	34 475	31 441	21 099	17 375
RD-4	17.3	1727	80.6	20.7	188	70 329	38 129	15 790	12 273
RD-5	19	1735	90	20.7	131	24 408	13 170	7 240	—
RD-6	21.2	1653	88.1	20.7	93	—	—	—	—

Note: 1 kg/m^3 = 0.06 lb/ft^3; 1 kPa = 0.145 lbf/in^2.
[a]Degree of saturation.

Table 4. Results of test series 3.

Sample	Water Content (%)	γ_d (kg/m^3)	S^a (%)	$(u_a - u_w)$ (kPa)	$(\sigma_1 - \sigma_3)$ (kPa)	M_R (kPa) $(\sigma_3 - u_a)$ = 20.7 kPa	$(\sigma_3 - u_a)$ = 68.9 kPa	$(\sigma_3 - u_a)$ = 137.9 kPa	$(\sigma_3 - u_a)$ = 275.8 kPa
RL-1	11.7	1711	51.2	792	48	97 564	112 871	115 078	143 899
RL-2	12.1	1749	58.3	800	48	65 916	106 666	117 284	156 448
RL-3	14.3	1725	66.5	778	69	116 457	116 526	95 978	162 998
RL-4	15.1	1767	74.9	734	69	53 092	66 744	72 811	88 049
RL-5	17.4	1764	86.2	469	69	26 684	29 580	28 270	32 544
RL-6	19.4	1759	95.2	262	69	14 273	20 340	22 823	27 097

Note: 1 kg/m^3 = 0.06 lb/ft^3; 1 kPa = 0.145 lbf/in^2.
[a]Degree of saturation.

Table 5. Results of test series 4.

Sample	Water Content (%)	γ_d (kg/m^3)	S^a (%)	$(\sigma_3 - u_a)$ (kPa)	$(u_a - u_w)$ (kPa)	M_R (kPa) σ_d = 20.7 kPa	σ_d = 34.5 kPa	σ_d = 48.3 kPa	σ_d = 82.7 kPa
FT-S1	11.4	1296	33.9	21	731	14 342	—	—	—
FT-S2	13.2	1506	44	21	483	42 473	—	21 237	11 101
FT-S3	15.2	1624	57.8	21	272	29 511	—	10 412	—
FT-S4	17.5	1724	81.4	21	169	9 239	4 013	5 364	9 998
FT-S5	19.5	1719	89.9	21	97	3 186	—	3 944	—
FT-S6	19.9	1680	86.4	21	66	8 412	15 721	11 101	—

Note: 1 kg/m^3 = 0.06 lb/ft^3; 1 kPa = 0.145 lbf/in^2.
[a]Degree of saturation.

Figure 6 shows the changes in resilient modulus versus confining pressure ($\sigma_3 - u_a$) for a wide range of water contents (series 3). The changes in resilient modulus with confining pressure are linear and more pronounced for water contents below optimum. The slopes of the resilient modulus versus confining pressure relation are plotted versus matrix suction in Figure 7. The slopes decrease to a relatively low value as the water content is increased. It should be noted that the confining pressure has been varied over a wide range and that field water contents will generally be in the vicinity of (or above) optimum conditions.

The results confirm that the confining pressure is relatively insignificant. Therefore, the proposed procedure of applying a correction for the confining pressure appears justifiable. The authors recommend that a constant slope (m_c) corresponding to the optimum water-content conditions be used in the correction equation.

The resilient modulus versus deviator stress ($\sigma_1 - \sigma_3$) can be plotted from series 1, 2, and 4. Figure 8 shows an arithmetic plot of the tests on the RC samples from series 1. They exhibit a characteristic decrease in resilient modulus with increasing deviator stress. At water contents above optimum there is some strain-hardening effect at deviator stresses greater than 83 kPa (12 lbf/in^2). The curves for resilient modulus versus deviator stress can be linearized on a semilogarithmic plot. Figures 9, 10, and 11 show the semilog plots from series 1 (RB and RC samples) and series 2. Test series 4 was not plotted because of the erratic results following freeze-thaw cycles.

The slopes and intercepts of the semilog plots of resilient modulus versus deviator stress are given in Table 6 and are shown plotted versus matrix suction in Figures

Figure 6. Resilient modulus versus confining pressure for test series 3.

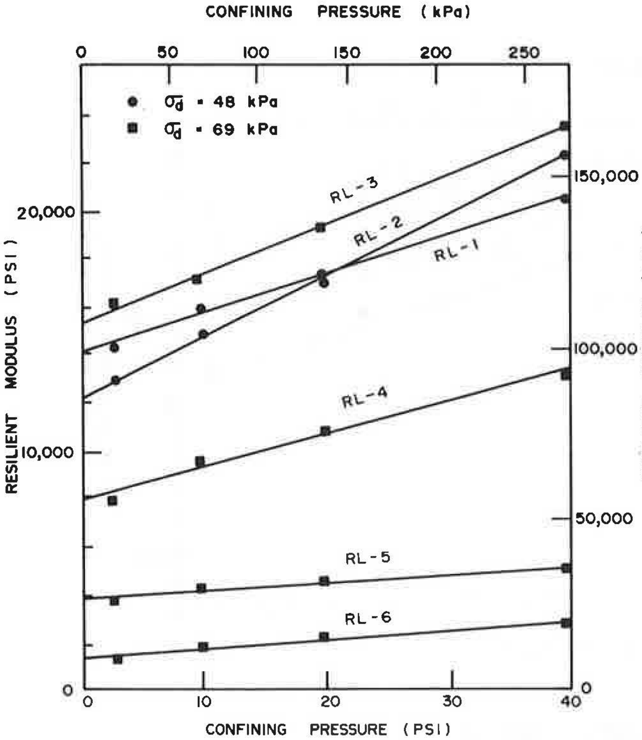


Figure 7. Slope of confining pressure versus resilient modulus for various matrix suctions.

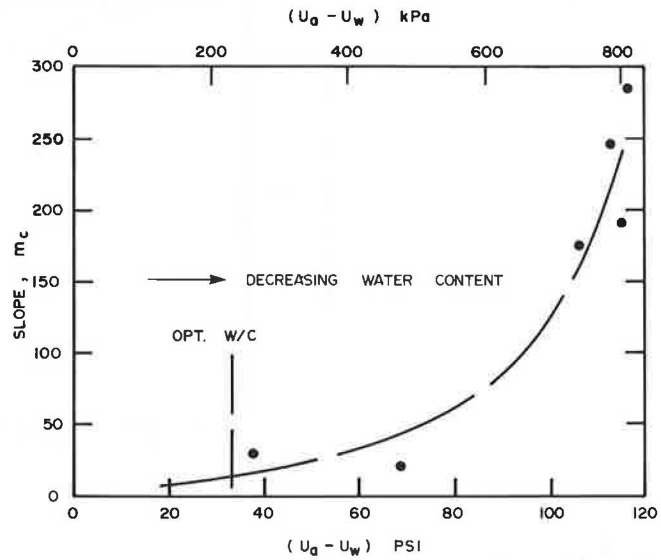
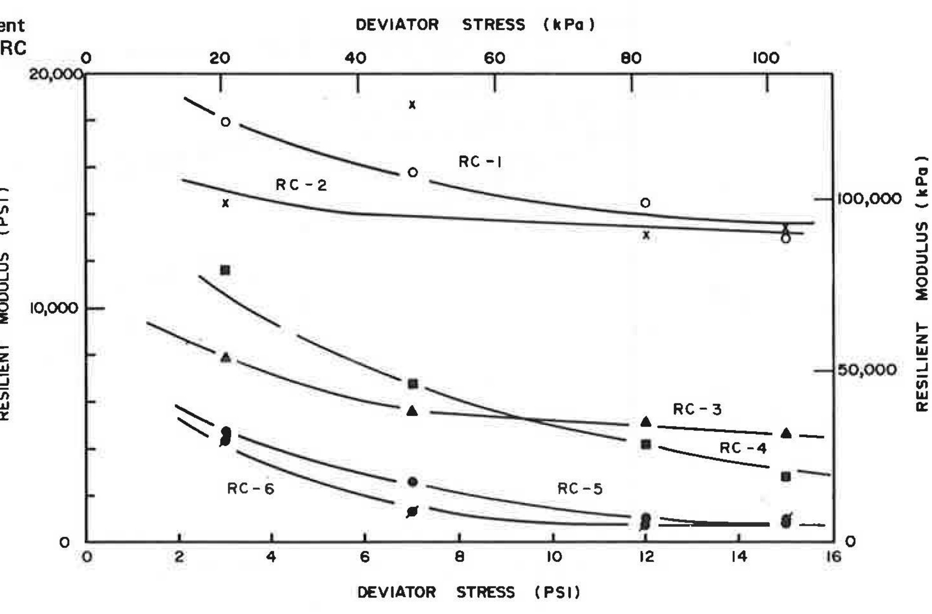


Figure 8. Arithmetic plot of resilient modulus versus deviator stress for RC samples of test series 1.



12 and 13 respectively. The slope (m_{1d}) is shown to increase as matrix suction decreases. The scatter within an individual series shows that it is not possible to differentiate between the samples prepared at constant dry densities and those with dry densities that vary according to the standard compaction curve. One result from the freeze-thaw samples indicates an increased slope (m_{1d}).

The logarithm of the intercept corresponding to zero deviator stress (c_{1d}) shows a decrease as matrix suction decreases (Figure 13). Again, the scatter within a test series is greater than are the variations produced by varying the dry density.

The best fit lines (dashed portion) from Figures 12 and 13 were used to obtain the intercept (c_{1d}) and slope (m_{1d}) values to be substituted into Equation 2. By assuming various deviator stresses, a family of curves of resilient modulus versus matrix suction was derived (Figure 14). The trend of the plots is similar to that presented in the cross-plotting technique of Fredlund, Bergan, and Sauer (5).

Figure 15 shows the relation between matrix suction and water content, and Figure 16 shows the relation between resilient modulus and water content for the samples tested. The best fit lines through each set of data were cross-plotted, and the results are superimposed on Figure 13. The resilient-modulus values used in cross-plotting correspond to a deviator stress of 48 kPa (7 lbf/in^2). The results from Equation 2 show good agreement with the results obtained by the cross-plotting technique.

The results from the proposed Equation 2 show that the plot of resilient modulus versus matrix suction can be highly nonlinear in the region of low matrix suction. That nonlinearity grows more pronounced as the deviator

Figure 9. Resilient modulus versus deviator stress for RB samples of test series 1.

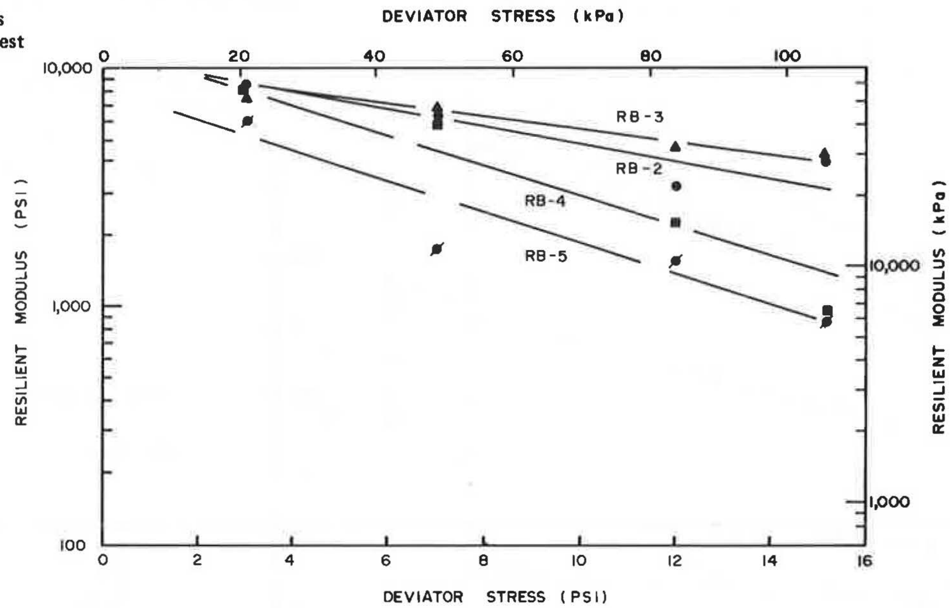


Figure 10. Resilient modulus versus deviator stress for RC samples of test series 1.

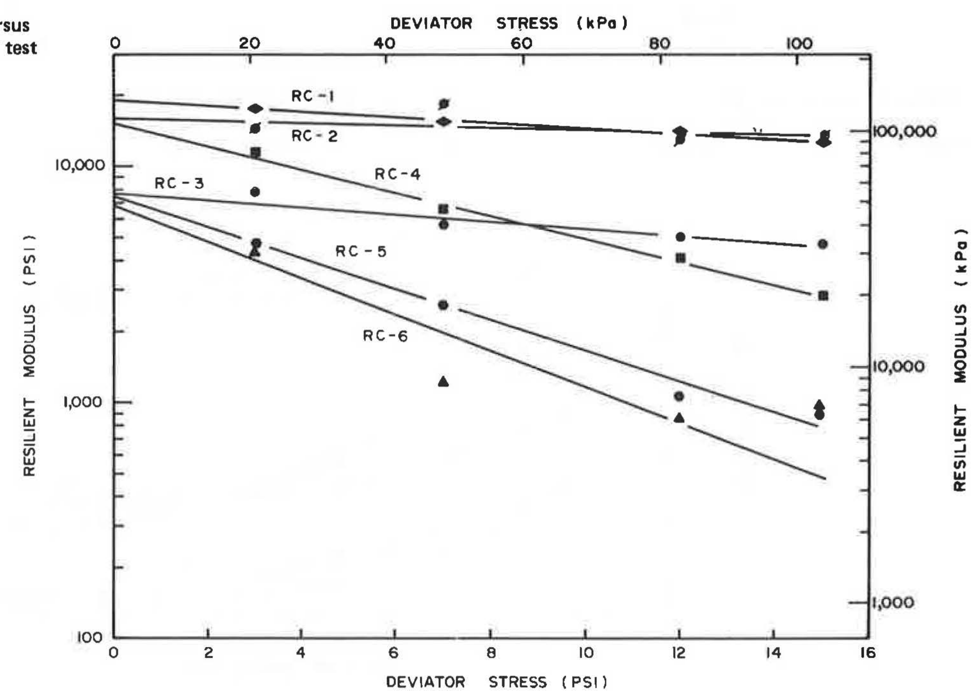


Figure 11. Resilient modulus versus deviator stress for test series 2.

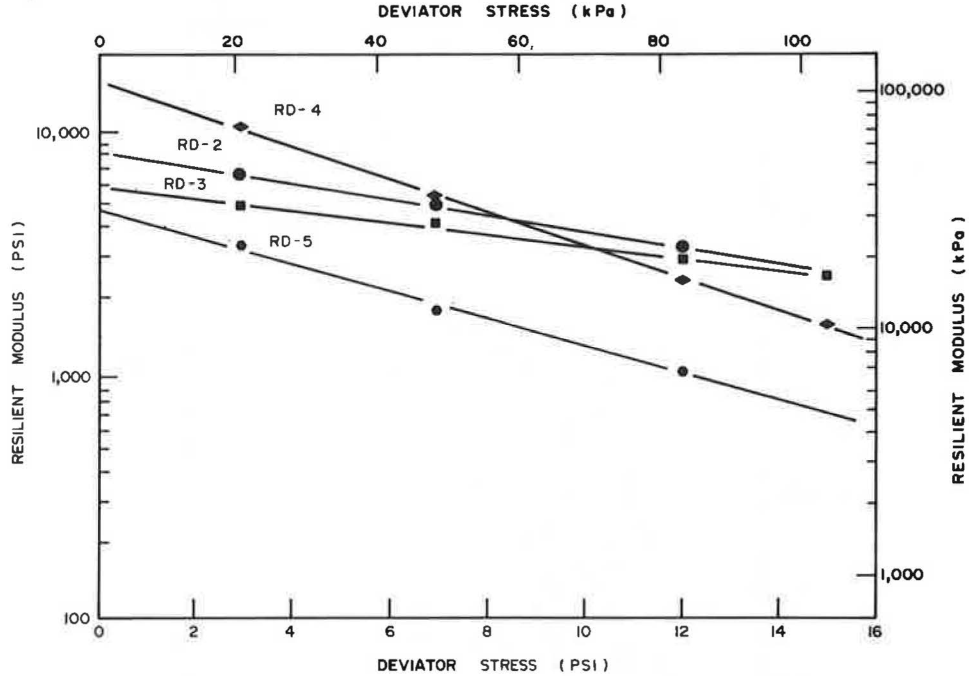


Table 6. Slopes and intercepts of resilient modulus versus log of deviator stress plots.

Sample	$(u_a - u_w)^a$ (kPa)	m_{1d}	M_R Intercept (kPa)	c_{1d}	Sample	$(u_a - u_w)^a$ (kPa)	m_{1d}	M_R Intercept (kPa)	c_{1d}
RB-2	345	0.0360	75 845	4.041	RC-5	217	0.0649	51 023	3.869
RB-3	269	0.0272	71 019	4.013	RC-6	205	0.0764	46 886	3.832
RB-4	207	0.0624	84 119	4.086	RD-2	530	0.0312	56 539	3.914
RB-5	186	0.0641	55 850	3.908	RD-3	262	0.0234	41 370	3.778
RC-1	896	0.0108	131 005	4.279	RD-4	188	0.0668	112 389	4.212
RC-2	559	0.0052	110 320	4.204	RD-5	131	0.0578	34 475	3.699
RC-3	355	0.0140	52 402	3.881	FT-S2	483	0.0854	77 914	4.053
RC-4	293	0.0477	103 425	4.176	FT-S3	272	0.0989	53 781	3.892

Note: 1 kPa = 0.145 lbf/in^2.
[a]Matrix suction value is in doubt.

Figure 12. Slopes versus matrix suction.

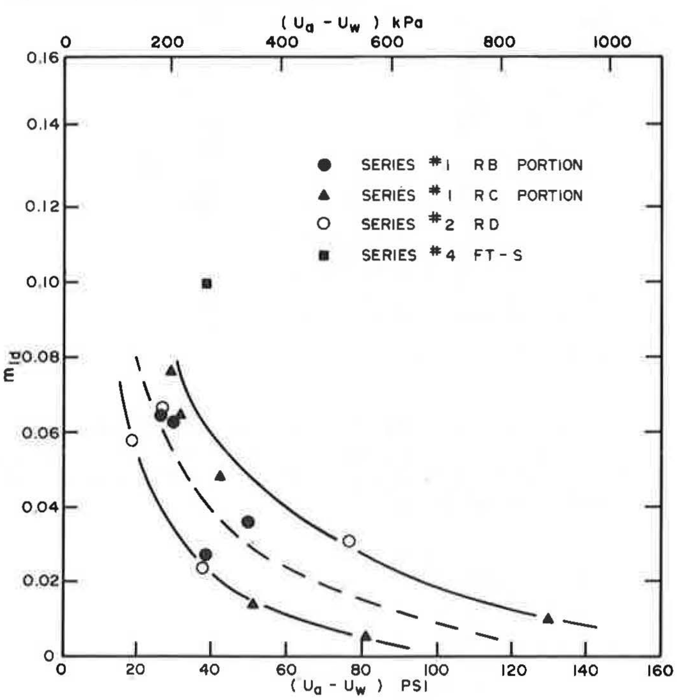


Figure 13. Log of resilient modulus for zero deviator stress versus matrix suction.

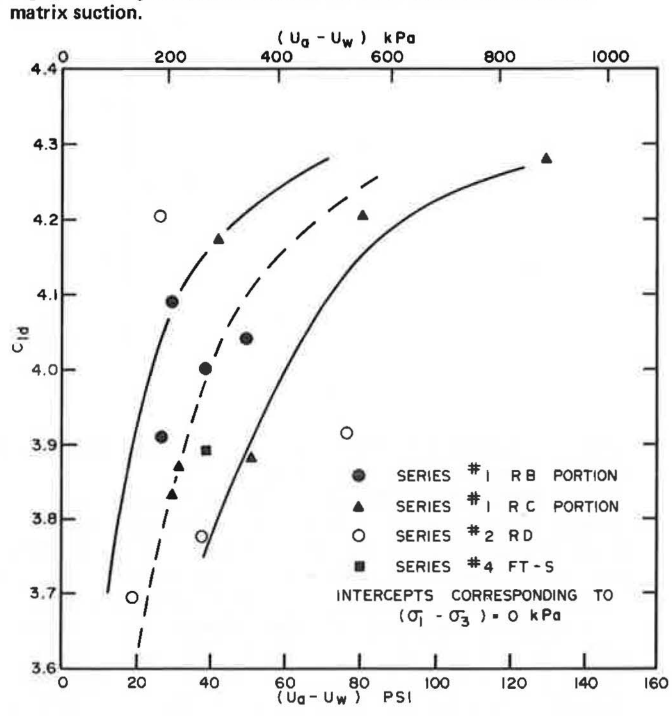


Figure 14. Cross-plotted relation for resilient modulus versus matrix suction.

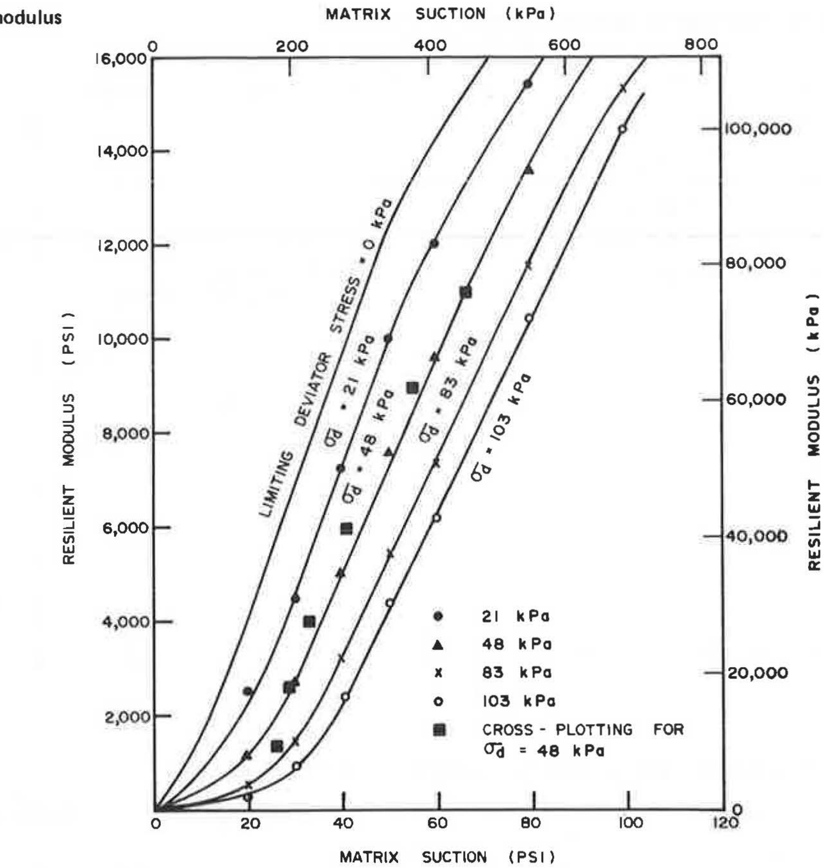
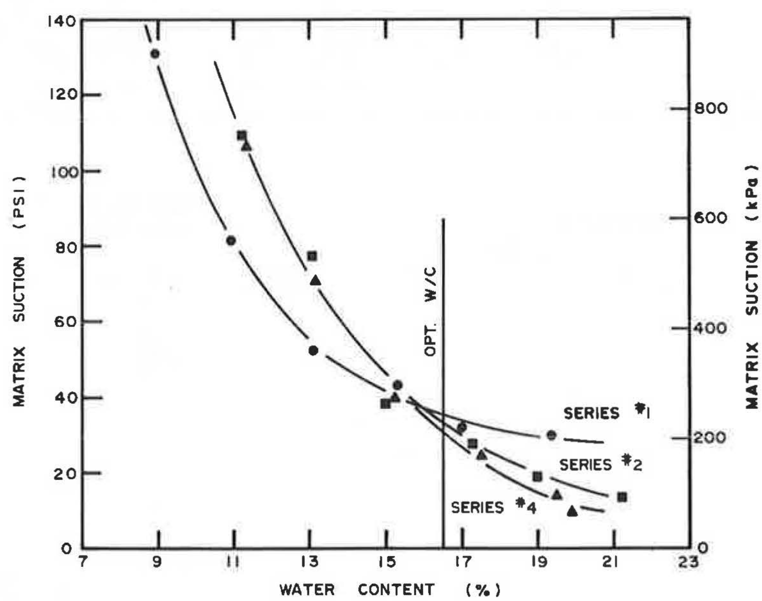


Figure 15. Matrix suction versus water content.



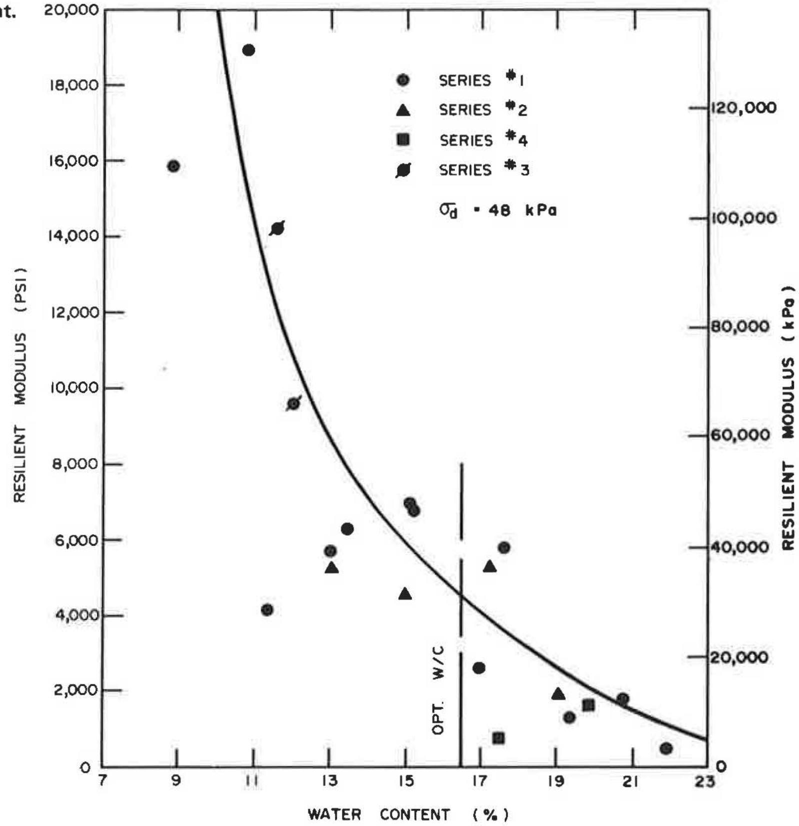
stress is increased. There is also a reversed nonlinearity in the high matrix-suction range.

The slopes (m_{1d}) (Figure 12) and intercepts (c_{1d}) (Figure 13) showed that the scatter within one series of tests was similar to that experienced between the different series. Therefore, Equation 2 appears to be unique in its accuracy in measuring resilient modulus.

Considering the typical ranges for the stress variables, it is possible to assess the significance of each stress in terms of corresponding changes in resilient modulus. As given in the following table, at a water content near optimum the deviator stress is the most significant stress variable, the matrix suction is also significant, and the confining pressure has little significance (1 kPa = 0.145 lbf/in^2):

Stress Variable	Approximate Change in Field (kPa)	Change in Resilient Modulus (kPa)
$(\sigma_1 - \sigma_3)$	0 to 83	43 439
$(u_a - u_w)$	227 to 0	24 132
$(\sigma_3 - u_a)$	21 to 41	69

Figure 16. Resilient modulus versus water content.



SUMMARY

The resilient modulus of a compacted subgrade soil can be linked to the stress variables by Equation 2, which appears to be unique within the limits of accuracy of the resilient-modulus measurements. The effect of confining pressure appears to be negligible for the soil tested.

The recommended testing program to evaluate c_{1d} and m_{1d} for Equation 2 is as follows:

1. Samples should be compacted at various water contents and densities and a compactive-energy input comparable to field placement conditions should be used.
2. Each sample should be subjected to at least 100 repetitions of deviator stresses ranging from 21 to 83 kPa (3 to 12 lbf/in^2).
3. After the completion of the repeated-load test, two or three matrix-suction tests should be performed on smaller samples cut from the tested sample.

Because of the difficulty of obtaining reproducibility in the measurements of resilient modulus, the procedure should be repeated on three carefully prepared specimens at each chosen water content and density. The testing program showed that it was extremely difficult to get reproducibility of resilient modulus on samples in cases in which the structure had been modified by freeze-thaw cycles.

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