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The Total Surface of Some Soils as Related to Permeability and Water Retention Characteristics

Warren W. Rasmussen

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THE TOTAL SURFACE OF SOME SOILS AS RELATED TO PERMEABILITY AND WATER RETENTION CHARACTERISTICS

by

Warren W. Rasmussen

A thesis submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE in

Soils and Irrigation

UTAH STATE AGRICULTURAL COLLEGE
Logan, Utah

1953
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Warren W. Rasmussen
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INTRODUCTION

It is generally recognized that many of the chemical and physical properties of soils are dependent upon the surface activity of the finer soil fractions. The importance of the magnitude of the surface areas to such properties as base exchange, water-holding capacity, absorption of gases, and the plasticity of soils has been demonstrated. Attempts have been made to determine or estimate the surface of soils and soil fractions by various methods and to relate the values obtained to the physical and chemical characteristics exhibited by these materials. Most determinations have been based on calculations of surface area from mechanical analysis data, heats of wetting, hygroscopic coefficients, and other methods, but the results in general have only been approximations.

Recent studies of the clay minerals have determined that many widely different characteristics of these materials can be attributed to the variation in surface area. Because of the effect the various minerals have on the properties of the soil, a great amount of work has been done in attempting to separate and identify the mineral components of soils. Most methods are complex and time-consuming. In recent years there has been a growing realization that the surface area may be a more important criteria of many of the properties of clay minerals than the mineralogical composition. Recently a simple method for determining the total surface, external surface, and internal surface of clay and clay fractions of soil has been developed. Although the method may not be highly exact, it appears satisfactory for
exploratory research.

The permeability of soils is an important characteristic, especially in regard to irrigation. This phenomena is difficult to characterize. Various methods have been proposed and developed to attempt to evaluate this property in soils. These methods have varied widely in basis and technique. A number of useful relationships and indices between the movement of water in soils and certain soil properties have been developed. At present it does not appear that there is any method entirely satisfactory for characterizing the water movement in soils.

The water retention characteristic is an important property of soil. This factor is extremely useful in irrigation work. Some knowledge of the relationship between soil moisture and soil moisture tension is necessary in sound irrigation practices. Suitable methods have been developed to determine the moisture retention characteristics of most soils. These methods require considerable time and labor for measurements. A more simple method or means of estimating the moisture characteristic from some commonly measured property of soil would be extremely useful. The total surface area of soils thought to be related to several physical and chemical properties of a soil may be such a common property.

Research problem

Since the surface area of soils is thought to affect the permeability (hydraulic conductivity) and the water-holding characteristics, it was proposed that a fundamental approach to an understanding of these important problems may be through a study of the relationship of area to these properties in soils. The objectives of this thesis research study have been (a) to investigate the relationships of the total surface area of some soils to the permeability to water and (b) to relate the
total surface area of the same soils to the water retention characteristics (moisture characteristics curve) within the plant growth range.

**Definition of terms**

To facilitate an understanding of the various phenomena and properties described in this paper, the following definitions are given:

**Atmosphere (Standard Atmosphere).** A unit of pressure defined as follows:

1 atmosphere $= 1.013 \times 10^6$ dynes per sq. cm. $= 14.7$ pounds per sq. in. $= 76.39$ cm. of mercury column $= 1036$ cm. of water column $= 33.01$ ft. of water column. (Water and mercury at $20^\circ C$).

**FIFTEEN ATMOSPHERE PERCENTAGE.** The moisture percentage in a soil sample which has been wetted and then brought to equilibrium on a cellulose membrane in a pressure cell held at a pressure of fifteen atmospheres. This characteristic moisture value for soils is expressed in terms of moisture percentage, dry-weight basis, and lies in the wilting range for many soils.

**Hydraulic Gradient (Water in Soil).** A vector (macroscopic) point function which is equal to the decrease in the hydraulic head per unit distance through the soil in the direction of the greatest rate of decrease. In isotropic soils, this will be in the direction of the flow velocity. The water-moving forces per unit of mass of water is represented both in direction and magnitude by the hydraulic gradient: This force is $980$ dynes per gram, or $1$ gram weight per gram, when $g \Omega = L$. The hydraulic gradient is dimensionless; i.e., $(g \Omega = L^2 \Omega = 1)$.

**Hydraulic Head (Water in Soil) ($H$).** The elevation with respect to a standard datum at which water stands in a riser or manometer connected to the point in question in the soil. This will include gravitational head, pressure head, and velocity head, if the
terminal opening of the sensing element is pointed upstream. For non-turbulent flow of water in soil, the velocity head is negligible. In unsaturated soil, a porous cup must be used for establishing hydraulic contact between the soil water and water in the manometer. Dimensionally, hydraulic head is a length \( h = L \).

**HYDRAULIC CONDUCTIVITY.** 1. The ratio of the flow velocity to the driving force for the viscous flow under saturated conditions of a specified liquid in a porous medium. Physical dimensions will depend on the equation selected to express the flow. 2. (Practical units) The ratio \( v/i = k \) where \( v \) is the flow velocity of a specified liquid under saturated conditions and \( i \) is the hydraulic gradient in the Darcy equation \( v = ki \). In this case, \( k = LT^{-1} \).

**MOISTURE CHARACTERISTICS (OF SOIL).** Refers to the relation between the soil moisture content and the soil moisture tension. This may be expressed in terms of the soil moisture characteristic curve or discrete characteristic moisture values such as the 1/3 atmosphere-percentage and the 15 atmosphere-percentage.

**MOISTURE RETENTION CHARACTERISTICS (OF SOIL).** Refers to the relation between the soil moisture content and the soil moisture tension during desorption (drying out).

**MOISTURE CONTENT (WATER CONTENT).** The ratio of the mass of water per unit mass of dry soil expressed as a percentage.

**ONE-THIRD ATMOSPHERE-PERCENTAGE.** The moisture retained in air-dried and screened samples of soil that have been wetted and then brought to equilibrium on a permeable membrane at a soil moisture tension of 3.5 cm. of water. This characteristic moisture value for soils is expressed in terms of moisture percentage, dry-weight basis, and closely approximates the moisture equivalent for many soils.
PERMEABILITY (SOIL). 1. (Qualitative). The quality or state of a porous medium relating to the readiness with which such a medium conducts or transmits fluids. 2. (Quantitative). The specific property designating the rate or readiness with which a porous medium transmits fluids under standard conditions. The equation used for expressing the flow will take into account the properties of the fluid so that proper measurements on a given medium will give the same permeability value for all fluids which do not alter the medium. The physical dimensions of the permeability unit will be determined by the equation used to express the flow.

SOIL MOISTURE TENSION. The equivalent negative pressure or suction in the soil moisture. This tension may be expressed in any convenient pressure units. In the 1 atmosphere tension range, it is the negative pressure to which water in a porous cup must be subjected in order to bring the water in the cup into static equilibrium through the porous wall with the moisture in the soil.

TOTAL SURFACE (OF SOILS). Refers to the total surface area of the soil exposed to the interaction of water, air, or other liquids within the soil mass. The surface area may include the external surfaces of the soil particles, minerals and organic matter, and the internal surface area of certain of the expanding clay minerals contained in the soil.

WATER CONDUCTIVITY (SOIL). 1. The ratio of flow velocity to the driving force for the viscous flow of water in soil. 2. (Practical units). The ratio \( \frac{v}{i} = k \) where \( v \) is the flow velocity and \( i \) is the hydraulic gradient in the Darcy equation \( v = ki \).

Most definitions above are from Richards (36, 40).
REVIEW OF LITERATURE

Much literature pertaining to the several separate phenomena and determinations involved in this study has been reviewed. The literature pertaining to each phenomenon thought to be directly pertinent to the problem is presented in detail.

**Surface area of soils**

Some experimental evidence has been presented that indicates that the finer particle fractions of the soil are responsible for much of the chemical and physical activity of the soil. This activity is largely attributed to the large amount of surface area exposed per unit mass of soil.

A number of methods differing in basis and technique have been developed or proposed for measuring the total surface area in soils.

King (20), as early as 1899, recognized the importance of the surface area of soil particles in relation to certain of their physical and chemical properties. He computed the surface area of soils by assuming spherical particles of certain size distribution. The computed areas ranged from about 1.7 to 13.6 square meters per gram of soil. These values are probably low in light of present information on the extent of surface area in soils of the types studied by King. Thomas (46), in 1921, suggested that the vapor-pressure of water at certain low pressures was a function of the moisture films on the surface of the soil particles and therefore related to the total surface of the soil. He expected a relationship between the moisture content at a certain vapor pressure and the total surface. He calculated the surface area
from the "mean effective diameter" of the soil particles and considered that the lack of agreement between the ratios of the moisture content at about 10 mm pressure and the ratios of the calculated total surfaces was due in part to insufficiency of the data of the mechanical analysis for calculating total surface.

Mahower, Shaw, and Alexander (26) determined the "specific surface" of some soils by the adsorption of nitrogen, oxygen, and carbon dioxide gases at temperatures of 0° centigrade and at -183° centigrade. Their data were apparently low for some of the materials studied and were of the same order of magnitude as the data of King (20) calculated from the mean effective diameter of the soil particles. They found that the colloid had a higher surface area than the whole soil from which the soil was extracted. This should not have been unexpected when it is considered that the coarser, non-colloidal fraction does not contribute much to the total surface. They also determined the total surface area of the clay minerals and found the total surface to be about the same range as the area of the soils and soil colloids. It is interesting to note that they found a higher value of total surface for one sample of halloysite than for a sample of montmorillonite, in variance to the values now considered correct for such materials.

They calculated the percentage of colloidal material in the soil from the relationship of the surface area of the soil to the surface area of the extracted colloid by the following formula:

\[
\frac{\text{Surface area of soil per gram}}{\text{Surface area of colloid per gram}} \times 100 = \% \text{ colloid}
\]

indicating that they correctly assumed the non-colloidal fraction to have a negligible surface in comparison to the colloidal fraction.

The data is of interest in that their assumption as to the probable
effect of total surface on such properties as base exchange capacity and heat of wetting were essentially correct. Since their surface area determinations were considered low, they concluded that certain other factors such as the chemical composition of the surface, as well as the total surface, probably influenced many of the phenomena studied.

Brunauer, Emmett, and Teller (12) measured the surface areas of soils and soil colloids by the adsorption of gases at low temperature. Their data, while considered to be highly exact, was achieved by rather laborious and involved techniques not readily adaptable to extensive investigation work. These data established confidence in exact surface measurements and served as a basis for checking results of surface area determinations by other methods developed later by Dyal and Hendricks (16).

A great number of workers reported by Baver (5), recognized the significance of the surface area to many of the physical and chemical phenomena exhibited by soils and soil colloids. The important relationship of particle size and the surface to such properties as base exchange, water-holding capacity, and plasticity have been extensively studied using surface area values calculated from mechanical analysis data. Such data were usually inadequate and inexact and often resulted in inaccurate analysis and conclusions.

Recent mineralogical studies have shown that the type of the clay minerals present in soils may have an important effect on the physical and chemical properties of soils. Much work has been done to separate and identify the individual mineral components by X-ray diffraction, thermal analysis determinations, and other methods. Most techniques have been highly involved and time-consuming, and the data obtained have not been readily interpreted.
In certain mineralogical studies ethylene glycol, glycol, and other polyhydroxylic aliphatic compounds have been used to form solvates which correctly space the mineral for X-ray diffraction analysis and other determinations. Bradley (11) and McIlwain (27) have shown that montmorillonite will form a definite solvate with certain of these compounds between the structural layers, forming two-layer solvates in the presence of excess solvent. These solvates are relatively stable under desiccation and to exposure to moist air. This stability and the fact that they space the crystal lattice a definite amount have made this a valuable aid in X-ray diffraction work.

Dyal and Hendricks (16), recognizing that a definite amount of the compounds would be required for the complete formation of the solvate, observed that the amount could serve as a basis for an analytical method of determining the surface of the absorbing material. They subsequently developed a simple gravimetric method for measuring the surface area and interlayer swelling of clays in polar liquids. The method appears to be quite exact and relatively simple, making it especially desirable for routine determinations as well as exploratory research analysis.

The method is based on the retention of ethylene glycol by clays under conditions of molecular distillation. The determinations are carried out by following the rate of loss of ethylene glycol from the clay material by evaporation at reduced pressure in a vacuum system. Under certain conditions of reduced pressure and temperature the rate of loss of ethylene glycol becomes very low at a very definite ethylene glycol content. This content in the case of montmorillonite has been shown to correspond to the two-layer solvate condition by X-ray diffraction patterns. Thus it appears that at these conditions the glycol forms a single molecular layer on the total surface of the absorbent. The
total surface area of montmorillonite was calculated on the basis of a unit cell and the surface determined to be about 310 square meters per gram of material. This value, together with amount of ethylene glycol retained, corresponding to the two-layer solvate between the silicate surfaces of montmorillonite (i.e., a single molecular layer on each surface), offered the basis for the estimation of the ethylene glycol per unit area. This value was determined to be $3.10 \times 10^{-3}$ grams of glycol per square meter of surface. With these facts established, the estimation of the total surface of a number of materials has yielded data that have compared closely with the highly reliable results of surface area determinations made by Brunauer, Emmett, and Teller (12). These comparisons gave credence to the simple technique so that the method has been adopted with confidence.

Recently Bower and Gschwend (9) at the U.S.D.A., Salinity Laboratory at Riverside, California, have developed a procedure based on the method of Dyal and Hendricks (16) for determining the surface area and the interlayer swelling of whole soils. The procedure developed provides a practical method suitable for a wide range of exploratory research on soils.

Further studies by Dyal and Hendricks (17) and Bower and Gschwend (9) have shown that the nature of the absorbed ions on the clays or soils may have an appreciable effect on the apparent surface area in clays. They show that exchangeable potassium, and in most cases ammonium, decreases the total glycol retention values. The data of Bower and Gschwed (9) also indicate that one percent of organic matter present in the soil increases the total surface value by an average of about 7 square meters per gram. They suggest this value as a satisfactory correction factor for high-surface soils containing a small
known amount of organic matter but not for general use. Treatment of 
soils to remove organic matter is recommended in most cases. These 
workers also found that the ethylene glycol retention is not significantly 
affected by the presence of large amounts of soluble salts when cal-
culated on a salt-free basis.

Permeability of soils to water

To facilitate an understanding of the relationship of the perme-
ability or hydraulic conductivity to the surface area of soils, the 
pertinent literature pertaining to the permeability determination has 
been reviewed.

Various opinions exist relative to the nomenclature and methods 
of measuring the permeability of soils. A number of definitions have 
been used to define the physical property of relating ease or readi-
ness of the transmission of water in saturated soils. This property 
has been variously called "Darcy coefficient of permeability," "perme-
ability," "coefficient of permeability," "water transmission constant," 
or "water conductivity." Recently the Soil Science Society of America, 
Richards (40), moved to adopt the general term of "hydraulic conductiv-
ity" to describe the saturated flow of any specified liquid in a porous 
medium. The physical dimensions depend on the equation used to express 
the flow. The specific case of the flow of water in soils has been 
defined as the "water conductivity." In this latter case, this property 
is specified in practical units as the ratio \( \frac{\nu}{i} = k \) where \( \nu \) is the 
flow velocity and \( i \) the hydraulic gradient in the Darcy equation \( \nu = 
ki \).

The term "permeability" is retained in this paper in conformity 
to the prior usage to avoid an ambiguity in regard to the literature 
reviewed. The implied quantity is the water conductivity as defined above.
The permeability of soils to water is a highly complex phenomenon. This characteristic has been shown to be dependent on a number of factors. Chief among the factors considered to be important are the structure of soil (which involves such physical characteristics as aggregation, pore size distribution, and bulk density), texture, mineralogical composition of the soil, the nature of the absorbed ions, and the chemical composition of the percolating water.

The movement of water and fluids through soils and other porous material has been extensively studied. The best known relations between the rate of flow, the hydraulic head, and "permeability" of the material were developed by Darcy in 1856. These formulae are quoted in Baver (5) and Richards (40). This relationship, known as Darcy's Law or Equation, is commonly stated in the general formula:

\[ v = ki \]  

where \( v \) is the velocity of moving water, \( k \) the Darcy coefficient of permeability, and \( i \) (or \( \frac{h}{z} \)) is the hydraulic gradient (potential gradient); that is, the change in the static hydraulic head per unit distance along the average flow line.

This expression combined with the cross-sectional area through which the flow is taking place yields the generally used formula:

\[ Q = kia \text{ or } k\frac{h}{z}a \]  

where "\( Q \)" is the quantity of water per unit time, "\( i \)" is the hydraulic gradient, "\( k \)" is the coefficient of permeability, and "\( a \)" is the cross-sectional area through which flow takes place. The hydraulic gradient "\( i \)" is the ratio of \( h/1 \), or the total loss of head divided by the distance through which the loss takes place, which, when rearranged to the following form:

\[ k = \frac{Q}{ah} \]
gives the form used for purposes of calculation of the permeability.

A vast amount of research has been done on the movement of water and fluids through water-bearing materials, soil materials, and other porous media.

Various methods, both direct and indirect, have been proposed as a means of evaluating permeability of soil materials. These methods have differed widely in characteristic measured and in technique. Measurements have been made with water and other fluids. Such work has been done to relate structural and technical factors to permeability. Measurements of texture, aggregation, and pore size distribution have been variously considered as indexes of permeability and have been used with varying success.

Slichter, quoted by Sawyer (5), developed the now classic formula to express the quantity of water per second transmitted through a saturated soil column. His formula, an attempt to introduce a variable soil characteristic (the nature of the pore space) into the equation of Darcy, follows:

\[ Q = \frac{10.22pd^2s}{Hk} \]

Where "Q" is the quantity of water transmitted in cubic centimeters per second, "p" is the difference in pressure head in centimeters, "d" is the mean diameter of the soil grains in centimeters, "s" is the cross-sectional area in square centimeters, "h" is the height of the soil column in centimeters, \( \mu \) is the coefficient of viscosity of the liquid in poises, "k" is a constant.

Zunker, from Sawyer (5), developed an equation similar to Slichter's in which he included other variables to characterize the value of the pore space and other surface factors more precisely. The Zunker equation:
\[ Q = \frac{\mu h}{10^{-14}} \cdot \left( \frac{P_0}{l - p} \right)^2 \cdot F \]

where \( Q \) refers to amount of water transmitted, \( h \) the pressure difference, \( \mu \) the coefficient of viscosity, \( l \) the length of the column, \( \mu \) the effective specific surface, \( \mu \) the type and arrangement of the particles, \( p \) the total pore space, \( P_0 \) the tension-free pore space, and \( F \) the cross-sectional area. Zunker considered the Slichter transmission constant to vary directly with the square of the tension-free pore space and inversely with the square of the effective specific surface. Other investigators have proposed modifications to the Darcy equation in an attempt to evaluate the amount and nature of the soil-pore space. Much work has been done in an attempt to determine relations between pore size, distribution, texture of the soil, bulk density and such other "structural" factors to soil permeability.

Saver (1), Bodman (5), Slater and Byers (11), Luts and Leamer (25), Lutz (23), Bradfield and Jamison (10), Nelson and Saver (20) were among the first workers to attempt to relate permeability to the amount and nature of the soil-pore space. The pore space was characterized by measurement of particle size and the volume of pores drained at a particular tension. The data of Slater and Byers (11) and Saver (1) have shown that the pore space alone may not provide a very good index unless the effectiveness of the difference in pore sizes and the continuity of the soil pores could be evaluated.

More recent investigations by Smith, Browning, and Pohlsman (12), Bendixen and Slater (6), and Bendixen, Hershberger, and Slater (7) have attempted to determine the relation of the "effective" pore size in water transmission. Smith, Browning, and Pohlsman developed a "porosity factor" based on the weighed values of the several pore sizes in an
attempt to develop a more quantitative appraisal of the actual rates of water movement through soils. It appears from much of the data that the pore size distribution, either based on texture measurements or volume of pores drained at different tensions, is not sufficient to characterize water movement in soils. Therefore, it appears that a combination of pore size determinations and percolation rates may offer a definition of the rate of water movement.

Other factors which are known to affect permeability are particle size or texture and the compaction of the soil samples. These factors have been variously studied.

Bodman (3) concluded that the textural differences of soils finer than fine sandy loams did not significantly affect permeability at high apparent densities.

Aronovici (2) developed a technique for utilizing the mechanical analysis data as an index of the permeability of subsoils in drainage work. He found that for aquifers in the range of permeabilities of from 0.1 to 100 cc/cm²/hour the index was sufficiently accurate for field application in drainage design. The direct correlation of permeability of prepared samples with the silt plus clay content was fairly reliable in the permeability range from 0.3 to 70.0 cc/cm²/hour.

Texture may be an important factor affecting permeability qualitatively, but from the results of critical studies it appears that texture alone is not a reliable index of permeability.

The permeability and infiltration rates of the soil are significantly affected by the nature of the absorbed ions in the soil, the composition of the percolating water, the amount of organic matter present and the tillage and management practices as well. The factors have been intensively studied in relation to permeability.
The problem of soluble salts in the soil and water is a vital problem in irrigation and drainage in arid regions. Harris (19), Christiansen (16), Reitnauer, Christiansen, Moore, and Aldrich (32) have demonstrated the effect of absorbed sodium on soil permeability.

Parker and Jenny (30), Reitnauer, et al. above (32), Pillebury and Huberty (31), and others have studied the effect of cropping and management practices, application of fertilizers and compaction, and other factors in the infiltration and permeability of soils.

It has been conclusively demonstrated by Baver (3) that organic matter incorporated into the soil improves the soil structure following decay and thereby increases the rate of water movement through the soil. Tilling and cultivation usually improves infiltration while soluble salts, especially sodium, tends to decrease permeability.

Methods of Measuring Soil Permeability

The variation of permeability as influenced by the factors discussed above makes the measurement of permeability and interpretation of data a difficult matter. Various methods of measuring permeability, both directly and indirectly, have been proposed varying widely in technique.

Indirect methods of evaluating permeability from structure characteristics and other clues in the field have been developed by O'Neal (29) and Uhland and O'Neal (17). These appraisals apparently have been useful in certain classification work.

Structure has been considered the most significant factor influencing permeability. Measurements of texture and aggregation do not appear too reliable to indicate permeability. Much work has been done in developing methods and measuring the permeability of undisturbed samples, but it appears that permeability cannot be reliably estimated from
structure alone without considering the interrelations of the permeabilities of other layers in the soil profile. Uhland and O’Neal (47), Lutz (21), and others have developed techniques for taking undisturbed samples for permeability measurements. Kirkham (21), Luthin and Kirkham (22), and van Ravel and Kirkham (49) have developed methods of measuring permeability in situ.

The difficulty in obtaining undisturbed soil samples and the rather special technique required for measuring the permeability on undisturbed samples has resulted in attempts to relate the permeability of disturbed samples to field percolation rates. Direct permeability measurements on undisturbed samples have proven of value in many studies, but results in general have shown that percolation rate alone is not sufficient to characterize water movement in soils.

It is not expected that the permeability of disturbed material would closely approximate the permeability of the soil in the natural state. Studies have indicated a relative agreement between laboratory and field rates, however, especially in regard to response to various salt or amendment treatments on saline and alkali soils.

Fireman (18) found rather close correlation between the relative change in permeability obtained in the laboratory with the relative change to a similar treatment in the field. This relative agreement, therefore, may be useful in evaluating expected results from certain treatments or in classifying soils for response to irrigation.

The ease and rapidity of measurements and relative value of results seem to justify the use of disturbed samples in much permeability and infiltration work.

Fireman (18), Christiansen (14), Christiansen, Fireman, Allison (15),
and Allison (1) have studied various factors affecting the permeability of soils in the disturbed state and have developed satisfactory techniques for measurement. The method has been extremely useful in evaluating certain treatments and in characterizing and classifying certain saline and alkali soils.

**Moisture retention characteristics of soils**

The moisture retention characteristics of soils are an important criteria in evaluating a soil, especially in regard to irrigation. The moisture characteristic refers to the relation between soil moisture content and the soil moisture tension and describes or defines the moisture supplying capacity, the total moisture capacity, the irrigation interval, and other qualities in soils. A concept of the type and shape of the moisture retention curve is necessary in sound irrigation practices.

The utility and the method of obtaining such curves have been demonstrated and perfected by Richards (35, 37, 38), Richards and Fireman (33), and Richards and Weaver (34). The relation between moisture content and soil moisture tension can be reliably determined by the use of the pressure membrane and porous plate apparatus described by the above authors.

Baver (5), Thomas (46), Childs (13), and Taylor (44) have investigated the nature of the forces holding the water in soils and hence determines the shape of the moisture retention characteristics curve.

Taylor (44) has suggested that total moisture potential is composed of at least four potentials that can be expressed in an equation:

\[ \phi = \beta g + \psi + \pi + w \]

where \( \phi \) = total potential

\( \beta g \) = gravitational potential
\[ \psi = \text{capillary potential} \]
\[ \pi = \text{osmotic potential} \]
\[ \kappa = \text{adsorption potential} \]

In the higher moisture ranges \( \psi \) and \( \kappa \) are negligible, the effect of \( \pi \) is negligible in fluid flow, and hence the gravitational potential is most important in soil water movement. In drier soils the capillary potential and to some extent the adsorption potential influences moisture movement and retention. At very low moisture contents the water is held very tenaciously by the adsorption forces and the moisture content then becomes a function of the total surface area exposed within the soil mass.

At low moisture content the adhesive force or attraction of the water particles to the surfaces of the soil particles becomes the limiting factor. It is considered by many workers that at low moisture content the surface area of the particles becomes the controlling factor in moisture movement and retention.

The value of the soil moisture tension characteristics for various soils in relation to plant growth has been demonstrated by Richards and Wadleigh (39), Richards and Weaver (38), Veihmeyer and Hendrickson (46), Taylor (45), and others. The relationship of moisture content to soil moisture tension has an important bearing on management practices on irrigated soils. Such relationships are being extensively used in many research studies and in practical field work as well.

The pressure membrane and porous plate apparatus of Richards (35) may be used to measure most of the resultant forces and to date is the only reliable practical method available for such characterization over the entire plant growth range. It is, however, a rather tedious job.
and, because of the amount of labor involved, not adaptable to intensive work on a large scale.

Conclusions drawn from the literature reviewed:

The literature reviewed suggests the following conclusions:

1. The permeability of soils is a complex phenomena and difficult to characterize.

2. It has been demonstrated that a great many factors affect the movement of water through soils. Present information indicates that the chief factors which influence permeability are:

   a. The structure of the soil which influences the amount, size, and continuity of the pore space. The structure is influenced by the mineralogical composition of the soil, texture, compaction, hydration of soil particles, organic matter, and channels of biologic origin (root channels and worm holes), composition of percolating water, and soil treatment.

   b. Texture of the soil (usually to the extent to which it influences pore space or other structural properties). Clays and colloidal material have been shown to decrease the permeability.

   c. Salts in the soil (absorbed ions) and in the percolating water. Sodium salts usually cause a decrease in permeability. Calcium or magnesium may have the opposite effect.

   d. Temperature (as it affects viscosity and density of water).

   e. Air entrapped in the voids of the soil (this tends to plug the pores for water movement). In true saturated permeability this should not be a factor since the air should be eliminated.

   f. Microorganisms (which tend to clog the soil with waste products or through production of gums, etc.).

   g. Surface area of the particles exposed in the mass of soil.
The total surface area exposed in the soil may influence permeability in a number of ways: (1) The shape of the particle may be influencing since flat shaped particles have a greater surface area per unit mass than spherical particles; (2) surface area is inversely proportional to particle size; the smaller particle exhibiting a much greater surface than larger particle per unit mass; (3) swelling, primarily a result of the composition of the clay mineral present (e.g., montmorillonite type minerals have a much greater total surface area and expand very greatly on wetting).

3. The moisture retention characteristic is an important criterion in evaluating a soil in regard to plant growth and irrigation management practices.

4. The total soil moisture potential may be regarded as being composed of the gravitational, capillary, adsorption and osmotic potentials. The interaction of these potentials at various moisture contents determines the moisture retention characteristics of the soil.

5. At very low moisture contents the moisture retention and movement may be some function of the surface area of the soil particles.

6. The total surface area of the soils (i.e., the total surface area exposed to interaction with water, air, or other fluids) has an important influence on the physical and chemical activity of soils.

7. The total surface is considered to affect the rate of water movement and retention by soils.

8. The magnitude of the total surface area may be influenced by three independent factors: (1) the shape of the soil particles, (2) the size of the particle, (3) the type of clay mineral present in the soil.

From the review of literature, it appeared that a study of some relations between the total surface area and the moisture retention
characteristics and permeability of soils would be useful in soils work.
METHODS AND PROCEDURES

In order to test the assumption that permeability in the saturated state and the water retention characteristics may be related to the total surface area of a soil rather wide variety of soil types were collected and tested. The soil samples were from several widely separated areas in the Western United States and in general represented good agricultural soils.

The samples, previously collected for other purposes, are described in table 1. The samples were selected and air dried; the larger clods were broken by kneading in the bag and the sample thoroughly mixed and divided. Approximately 5 pounds of material was crushed in a jaw crusher and passed through a 2 mm round hole screen. A smaller sub-sample was further prepared by passing through a soil pulverizer.

The 2 mm portion was used for mechanical analysis, the permeability tests and for determining the moisture retention characteristics. The pulverized sample was subsequently prepared and used for the total surface area determinations.

Method of determining total surface area

Apparatus. The apparatus for determining the total surface area of the soils is shown on figure 1. The equipment consists of a Conco Hyvac vacuum pump (The vacuum pump must be capable of reducing the vacuum to 0.1 mm of mercury.), two 10-inch pyrex vacuum desiccators equipped with a collar or sleeve type stop cocks in the lids, a Stokes McCleod vacuum gage, a drying tube containing calcium chloride, aluminum weighing dishes 2 1/2 inches in diameter and 3/8 inch in depth, an accurate
Table 1. Soil type and characteristic data of soils tested

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Sample No.</th>
<th>Soluble Salts</th>
<th>Organic Matter</th>
<th>Sand 2-0.05mm</th>
<th>Silt 0.05-0.002mm</th>
<th>Clay 0.002mm</th>
<th>Clay 0.005mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Millville silt loam</td>
<td>R1</td>
<td>0.066</td>
<td>2.6</td>
<td>17</td>
<td>57</td>
<td>26</td>
<td>39</td>
</tr>
<tr>
<td>Salt Lake silt loam</td>
<td>R2</td>
<td>0.10</td>
<td>2.4</td>
<td>16</td>
<td>56</td>
<td>26</td>
<td>43</td>
</tr>
<tr>
<td>Houston black clay (1)</td>
<td>R3</td>
<td>0.01</td>
<td>6.8</td>
<td>12</td>
<td>40</td>
<td>43</td>
<td>62</td>
</tr>
<tr>
<td>Houston black clay (2)</td>
<td>R4</td>
<td>0.01</td>
<td>3.8</td>
<td>9</td>
<td>65</td>
<td>26</td>
<td>67</td>
</tr>
<tr>
<td>Amarillo fine s. loam</td>
<td>R5</td>
<td>0.018</td>
<td>1.1</td>
<td>74</td>
<td>11</td>
<td>15</td>
<td>18</td>
</tr>
<tr>
<td>Pullman sil. cl. loam</td>
<td>R6</td>
<td>0.01</td>
<td>1.9</td>
<td>23</td>
<td>43</td>
<td>34</td>
<td>43</td>
</tr>
<tr>
<td>Zita clay</td>
<td>R7</td>
<td>0.035</td>
<td>1.8</td>
<td>32</td>
<td>37</td>
<td>31</td>
<td>37</td>
</tr>
<tr>
<td>&quot;Springer&quot; fine s. loam</td>
<td>R8</td>
<td>0.01</td>
<td>0.9</td>
<td>81</td>
<td>6</td>
<td>13</td>
<td>14</td>
</tr>
<tr>
<td>Napleton loam</td>
<td>R9</td>
<td>—</td>
<td>1.9</td>
<td>51</td>
<td>26</td>
<td>23</td>
<td>32</td>
</tr>
<tr>
<td>Jordan loam</td>
<td>R10</td>
<td>—</td>
<td>1.8</td>
<td>10</td>
<td>60</td>
<td>30</td>
<td>49</td>
</tr>
<tr>
<td>&quot;Keller&quot; clay</td>
<td>R11</td>
<td>—</td>
<td>2.8</td>
<td>1</td>
<td>57</td>
<td>39</td>
<td>57</td>
</tr>
<tr>
<td>Taylorsville sil. cl. loam</td>
<td>R12</td>
<td>—</td>
<td>2.4</td>
<td>16</td>
<td>58</td>
<td>26</td>
<td>45</td>
</tr>
<tr>
<td>Richfield loam</td>
<td>R13</td>
<td>—</td>
<td>1.4</td>
<td>20</td>
<td>58</td>
<td>22</td>
<td>38</td>
</tr>
</tbody>
</table>

1/ The soil type name in most soils is believed to represent the true soil type; however, the true type for some soils is uncertain. The soil type should be considered for descriptive purposes only.
Figure 1. Apparatus used in determining the surface area of soils
analytical balance, drying oven, one ordinary desiccator (for cooling the weighing dishes) and necessary pressure tubing and vacuum stop cocks. The necessary materials used included ethylene glycol, purest grade, calcium chloride, and phosphorus pentoxide desiccants.

The two vacuum desiccators were connected to the vacuum pump through the same drying tube. In use only a single desiccator was attached to the pump at one time, the desiccators were disconnected and connected by the collar type stop cock on the lids. The drying tube was constructed of a discarded glass peristaltic with a side outlet; for connecting the tube inlet, a second connection was made by passing a 1/8 inch glass tube through the rubber stopper. The rubber stopper permitted the removal and replacement of the calcium chloride in the tube as necessary. All of the points were sealed with "Fernate" glass and rubber sealing compound and secured by wire tightly twisted over the tubing. The McLeod gage was permanently connected to the system with a short length of rubber pressure tubing. A pinchcock was used to close the tubing except when the pressure measurements were being made.

The adequacy of the system was tested by determining the rate of evaporation from a weighing dish containing pure ethylene glycol. This rate should be at least 1 gram of glycol per hour as suggested by Bower and Gschwend (9). The rate was slightly less than this value in the equipment used. The equipment was calibrated by making a number of determinations on soils of known retention values.\(^1\) During each determination a soil sample of known glycol retention was placed in the desiccator as a check to determine the probable retention values.

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\(^1\) The soil samples were supplied by Dr. C. A. Bower, Soil Scientist, U.S.D.A. Salinity Laboratory, Riverside, California.
for the surface calculation.

Procedure. The procedure for the surface area determinations on whole soils outlined by Powar and Cschwend was followed in this study. These instructions were followed in all of the determinations except that the soils were not treated for the removal of organic matter.

In the preparation of the soil for surface determinations the samples were ground in an iron mortar and pestle and passed through a 60-mesh screen. In the case of the Amarillo fine sandy loam and the soil referred to as "Springer", the coarser sand fractions were difficult to crush. As a result, approximately 5 percent of the sand fraction was discarded after repeated grindings failed to reduce the size sufficiently to pass the 60-mesh sieve.

The point which the glycol retention was considered to represent the surface was taken at the exact time when the known sample reached the predetermined value. Only the total surface area was determined in this study. It was felt that for purposes of the study this property would be of primary interest in relation to the factors studied.

Method of determining soil permeability

Many of the variable factors that affect permeability and the rather limited and transient nature of permeability values was recognised in regard to the permeability measurements carried out in this study.

In this study a very close agreement was found between the permeability of the several replicates of each soil. Also a significant difference was observed between the various soils. Since the major purpose of the permeability measurements was to establish a "relative" difference between the soils in relation to surface area, it was felt that measurements on disturbed samples were applicable for the purposes of this study.
The permeability was carried out by the method suggested by Fireman (18) with some modifications. The method is outlined below:

Apparatus. The apparatus used for the permeability measurements is shown in figure 2. The apparatus consists of constant head water supply tank, connecting pipes and tubing, and a number of perusimeters. The glass perusimeters used were 3.3 cm. in diameter and approximately 25 cm. in length. The outlet end of the perusimeter tube is sharply beveled to form a drip point. The water was passed downward through the samples and the percolate collected in graduate cylinders of appropriate size and the volume collected per unit time was determined.

Procedure. In previous work, it was observed that when tap water was used directly in permeability determinations, the excessive air entrained and dissolved in the water would be released in the tops of the perusimeters. The water which was saturated with air at normal temperature would not dissolve the air in the soil pores but would result in increased air collection. The samples were frequently disturbed by the increased air pressure in the pores.

Stanley F. Marsh developed a unique method of desairating the water used in permeability determinations. He found that by mixing hot and cold water in sufficient proportions to raise the water slightly above room temperature, the amount of air was reduced. Since water retains more air at a lower temperature, the increase in temperature reduced the amount of air. He also found that by agitating the water (by forcing through a small glass tube drawn to a point) the fine bubbles entrained in the tap water were completely removed. When the water

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2/ Permeability measurements on disturbed samples in studies on seepage losses from canals. Unpublished data.
Figure 2. Arrangement of apparatus for soil permeability tests. Constant head tank, deairing jet arrangement, water supply pipes and inlet tubes and glass parameters are shown.
was pretreated for the removal of air, the air within the soil in the permeameter was observed to dissolve rapidly.

The soil samples used in the permeability determinations were air-dried, crushed, and screened through a 2 mm round hole sieve. The entire sample was then placed in a shallow pan and thoroughly mixed. A one hundred gram sample was weighed into a small beaker. The sample was obtained by taking small portions from several locations in the pan with a thin-walled spoon to prevent separation and to obtain a more representative sample.

The permeameter was prepared by fixing a small circular fine mesh screen disc in the bottom of the glass tube. The disc was held in place over the outlet by running a very small diameter wire from the center of the disc, out through the outlet tube, and attaching to the inlet tube at the top of the permeameter. Approximately one inch of fine screened Ottawa sand was placed on the screen to support the sample.

The soil was transferred to the permeameter by means of a glass funnel attached to a 3/8-inch I. D. glass tube approximately 6 inches long. The soil was distributed in the tube by revolving the tube inside the permeameter to prevent segregation.

The soil was compacted by dropping the permeameter a distance of one inch onto the tip of the outlet tube on a wooden block. A ring on a ring stand served as a stop to gauge the distance the permeameter was dropped. After compaction the surface of the soil was level and uniform. The length of the soil column was recorded for use in the permeability calculations.

The water was introduced into the tube with a rubber syringe. A rubber stopper just slightly smaller than the inside diameter of the permeameter and attached to a string was placed on the soil surface to
prevent washing and eroding of the soil surface. Later it was found that if the water was introduced very slowly from the inlet tube, the permeameter could be filled without disturbing the soil surface. This method was much faster and as satisfactory as using the syringe.

When the permeameters were filled, the samples were allowed to stand until the soil columns were wetted through. Then the rubber stoppers were placed in the top of the permeameters and the full head applied.

The head on each individual permeameter was determined by attaching a length of 1/4 inch glass tubing to the outlet of the water supply pipe and then with the glass tube placed vertically near each permeameter, the head was measured.

The permeability of the samples was determined by measuring all of the water passing through the soil column at periodic intervals. Usually measurements were made twice daily on the soils of high permeability and once each day of the soils of lower permeability.

From the measurements of the hydraulic head, the length of the soil column, the temperature of the water, the viscosity data of water, and the amount of percolate per unit time the permeability at a standard temperature of 20°C, was determined by the following formula:

\[ Q = \frac{k a h}{l} \]  \hspace{1cm} (h)

rearranged in the form:

\[ K = \frac{Q a h}{l} \]  \hspace{1cm} (5)

where \( Q \) is the flow (volume per unit time), \( K \) is the water conductivity (permeability as used in this paper), \( a \) is the cross-sectional area of the sample, \( h \) is the difference in hydraulic head through the soil column.
(in this case the difference in height between the water surface in the constant head tank and the lower end of the soil column), \( l \) is the length of the column (measured in the dry state after compaction), \( \eta \) is the viscosity of water in centipoises at the average temperature at the time of measurement and \( \eta_0 \) is the viscosity of water at 20°C as the "standard" value.

The volume of flow (Q) was reported in units of cubic centimeters per hour, the ratio of the viscosities (unitless), the hydraulic gradient (unitless), and the area of the sample in square centimeters. Therefore, the units of permeability were in centimeters per hour (cm/hr.).

The determinations were made with five replicates on most soils, determinations were made in triplicate on four samples because of lack of permeameters. The initial permeability was determined as soon as practical after the first percolate came through the sample. All of the water passing through the sample was collected and measured. Measurements were continued on all of the samples for approximately fifteen days. The measurements were continued until the permeability has passed over the first maximum rate. This usually occurred three to four days after the tests were begun, and the rate was gradually decreasing.

The permeability corresponding to the first maximum rate was taken as the permeability for comparison purposes. In the case of some of the coarse-textured soils, the typical maximum did not occur and in these cases the rate was taken at approximately four days after the beginning of the test.

**Moisture retention characteristics determinations**

The moisture retention characteristics curve over the entire plant growth range 0.1 atmosphere tension to 15 atmosphere tension was determined.
Apparatus. The moisture retention in the low pressure 0.1 atmosphere to 1.0 atmosphere range was determined in low pressure cells containing porous plates similar to the units described by Richards and Fireman (33). The pressure cells or units used consisted of small diameter brass cylinders with a porous ceramic plate. The small diameter copper outflow tube in the base of the cell is passed through a rubber stopper in a dispensing burette. The volume of water removed in cc (equivalent to grams between successive equilibria at the successive pressures was determined by measuring in the burette. When the equilibrium at the highest pressure was reached, the cell was uncovered and the entire sample removed and the moisture content determined. The moisture content at various pressures was determined from the final moisture content and the volume of water extracted between the various pressure settings.

The moisture retention at the various pressures in the high pressure (1 atmosphere to 15 atmospheres) range was determined by the use of the pressure-membrane apparatus developed by Richards (35). The apparatus consists of the pressure cell formed of a narrow brass cylinder or ring clamped between two heavy steel plates. A fine mesh screen resting on a brass plate serves as a support for the cellophane membrane. A small diameter outflow pipe in the center of the brass plate is used to conduct the water extracted through the membrane into a graduate or burette. The graduate or burette serves only to determine the equilibrium condition (i.e., when the outflow becomes very slow).

Procedure. During the initial soil moisture retention determinations, the soil was placed in brass rings with the bottom covered with a fine-gauge nylon cloth. The known amount of soil equivalent to 20 grams of oven-dry soil was added to the ring and placed on the membrane which was covered with a very thin layer of pulverized fine-textured soil. The
different pressures were applied to the membrane and the moisture
extracted between the successive pressures was determined by weighing the
cloth-covered containers. After weighing, the containers were returned
to the apparatus and the procedure repeated. At the final pressure,
the sample was oven-dried to determine the residual moisture content.
This value was then used to calculate the moisture content at the
successive pressures. The measurements were extremely variable in the
case of the heavier-textured soils and the method was discontinued.

The measurements were then carried out by the original method
suggested by Richards (35). Seven samples of each soil were placed in
open rings in the apparatus and the whole samples were removed at
equilibrium at successive pressures and oven-dried. After the moisture
determinations were made, the samples were discarded. Duplicate
determinations were made at the 1 atmosphere and at the 15 atmosphere
pressures. Single determinations were made at various intermediate
pressures.

Some discrepancies were found in the moisture contents at several
of the pressures during the first determinations. The pressure control
on the pressure system used in the determination with the pressure mem-
brane had a tendency to change or drift at low (1 to 3 atmospheres)
pressure. The moisture retention values in this range were not used in
the analyses. The measurements were repeated on all of the soils over
the entire range from about 0.1 to 15 atmospheres.
Total surface determinations

The total surface areas of the thirteen soils were determined by the ethylene glycol retention method. The determinations were usually made on duplicate samples contained in the same desiccator. Occasionally a single sample was used in some determinations because of the limited space in the desiccators. In all cases, at least four determinations were made on each soil.

The glycol retention values obtained on the replicate samples checked very closely, usually within 1 percent; therefore, the simple mean of the several determinations was used for the surface area calculations. There was some variation in the time required to reduce the glycol content to the proper value (as determined by the check samples) between the different determinations. This was very probably due to the slightly different depths of the soils in the weighing dish and the vacuum conditions attained. The rate of loss of ethylene glycol with time was plotted for all determinations so that approximate constant retention values at uniform times could be observed on the curves. Typical curves illustrating the rate of loss of ethylene glycol with time for all soils are shown in figures 3, 4, and 5. The retention values of the unknown soils corresponding to the same time when the correct values for the check samples was obtained were used. From the curves, this appeared to be very consistent at the time when the loss of ethylene glycol was very low and constant. The mean ethylene retention values and the calculated total surface areas are shown in table 2.
Fig. 3. Ethylene Glycol Evaporation Rate from Soils
Fig. 5. Ethylene Glycol Evaporation Rate from Soils
Table 2. Results of indicator tests on the soils.

<table>
<thead>
<tr>
<th>Sample no.</th>
<th>Glycol retention value</th>
<th>Total surface</th>
<th>Permeability</th>
<th>% Moisture</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mgm/gm</td>
<td>m²/gm</td>
<td>cm/hr</td>
<td>cm/hr</td>
</tr>
<tr>
<td>R 1</td>
<td>38.6</td>
<td>124.52</td>
<td>.245</td>
<td>.361</td>
</tr>
<tr>
<td>R 2</td>
<td>18.5</td>
<td>59.68</td>
<td>.690</td>
<td>.398</td>
</tr>
<tr>
<td>R 3</td>
<td>86.3</td>
<td>278.39</td>
<td>.0220</td>
<td>.00914</td>
</tr>
<tr>
<td>R 4</td>
<td>110.1</td>
<td>355.16</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>R 5</td>
<td>16.0</td>
<td>51.61</td>
<td>1.54</td>
<td>1.38</td>
</tr>
<tr>
<td>R 6</td>
<td>37.5</td>
<td>120.97</td>
<td>.0647</td>
<td>.00998</td>
</tr>
<tr>
<td>R 7</td>
<td>36.0</td>
<td>116.13</td>
<td>.177</td>
<td>.316</td>
</tr>
<tr>
<td>R 8</td>
<td>14.5</td>
<td>46.77</td>
<td>4.46</td>
<td>4.50</td>
</tr>
<tr>
<td>R 9</td>
<td>24.8</td>
<td>80.00</td>
<td>.224</td>
<td>.179</td>
</tr>
<tr>
<td>R 10</td>
<td>39.6</td>
<td>127.74</td>
<td>.00794</td>
<td>.00794</td>
</tr>
<tr>
<td>R 11</td>
<td>51.1</td>
<td>164.84</td>
<td>.020</td>
<td>.0122</td>
</tr>
<tr>
<td>R 12</td>
<td>35.5</td>
<td>114.52</td>
<td>.020</td>
<td>.0122</td>
</tr>
<tr>
<td>R 13</td>
<td>23.3</td>
<td>75.16</td>
<td>.061</td>
<td>.111</td>
</tr>
</tbody>
</table>

1/ The values given are the mean values of the results of the different tests on the several replicates of each soil.
Permeability determinations. The permeability measurements were determined by the method described in the procedure. The permeabilities of the replicates were quite consistent. The variation between samples was usually less than 15 percent of the mean at the selected time interval.

The interpretation of permeability data is often variable and uncertain. The variation of the percolation rate with time makes the selection of an "average" permeability very arbitrary. For purposes of this study where the author was most interested in relative permeabilities between soils, it seemed most advisable to select some point on the various curves that would be most representative for comparison between the soils tested.

The permeability curves for most agricultural soils usually follows a typical pattern. The percolation rate initially decreases to some minimum, then increases again to a maximum, usually somewhat above the initial rate, and then gradually decreases again with time to usually a very low rate. The permeability-time curves for the several soils are shown in figures 6, 7, and 8. From the work of Christiansen (14), Allison (1), Christiansen, Fireman, and Allison (15), Fireman (18), and others, this typical curve is explained. The initial reduction in permeability is attributed to the swelling of the colloids or dispersing in the case of saline soils (as the salts are removed). This increase in permeability during the second phase has been found to be due to the gradual elimination of air entrapped in the soil. The decrease in permeability during the third phase is considered due primarily to the sealing effect resulting from microbial activity.

For purposes of the study the permeability corresponding to the first maximum value was considered to be the most representative value.
Fig. 6. Permeability—Time Curves for the Soils Tested. (Curves are for mean values of each soil)
Fig. 7. Permeability—Time Curves for the Soils Tested. (Curves are for mean values of each soil)
**Fig. 3. Permeability—Time Curves for the Soils Tested.** (Curves are for mean values of each soil)
and was used for comparison purposes between the several soils.

**Moisture retention determinations.** The moisture retention characteristics values at various tensions over the plant growth range was determined. The values in the 0.1 to 1.0 determined by the use of the porous plate apparatus and the values in the 1 to 15 atmosphere range determined by the use of the pressure-membrane apparatus previously described.

The moisture retained at the various pressures is given in table 3. These data are shown graphically in figures 9a and 9b. The results in the case of several of the soils were variable with a considerable difference between the values near the 1 atmosphere tension obtained by the two methods. In an attempt to check the inconsistencies, the measurements were repeated at the 1/3 and the 1 atmosphere range in both the low and the high pressure equipment. The data obtained were more consistent and were considered to be more reliable.

The results of the several determinations were subjected to appropriate statistical analyses using methods outlined by Snedecor (43).

**Relation between the total surface and the permeability of the soils.**

The permeabilities of the several replicates of each soil tested were in general in good agreement. The variation between replicates was less than 15 percent of the mean except in two soils (R2 and R9) in which the variations were 24 and 31 percent of the mean. This variation was largely due to a single inconsistent sample. These mean data are given in table 2.

The relation between the permeabilities and the total surface area of the several soils is shown graphically in figure 10.

These data indicate that there is apparently a consistent relation between the permeability and surface area for the soils tested.

It was expected that this relationship would not be exact since it...
### Table 3. Moisture retained by the soils at various extraction pressures

#### Part A

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>0.13</th>
<th>0.31</th>
<th>0.63</th>
<th>0.79</th>
<th>0.99</th>
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<th>1.7</th>
<th>3.0</th>
<th>6.0</th>
<th>10.0</th>
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</tr>
<tr>
<td>R1</td>
<td>26.11</td>
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<td>R2</td>
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<td>R3</td>
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<td>42.2</td>
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<td>39.7</td>
<td>36.9</td>
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<td>45.0</td>
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<td>36.3</td>
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<td>7.2</td>
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<tr>
<td>R6</td>
<td>34.3</td>
<td>31.7</td>
<td>25.8</td>
<td>23.0</td>
<td>21.2</td>
<td>25.0</td>
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<tr>
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<td>25.0</td>
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#### Part B

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<tr>
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<td>27.6</td>
<td>25.8</td>
<td>26.1</td>
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</tbody>
</table>

Note: The table data represents moisture retention in percentage.
Table 3. continued

<table>
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<th>Part C³/</th>
<th></th>
<th>Pressure - Atmospheres</th>
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<td>%</td>
<td>%</td>
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<td>R7</td>
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<td>6.7</td>
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<td>5.6</td>
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</tbody>
</table>

1/ The extraction pressures varied between the several separate determinations.
2/ Moisture determined at pressures in the 0.1 to 1.0 atmosphere range shown in part B
3/ Moisture determinations were repeated on several of the soils (R1 to R8) as a check on previous work.
Fig. 9a. Soil moisture retention characteristics for soils
Fig. 9b. Soil moisture retention characteristics for soils
Fig 10. Relationship between the total surface area and the permeability of the soils tested.
is generally considered that the movement of water through soils is influenced more directly by structural factors than by textural or surface factors.

Relation between the total surface area and the percent moisture retained at the one-third and the fifteen atmosphere tensions

One-third atmosphere tension. The measurements for the percent moisture retained at the one-third atmosphere tension were replicated twice on all soils and three times on some of the samples. The values obtained on the limited replications were observed to be quite consistent. These values are given in table 3. The mean values used for the comparison and analysis are given in table 2.

The relationship between the total surface area and the percent moisture retained at the one-third atmosphere is shown in figure 11. The regression equation is:

\[ \hat{Y} = 0.103X + 15.83 \]

with \( r^2 = .697 \)

These data indicate a definite relation between the factors. The relatively high \( r^2 \) value indicates that for the soils tested, the moisture retained is interrelated to the surface area or other factors related to surface area.

This close relationship was hardly expected since moisture retained at the higher moisture levels has been considered to be more closely associated with structural characteristics than surface phenomena. However, it is known that heavier textured soils (i.e., high surface area soils) retain more water at a given tension than lighter soils. The observed relation is probably explained as well by textural differences in the soils as by the differences in total surface area.

Fifteen atmosphere tension. The moisture retention values over the
Fig. 11. Relation between the total surface area and the percent moisture retained at one-third atmosphere tension.

\[
\hat{Y}_2 = 0.103X + 15.83 \\
\hat{r}^2 = 0.697 = 69.7\%
\]
range of 1 to 15 atmosphere were obtained from two separate determinations (i.e., runs) for all soils with some soils replicated three times. In each replication duplicate samples were used for the 1 atmosphere and the 15 atmosphere tensions. There were some inconsistencies in the results obtained at the 1 atmosphere tension by the porous plate and the pressure-membrane apparatus. These inconsistencies were probably a result of the variation in the pressures at low values in the pressure-membrane system and from evaporation from the measuring burettes in the porous plate system.

The moisture retention values obtained at the 15 atmosphere tension were in general very consistent; usually duplicates checked within 0.5 percent. In one soil the replicates varied as much as 2 percent.

The relation between the moisture percent at the 15 atmosphere tension is shown in figure 12. The regression equation is: 
\[ \hat{Y} = 0.0850X + 4.62 \]
with \( r^2 = 78.1\% \)

These data indicate a definite relationship between surface area and the moisture retained in soils at the higher tensions.
Fig. 12. Relation between the total surface area and the percent moisture retained at the 15 atmosphere tension.

\[ Y_2 = 0.085X + 4.62 \]
\[ r^2 = 0.781 = 78.1\% \]
The general relation between the surface area and permeability of the samples tested is probably not a satisfactory appraisal of the differences in the soils. Since the primary object was to study the relationships between surface and permeability, a standard simple technique of preparing all of the samples was adopted. It was observed during the preparation that predominant size of the aggregate in the samples varied considerably. In some samples the 2 mm size were predominant, while in others the slight crushing treatments reduced the aggregate to a relatively fine size. It is known that the sieve size will significantly affect the result. Thus the variation in permeability may be largely due to the effect of pretreatment. The effect of the variation in aggregate size would be extremely difficult to evaluate. Then, too, while the refinement of technique on a basis of the size of the aggregates may more nearly evaluate structural differences, it would hardly be expected to be of value in appraising the effect of surface area. Thus it appeared that any further refinements as to sieve analysis would not be worth-while in the present study. From the results, it does not appear that there can be any useful application of total surface area to soil permeability over a wide range of textures. It was felt, however, that surface area measurements, particularly internal surface measurements, might be a useful index to permeability on soils containing a high percent of clay. This might be a basis for future study.

The results obtained would be expected in view of the generally
accepted condition that the permeability of soils is primarily a function of soil structure.

The relative good relationship between the total surface area and the moisture retained at the 15 atmosphere tension should probably be expected, since it is considered that the surface forces predominate in moisture retention at high tensions.

The relationship of the total surface area to the moisture retained at the one-third atmosphere may within wider limits be a useful method of characterizing the upper limit of the soil moisture range.

The limited data seems to indicate very definite trends in the relationship of surface area to the moisture retention by soils. However, it does not appear that any wide generalization should be attempted from these results.
CONCLUSIONS

From the limited data obtained from the experimental work, the following conclusions are suggested:

1. The ethylene glycol retention determination appears to be a useful and simple method of determining the surface area of soils.

2. The permeability or water conductivity does not appear to be closely related to the total surface area of the soils tested.

3. There apparently is some relation between the amount of moisture retained at the one-third atmosphere tension and the total surface area of the soils tested. This relationship is shown in the regression equation:

\[ \hat{Y} = 0.103X + 15.83 \]

with \( r^2 = 0.697 \)

4. There appears to be a definite relation between the amount of moisture retained at the fifteen atmosphere tension and the total surface area of the soils tested. This relationship is shown in the regression equation:

\[ \hat{Y} = 0.0850X + 4.62 \]

with \( r^2 = 0.781 \)
SUMMARY

The relationship of total surface area of soils to the saturated permeability (i.e., hydraulic conductivity) and the moisture retention characteristics was investigated. The simple laboratory procedures for determining the total surface area of soils by the ethylene glycol retention method for determining the permeability of disturbed soil samples and for determining soil moisture characteristic curves are described.

The total surface area, permeability, and moisture retention curve were determined on soils ranging in texture from sandy loam to clay. The interrelations of the total surface area to the saturated permeability and the moisture at the one-third and the fifteen atmosphere moisture tension were studied. These results indicate a definite relation between the total surface and the moisture retained at the one-third and fifteen atmosphere tensions. There appears to be no simple useful relation between the surface area and the movement of water in the saturated soils.
LITERATURE CITED


(44) Taylor, S. A. Physical conditions of water in the soil. Interdepartmental Faculty Seminar, Utah State Agricultural College. 1952.

(h6) Thomas, W. A. Aqueous vapor pressure of soils. Soil Sci. 11: 589-590. 1921.


