

METHODS FOR DETERMINING SOIL MOISTURE RETENTION

by

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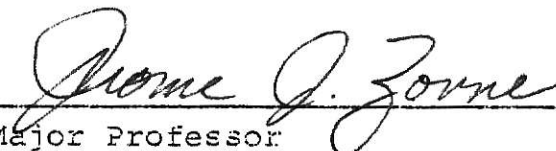
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INTRODUCTION

The phenomenon of water being "retained" by a soil against various external forces is one of the primary functions of soil which is responsible for sustaining life. The amount of water retained by soil, or soil moisture retention, is directly dependent upon the particular soil under study.

Soil by itself refers to the weathered and fragmented outer layer of the earth's crust existing in a heterogenous, polyphasic, particulate, dispersed and porous system. The three phases of soil are: the soil phase, consisting of soil particles; the liquid phase, consisting of soil water which contains dissolved substances; and the gaseous phase, consisting of soil air.

Thus, soil can be seen as an exceedingly complex system. Its solid matrix consists of particles differing in chemical and mineralogical composition, as well as in size, shape, and orientation. The arrangement or organization of these particles determines the characteristics of the pore spaces in which water and air are transmitted or retained.

This retained water or soil water contains energy in different quantities and forms. The two principal forms, kinetic and potential, are the basis for the methodology of soil water retention measurement. Since the movement of water is quite slow, kinetic energy is considered to be negligible. Potential energy, however, is important in determining the state and movement of the retained water in soils.

In observing the facts relating to the equilibrium of soil water, it is found that if an external body of water is placed in contact with soil in some way, an exchange will take place in one direction or the other according to the forces imposed on the external water. It also follows that this external force may be adjusted until the flow ceases. The external water is then in equilibrium with the soil water, and the measure of the force on the external water is said to be equal to the soil water potential. The problem of measuring soil moisture retention is essentially the problem of maintaining an external force in contact with the soil water until static equilibrium is reached.

The actual determination of the amount of soil water present or retained under a given set of circumstances contains two main problems. The first is that of devising a method or methods of measuring the external force applied to the soil water and obtaining the relationship between this and the actual soil water content. The second is the interpretation of the resultant curves.

This report is concerned only with the measurement of the amount of soil moisture retained using a pressure plate apparatus. The purpose of the report is to outline a method of determining soil moisture retention using the equipment as supplied by the Soilmoisture Equipment Corporation, Santa Barbara, California*.

*Soilmoisture Equipment Corporation, P.O. Box 30025, Santa Barbara, California 93105

This report can be divided into two main sections: procedures to determine the soil moisture retention, and a brief discussion concerning the moisture retention characteristics of soils.

The first main section gives the procedures for determining soil moisture retention values for a specific pressure setting for pressure ranges of 0 to 2 atmospheres and 1 to 15 atmospheres (Soil moisture retention curves may be developed using a range of specific pressure settings for the particular pressure range the apparatus will handle).

The second main section contains a brief discussion concerning moisture retention. The three areas discussed within this section are the different categories of soil water, soil water potentials, and the determination of the soil water moisture.

MATERIALS AND METHODS

Two methods of determining soil moisture retention are given in this section: one for pressure ranges of 0 to 2 atmospheres and the other for pressure ranges of 1 to 15 atmospheres. These methods were to allow the use of the equipment as supplied by the Soilmoisture Equipment Corporation, Santa Barbara, California. The methods were compiled using several existing methods adopted to give the best accuracy using the existing equipment (2, 3, 28, 41, 42, 44).

A. TWO (2) BAR PLATE EXTRACTOR

I. SCOPE

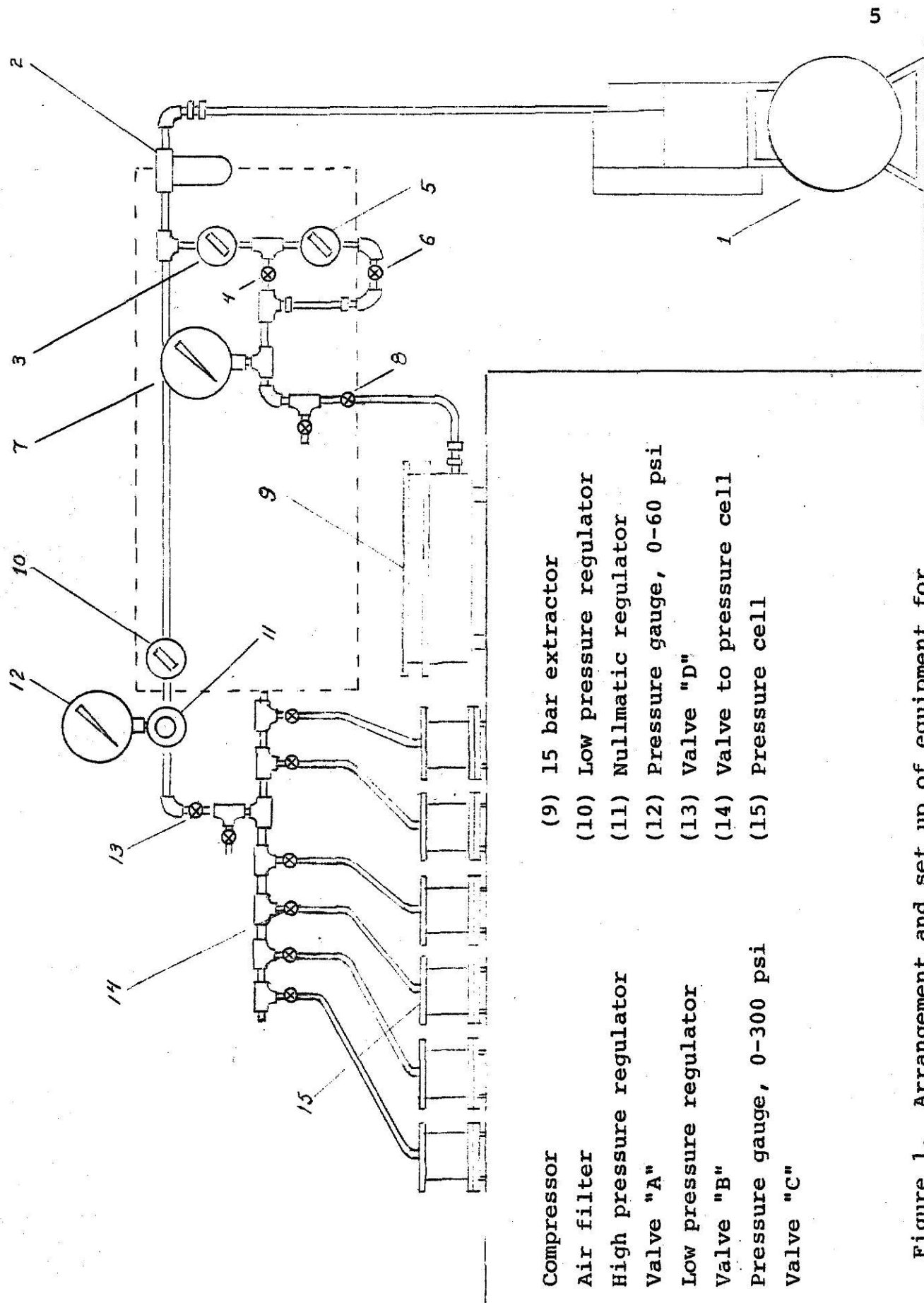
This method covers the determination of moisture retention properties of soils as determined by the pressure membrane apparatus using tension between 0 and 2 atmospheres.

II. APPARATUS (See Figure 1)

1. Pressure Source - high pressure compressor.
2. Pressure Manifold - consists of air filter, pressure regulator, valves and a 0 - 60 psi test gauge.
3. Pressure Membrane Cells - 2 bar ceramic pressure plate cells as supplied by Soilmoisture Equipment Corporation.
4. Spatula - or similar device for removing samples from pressure cell.
5. Balance - with the capacity of at least 200 g and sensitive to 0.01g.

**THIS BOOK
CONTAINS
NUMEROUS PAGES
WITH DIAGRAMS
THAT ARE CROOKED
COMPARED TO THE
REST OF THE
INFORMATION ON
THE PAGE.**

**THIS IS AS
RECEIVED FROM
CUSTOMER.**



- | | |
|-------------------------------|-------------------------------|
| (1) Compressor | (9) 15 bar extractor |
| (2) Air filter | (10) Low pressure regulator |
| (3) High pressure regulator | (11) Nullmatic regulator |
| (4) Valve "A" | (12) Pressure gauge, 0-60 psi |
| (5) Low pressure regulator | (13) Valve "D" |
| (6) Valve "B" | (14) Valve to pressure cell |
| (7) Pressure gauge, 0-300 psi | (15) Pressure cell |
| (8) Valve "C" | |

Figure 1. Arrangement and set up of equipment for determining soil moisture retention values

6. Moisture Sample Containers - made of material resistant to corrosion, and not subject to change in weight or disintegration with repeated heating and cooling. Containers must have close-fitting lids to prevent loss of moisture from samples before initial weighing and to prevent absorption of moisture from the atmosphere between drying and final weighing. One container is needed for each moisture content determination.

7. Drying Oven - thermostatically controlled, capable of maintaining a temperature of 105°C.

8. Desiccator - of suitable size to hold samples for cooling after removal from the drying oven.

III. SAMPLES

Take an undisturbed core sample at least 3 in (76.2 mm) in diameter and 3 in (76.2 mm) in height. Core is to be inserted undisturbed in a 3 in (76.2 mm) I.D. schedule 20 plastic pipe or similar material, resistant to corrosion, and not subject to change in weight or disintegration with repeated heating and cooling.

IV. PROCEDURE

1. Place sample on base plate of pressure cell. Place cell wall on base plate. Draw cell wall and base together using a retaining bar and two bolts.

2. Thoroughly saturate the sample by gradually adding distilled water to the open cell increasing the depth of water slowly until the water just covers the top of core. Maintain this water depth for at least 24 hours.

3. Remove excess water from the pressure cell with a pipet or rubber syringe. Remove retaining bar and replace it with the cell cover. Tighten bolts snugly.

4. Connect the outflow tube from the pressure cell to the tip of a burette with a piece of small diameter tubing.

5. Close all valves. Turn on the air compressor.

6. For extractions 1 to 30 psi, open valve "D" and the valve for each pressure cell being run. Open the pressure regulator slowly admitting pressure to the pressure cell and set at the desired extraction pressure as read on the test gauge.

7. Remove the sample any time after the outflow burettes indicate flow has stopped and equilibrium has been attained.

8. Close off (pinch off) or remove the outflow tube assemblies. Close the pressure regulator slowly allowing the pressure in the pressure cells to come into equilibrium with the existing atmospheric pressure.

9. Remove the cell top and wall. Remove sample with a spatula, transferring the sample immediately to sample container and weigh on a balance. Record this weight of wet sample, retaining column and container.

10. Dry the sample, still in the retaining column and container, to a constant weight in an oven at 105°C. Desiccate sample until cool. Weigh and record the weight of the oven-dried sample, retaining column and container.

11. Remove the sample. Weigh and record the weight of the retaining column and container.

V. CALCULATIONS

1. Calculate the moisture content of the soil as follows:

$$w = [(W_{s_w cr} - W_{s_d cr}) / (W_{s_d cr} - W_{cr})] \times 100$$

$$w = (W_w / W_s) \times 100$$

where

w = moisture content, percent by weight,
 $W_{s_w cr}$ = weight of wet sample (from pressure cell),
 retainer column, and container, g.
 $W_{s_d cr}$ = weight of dry sample (after drying), re-
 tainer column, and containers, g.
 W_{cr} = weight of retainer column and containers, g.
 W_w = weight of water ($W_{s_w cr} - W_{s_d cr}$), g.
 W_s = weight of dry sample (after drying),
 ($W_{s_d cr} - W_{cr}$), g.

B. FIFTEEN (15) BAR CERAMIC PLATE EXTRACTOR

I. SCOPE

This method covers the determination of moisture retention properties of soils as determined by the pressure membrane apparatus using tensions between 1 and 15 atmospheres.

II. APPARATUS (See Figure 1)

1. Pressure Source - high pressure compressor.
2. Pressure Manifold - consists of air filter, two pressure regulators, valves and a 0 - 300 psi test gauge.

3. Pressure Membrane Chamber - 15 bar ceramic plate extractor as supplied by the Soilmoisture Equipment Corporation.

4. Ceramic Pressure Plate - as supplied by the Soilmoisture Equipment Corporation.

5. Sample Retainer Rings - flexible rubber rings capable of holding approximately 25g of disturbed sample.

6. Saturation Trays - waterproof trays large enough and deep enough to hold the circular ceramic pressure plate with samples while being saturated.

7. Spatula - or similar device for removing samples from ceramic pressure plate.

8. Balance - with the capacity of at least 200g and the sensitive to 0.01g.

9. Moisture Sample Containers - of 60 to 90 ml capacity, made of material resistant to corrosion, and not subject to change in weight or disintegration on repeated heating and cooling. Containers must have close-fitting lids to prevent loss of moisture from samples before initial weighing and to prevent absorption of moisture from the atmosphere following drying and before final weighing. One container is needed for each moisture content determination.

10. Desiccator - of suitable size to hold samples and moisture sample containers for cooling after removal from drying oven.

11. Drying Oven - thermostatically controlled, capable of maintaining a temperature of 105°C.

III. SAMPLES

Take a sample weighing approximately 25 g from the thoroughly mixed portion of air-dried soil that has been passed through a No. 10 (2 mm) sieve. Pour the sample into a retainer ring, leveling the surface.

IV. PROCEDURE

1. Place duplicate samples on the ceramic plate. Record the sample numbers.

2. Thoroughly saturate the sample by placing the ceramic plate containing the sample into the saturation tray. Gradually add distilled water to the saturation tray increasing the depth of water over a minimum period of four hours until the water is at the top edge of the sample. Maintain this water depth for at least 24 hours.

3. Remove the excess water from the saturation tray with a pipet or rubber syringe.

4. Remove the ceramic pressure plate from the saturation tray, mount it into the plate extractor and connect the out-flow tubes. Be sure the triangular support is in the bottom of the vessel. If more than one pressure plate is used, use the plastic spacers to separate the pressure plates. Carefully center the chamber top with the O-ring gasket in place and screw down the clamping bolts.

NOTE: Secure the two bolts, one on each side of the lid hinge first, then secure the bolts next to bolts just secured. Go back to ensure the first bolts are tight, then check the second bolts. Proceed to the third set of bolts and so forth,

working towards the front of the extractor until all bolts are secure. When opening the extractor, this procedure is reversed.

5. Connect the outflow tube from the extractor to the tip of a burette with a piece of small diameter tubing.

6. Close all valves. Turn on the air compressor.

7. Set the pressure regulators, admitting pressure to the extraction chamber:

a. For low extraction pressures in the range of 0 to 125 psi, valve "A" is closed and valve "B" is opened. The air flow is through the high pressure regulator to the low pressure regulator. The low pressure regulator is fully opened and the high pressure regulator is set so that the test gauge reads about 5 psi higher than the desired extraction pressure. The low pressure regulator is closed. Valve "C" is opened. The low pressure regulator is again opened slowly, admitting pressure to the extractor and set at the desired extraction pressure as read on the test gauge.

b. For high extraction pressures in the range of 125 psi to 225 psi, valve "A" is open and valve "B" is closed. The high pressure regulator is closed. Valve "C" is opened. The high pressure regulator is opened slowly, admitting pressure to the extractor and set at the desired extraction pressure as read on the test gauge.

8. Remove the sample anytime after the outflow burettes indicate flow has stopped and equilibrium attained.

9. Close off (pinch off) or remove the outflow tube assemblies. Close the pressure regulator slowly, allowing the

pressure in the extraction chamber to come into equilibrium with the existing atmospheric pressure. (For low pressure extractions, close the low pressure regulator. For high pressure extractions, close the high pressure regulator.)

10. Remove the ceramic pressure plate. Using a spatula, transfer the samples immediately to sample containers and weigh on a balance. Record this weight of wet sample, retainer ring, and container.

11. Dry the sample still in the retaining ring and container to constant weight in an oven at 105°C. Desiccate sample until cool. Weigh and record the weight of the oven-dried sample, retainer ring, and container.

12. Weigh and record the weight of the container and retainer ring.

V. CALCULATIONS

1. Calculate the moisture content of the soil as follows:

$$w = [(W_{s_w cr} - W_{s_d cr}) / (W_{s_d cr} - W_{cr})] \times 100$$

$$w = (W_w / W_s) \times 100$$

where:

w = moisture content, percent by weight,

$W_{s_w cr}$ = weight of wet sample (from extractor),
containers, and retainer ring, g.

$W_{s_d cr}$ = weight of dry sample (after drying), con-
tainer and retainer ring, g.

W_{cr} = weight of container and retainer ring, g.

W_w = weight of water ($W_{s_w cr} - W_{s_d cr}$), g.

W_s = weight of dry sample (after drying),
($W_{s_d cr} - W_{cr}$), g.

DISCUSSION

The Materials and Methods section described two methods for determining soil moisture retention. One is for the pressure range of 1 to 2 atmospheres and the other for the pressure range of 1 to 15 atmospheres. The principle (41) behind the methods is that as the pressure is raised above atmospheric, forcing excess water from the soil through the microscopic pores in the ceramic pressure plate. This high pressure air will not flow through the pressure plate pore since they are filled with water and the surface tension of the gas-liquid interface at each of the pores will support the pressure. At any given air pressure in the pressure cell or extractor, soil moisture will flow around each of the soil particles and out through the ceramic plate until the effective curvature of the water films throughout the soil are the same as at the pores in the ceramic plate. At this time, an equilibrium is reached and the flow of moisture ceases.

There is a problem with these methods of determination. To show this, a brief discussion of the moisture retention properties is given followed by experimental results as determined by several researchers.

A. CATEGORIES OF SOIL WATER

The liquid phase of soil -- soil water, or more precisely soil solution -- maintains a state of complex physical interrelationships with the solid and gaseous phases of the soil.

The degree of availability of soil water and the form of its movement in the soil are determined by these interrelationships. Water existing in soil in one of the three phases, solid, liquid, and gaseous, may be classified into the following categories (45) according to its relationship with soil: structural water, vapor-form water, absorbed water and free water. This classification has no regard to the three phases of water, but is concerned with the relationship of water retained by the soil.

1. Structural water may be looked at as water that is chemically combined in the crystalline structure of the soil, which can be removed only by breaking the structure.

2. Vapor-form water (water vapor) is water that moves by diffusion in the soil pores not filled with liquid water and is under the influence of air movement.

3. Absorbed water is water that is chiefly under the influence of differential forces of attraction or repulsion occurring among molecules of different phases of contact at their contact surfaces.

4. Free (liquid) water is water that moves and is retained in the soil chiefly under the influence of gravitational and matrix (capillary) forces, depending upon the quantity of water in the soil pores.

To more accurately evaluate the methods given in Materials and Methods, it is necessary to look at these categories of soil water in greater detail. Structural water, however, will be deleted because it is chemically combined in the crystalline

structure of the soil itself and is regarded as an integral part of the soil particle.

Water in the vapor state is present in all soil pores that are free of liquid water. It forms readily through the evaporation of all other forms of soil water (except structural) and moves by diffusion from high water vapor pressure to lower vapor pressure (45).

Absorbed water (15) results from the differential forces of attraction or repulsion occurring among molecules of different phases at their contact surfaces. As a result of these cohesive and adhesive forces, the contact zone may exhibit a concentration or a material density different from that inside the phases themselves. According to the different phases which may come into contact, various types of absorption can occur, such as the absorption of gases upon solids, of gases upon liquid surfaces, and of liquids upon solids.

The interfacial forces of attraction or repulsion may themselves be of different types (15, 45), including electrostatic or ionic (Coulomb) forces, intermolecular forces known as van der Waals' and London forces, and short range repulsive (Born) forces. The absorption of water onto solid surfaces is generally of an electrostatic nature.

The amount of moisture which a soil can absorb from the air depends first on the relative humidity of the air and second on the properties of the soil sample (30). Initially, as the relative humidity increases from zero to approximately 10 percent, the amount of moisture absorbed by the soil

increases rapidly. From 10 percent to 80 percent, the amount of moisture absorbed by the soil increases relatively slowly. Finally, when the relative humidity increases from 80 percent approaching 100 percent, the amount of moisture absorbed by the soil begins to increase rapidly. This is shown in Figure 2.

The properties of a soil also affect the amount of moisture which a soil can absorb from the air. The most fundamental influencing property is the soil's mechanical composition, smaller the soil's particle sizes are, higher the hygroscopicity. (Hygroscopicity is defined as readily absorbing moisture, as from the atmosphere.) This influence of the size of soil particles upon the absorption of moisture in the vapor phase at different relative humidities is shown in Figure 3. The curves show that at the same relative humidity the finer gradations absorb more moisture than courser gradations.

Hygroscopicity of a soil is mainly dependent upon the soil's clay content (12, 15, 19, 23, 32). This is due to the small particle size and its charge. Also, as the humus content increases (43) and the presence of certain salts (30, 43), especially calcium chloride and magnesium chloride, considerably increase the hygroscopicity of a soil.

When a completely dry soil comes into contact with moist air, the free force fields associated with the surface layer of the soil particles come into action. The dipolar water molecules are attracted by the free bonds, thus becoming

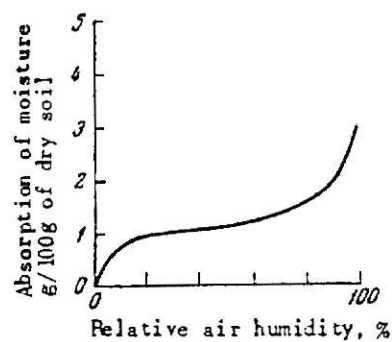


Figure 2. The dependence of the amount of moisture in the vapor state, which is absorbed by a soil, on the relative humidity of the air [From Rode (30)].

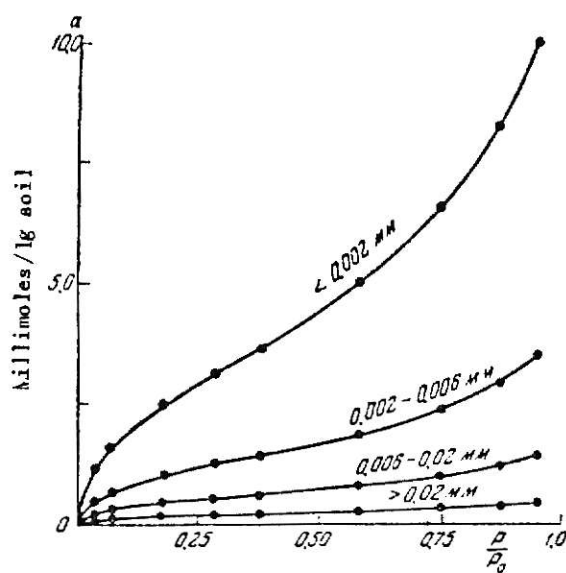


Figure 3. The influence of the size of soil particles upon the absorption of moisture in the vapor-phase at different relative humidities of the air [From Rode (30)].

attached to the surface of the soil particles. The binding forces that emerge from the surface of the soil particles act only at very short distances. Thus, only a limited number of water molecules can be directly attached forming a shell two or three molecules thick around each particle. This shell can be formed even at a very low relative humidity (only a few percent). Therefore, these free bonding forces become saturated very quickly.

The interaction of the charges of the solid with the polar water molecules may impart to the absorbed water a distinct and rigid structure in which the water dipoles assume an orientation dictated by the charge sites on the solids. After a water molecule has been absorbed by a soil particle, the remaining charge pole serves as a point of attachment for additional dipolar water molecules, eventually forming a hydration shell around a cation as shown in Figure 4. In this fashion, a multi-layered shell of water molecules is formed with its thickness increasing as the relative humidity increases. The number of molecular layers may reach several tens.

As was stated before, the growth of the shell of hygroscopic water is strictly parallel to the increase of the relative humidity. However, as the humidity approaches conditions of saturation, the process of water vapor absorption becomes complicated by capillary condensation. Here vapor pressure depends not only on temperature but also on the shape of the water surface.

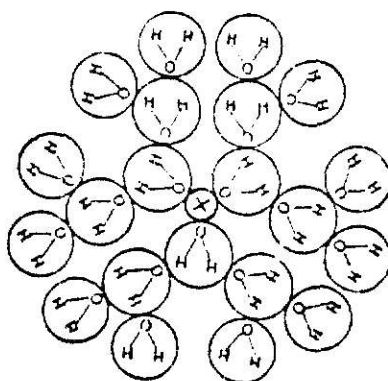


Figure 4. Structure of the hydrate shell formed around a free metal cation [From Rode (30)].

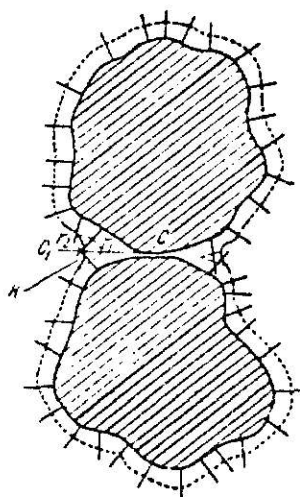


Figure 5. Formation of a convex-concave meniscus at the point of contact of two soil particles, resulting from the coalescences of the envelopes of adsorbed water [From Rode (30)].

Capillary condensation occurs when the hygroscopic shells of two soil particles coalesce, forming a water collar having a negative curvature. When soil is exposed to water vapor saturated with respect to a flat surface, water vapor will distill onto the concave surfaces of the water collar (Figure 5). As a result of this process, the amount of hygroscopically absorbed moisture will increase. The superimposition of this phenomenon offers an explanation to the upward bend of the right part of the moisture absorption curves which are shown in Figures 2 and 3.

One aspect that has not been mentioned is the fact that when liquid water is being bound, a certain amount of heat will be liberated (45). When the water molecules are bound by the soil, they pass into a state where they are immobile and must give up their kinetic energy, which is liberated as the heat of adsorption. Simultaneously, the surface energy associated with the soil particles decreases. The water whose binding liberates heat is known as firmly bound water (30).

Bound water is dependent upon the concentration of a solution. Using a sugar solution, Figure 6 shows this dependence. It can be seen that at small concentrations of the sugar solution, the soil binds a considerable amount of water. However, as the concentration of the solution increases, the amount of bound water decreases, rapidly at first then very slowly afterwards.

It follows from this, that water bound by soil falls into two categories. First, the firmly bound water which cannot

be detached from the soil particles even by a solution of very high concentration, and second, the water that can easily be detached by solutions of low concentrations, apparently held by weaker forces. The second category of water is termed loosely bound water (30).

Movement of the tightly bound (and probably a small percentage of the loosely bound) moisture in the soil is only possible in the vapor state (30). If a certain soil layer has a higher moisture content than that of a neighboring layer, and if the moisture of both layers does not exceed the maximum hygroscopicity, the absolute pressure of the vapor (the concentration of water molecules in the soil air) in the first layer will be higher than that of the second. Consequently, the water vapor will diffuse from the first layer into the second, continuing as long as there is a gradient in the moisture content which maintains a gradient in the water vapor pressure.

The loosely bound moisture may also move in the soil in liquid form (30). As moisture forms a film around the soil particles, the inner layers are retained more strongly than the outer ones. In Figure 7, it is assumed that for two equi-sized soil particles the film of loosely bound water on particle B is slightly thinner than on particle A. The water molecule C is located closer to the center of soil particle B than to the center of particle A. Therefore, molecule C will start moving towards particle B. This process

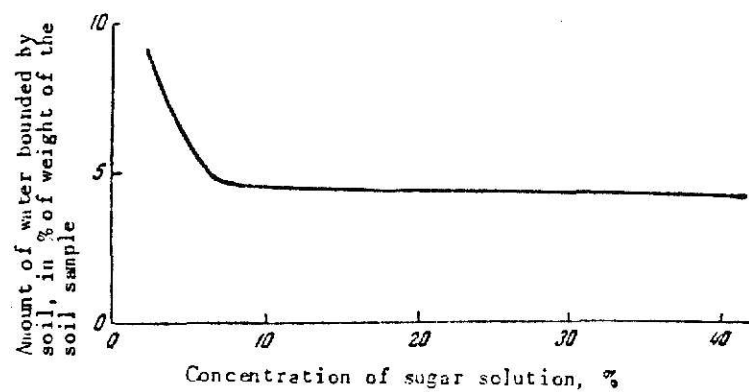


Figure 6. Influence of solution concentration on the amount of water bound by soil [From Rode (30)].

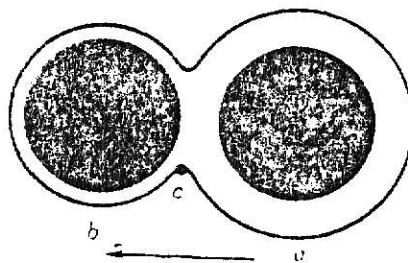


Figure 7. The movement of film moisture from one particle to the other [From Rode (30)].

will continue until the thicknesses of the water membranes become equal. Rode (30) pointed out that the essential item in this process is the fact that bound moisture does not move as a mass but from particle to particle and that bound moisture does not transmit hydraulic pressure.

The water in the soil not under the influence of absorption is called free water. The behavior of free water is determined almost exclusively by a combination of capillary and gravitation forces.

Capillary water is the free (non-bound) water which moves in the fine pores of the soil by means of the capillary (meniscal) forces caused by surface tension and moisture (45).

Gravitational water, in contrast to capillary water, is water that freely percolates downwards through the soil under the influence of the force of gravity.

Depending upon the amount of free water and on the filtration properties of the soil, water may fill all or part of the soil pores. If the pores are not totally filled, trapped air may remain in the form of separate isolated bubbles.

A situation that has not been discussed is that of suspended moisture (30). Basically, suspended moisture is water not hydraulically connected. However, the mechanism of retention differs depending on the mechanical and aggregate structure of the soil and its composition. There are four cases to be reviewed.

The first case is when the soil is uniform in its

mechanical composition (not stratified). (Sandy soils as well as soils having a coarser mechanical composition may usually be looked upon as structureless.) The suspended water is retained as bound moisture in the form of biconcave lenses forming at the point of contact between soil particles. The moisture is retained because the water lacks hydraulic connection. This does not rule out the existence of a film of bound water. The contact accumulations are retained by capillary forces. If the areas of moisture were in contact with one another, all the moisture would easily flow downwards. The situation is shown in Figure 8.

A second case of suspended moisture is that retained in soil of a heavy clayey mechanical composition. In this case, the voids in the soil pores are so small they are entirely filled by bound water. All the suspended water is completely or almost completely bound water and is retained entirely by absorption forces. Figure 9 represents this case.

The third case exists in soils of loamy mechanical composition having a well developed micro-structure. In such soils, the internal spaces in the regions of enlarged pores are so large that they cannot be completely filled by the suspended water. However, the narrow passages between the pores are entirely filled by suspended water. Inside the pores, a micro-accumulation of free moisture forms and is surrounded on all sides by films of bound water. Even though part of the water is free, the suspended water as a whole is retained. Figure 10 represents this case.

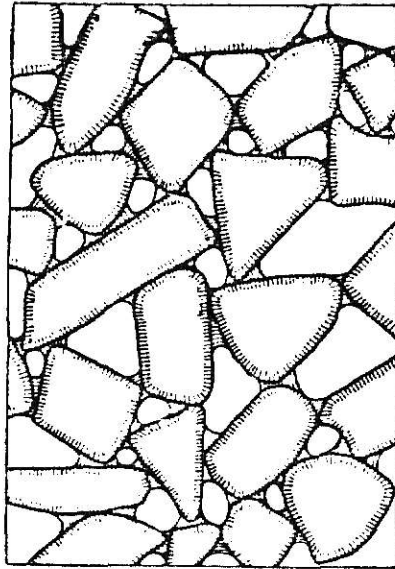


Figure 8. Jointed moisture in a soil with a sandy mechanical composition [From Rode (30)].

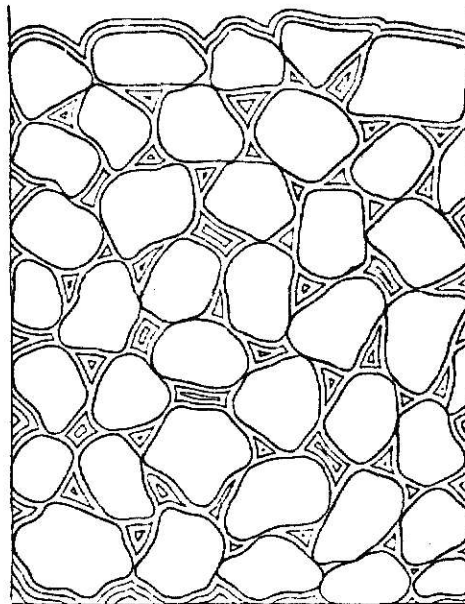


Figure 9. Suspended moisture in soils and grounds of a heavy mechanical composition [From Rode (30)].

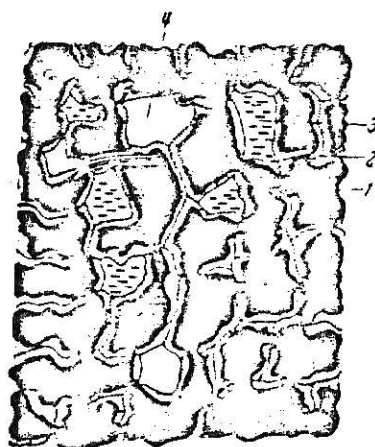


Figure 10. Suspended moisture in soils and grounds of medium mechanical composition.

- (1) Soil particles or micro-aggregates;
- (2) Membranes of bound water on the surface of the particles;
- (3) Micro-accumulations of absorbed closed free moisture;
- (4) Empty pores [From Rode (30)].

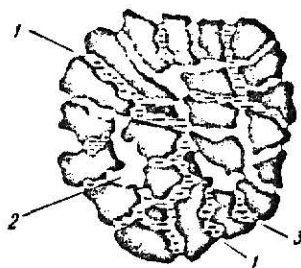


Figure 11. Soil aggregate with a capillarily suspended moisture inside the aggregates.

- (1) Memisci terminating the filaments of the suspended capillary moisture;
- (2) Pores filled with air;
- (3) Filaments of capillarily suspended moisture [From Rode (30)].

The fourth case is characteristic of soils with a well-expressed lumpy structure. The space between the structural lumps (the pores between the aggregates) are so large that water is not retained in them, but percolates downwards. If water is retained, it is retained only in small amounts in the form of contact accumulations at the points of contact between the aggregates. The aggregates themselves are usually traversed by thin capillaries. The water penetrating into these capillaries takes the form of winding branching filaments, each terminating with a concave meniscus. It is noted that the area of the contact surface between aggregates is very small and consequently, the capillary systems of the different aggregates are almost isolated. Figure 11 schematically depicts this case.

B. SOIL WATER POTENTIALS

The problem is to determine the amount of water retained by the soil under a given condition. When pore pressure in the liquid phase is positive (e.g., in soil below a water table), any gaseous phase present in the soil can exist only as trapped gas at a pressure higher than the ambient air pressure on the soil. This gas will tend to diffuse out of the system allowing the soil to reach a fully saturated condition where all (or nearly all) the pore spaces are completely filled with water. At the opposite end, when the pore pressure becomes negative, the air-water interface tends to become

concave and recedes into soil pores where large pores may empty and air bubbles may not only form, but also grow in size.

The problem of understanding the mechanisms where pore water pressures become negative is currently being treated thermodynamically (22). When an unsaturated soil comes in contact with a pool of free water, it absorbs water; the soil exerts a suction (Figure 12). Soil suction can be determined by the more flexible thermodynamic variable of potential, or in this particular case, soil water potential. According to the definition quoted by the International Society of Soil Science (22):

"Soil water potential (ψ) is the work done per unit quantity of pure water in order to transport reversibly and isothermally an infinitesimal quantity of water from a pool of pure water at a specified elevation and at atmospheric pressure to the soil water (at the point under consideration)."

As shown in Figure 12, the pool of pure water has its potential lowered from that of the soil water. The concept of an equivalent soil suction which would produce the same lowering of the soil water potential as occurs in the soil now has a thermodynamic definition.

While the mechanisms of soil water retention, as seen earlier, do not form useful components of the soil water potential, it is convenient to subdivide soil water potential into components on the basis of the forces responsible for

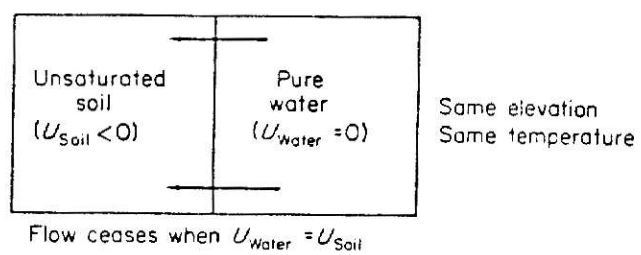


Figure 12. Diagrammatic representation for soil suction [From Lee (22)].

the energy differences between the water in question and that of the reference state. As stated before, these components are not necessarily related to the actual mechanisms.

1. Matrix potential (ψ_m). This results from the interaction of water with the adsorptive force fields emanating from solid surfaces. The equivalent soil suction component in the matrix suction (h_m).

2. Osmotic or solute potential (ψ_o). This results from the interaction of water with force fields emanating from dissolved substances. The equivalent soil suction component is the solute suction (h_s).

3. Pressure potential (ψ_p). This results from the difference in energy of the water caused by an external pressure other than that applied to the reference water.

4. Gravitational potential (ψ_z). This results from the potential energy water has due to its position in the gravitational field relative to that of the reference water. There is no equivalent gravitational soil suction component.

Potentials may be expressed physically in at least three ways: energy per unit mass, energy per unit volume, or energy per unit weight (hydraulic head). The common practice (15) is to characterize the state of soil water in terms of the "total potential head" expressed as a hydraulic head.

In attempting to express the negative pressure potential of soil water in terms of an equivalent hydraulic head, this head may be as much as 10,000 or even 100,000 cm of water. To avoid this, the "pF" scale, which is defined as the common

logarithm of the negative pressure (tension or suction) head in centimeters of water, is used. A pF of 1 is a tension head of 10 cm of water. A pF of 3 is a tension head of 1000 cm of water, etc.

C. DETERMINATION OF SOIL MOISTURE--SOIL WATER POTENTIAL RELATIONSHIPS

In a saturated soil at equilibrium with free water at the same elevation, the actual pressure is atmospheric and hence, the hydrostatic pressure and the suction (or tension) are zero. If a slight suction, i.e., a water pressure slightly below atmospheric, is applied to water in a saturated soil, no outflow may occur until (as suction is increased) a certain critical value is exceeded at which the largest pore of entry begins to empty. As suction is further increased, more water is drawn out of the soil and more of the relatively large pores, which cannot retain water against the suction applied, will empty out. This will continue with progressively smaller pores until at high suction values, only the very narrow pores retain water. Similarly, an increase in soil water suction is associated with a decreasing thickness of the hydration envelopes covering the soil particle surface.

Because it is commonly arranged that air in contact with the soil is at atmospheric pressure and the water is at less than atmospheric pressure, the term soil water suction is

used. However, it is a simple matter to seal the soil in a chamber and to raise the air pressure within, leaving the soil water to drain through the porous platform and to escape freely at atmospheric pressure. As defined by Childs (10), soil water will be in equilibrium with a moisture content appropriate to the pressure difference between it and the air external to it, whether the external air is at atmospheric pressure and the water under suction, or whether the water is at atmospheric pressure and the external air pressure is artificially raised above atmospheric pressure.

This latter arrangement has been called the pressure plate apparatus (10, 35) or pressure-membrane apparatus (34). The main advantage is that its use may be readily extended to soil water suctions much in excess of one atmosphere, because the water drains freely at atmospheric pressure and does not require the maintenance of contact between the underside of the porous platform and a hanging column of water under tension.

The common belief (15) is that soil moisture retention in the low-suction range (0 - 1 bar) is strongly influenced by soil structure and pore size distribution. Hence, measurements made with disturbed samples (e.g., dried, screened and artificially packed samples) cannot be expected to represent field conditions. The use of undisturbed soil cores is therefore necessary. Soil moisture retention in the high suction range is due primarily to adsorption and thus is correlated with its structure (15).

According to Richards (34), the amount of moisture retained in soil which has come to equilibrium with the membrane in the pressure-membrane apparatus depends on the gas pressure in the chamber. The higher the pressure, the more moisture is removed. He continues by stating that replicate determinations will agree within 0.1 percent of moisture if the subsampling process does not introduce differences in mechanical composition between replicates.

When Richards and Fireman (35) compared the data obtained with the pressure plate apparatus against data obtained with the suction-plate apparatus, they determined that for a pressure of one-third atmosphere the values were in agreement with each other. They also said that various writers have also shown this. For moisture retention determinations such as moisture equivalent and wilting percentage made on an air-dried screened sample, the results closely relate to the behavior of the soil in the field. They also claimed that despite the many objections to air-drying and screening, this treatment does reduce the sample to a standard reproducible state that can be attained economically when large number of samples are handled. Table 1 lists Richards and Fireman's moisture retention data obtained on six replicate samples of air dried and screened soil. They show agreement is obtainable when subsamples are carefully taken.

Richards and Fireman continue by showing curves comparing moisture retention values obtained on disturbed and undisturbed samples of Fallbrook loam (Figure 13). The two

Table 1. Comparison of one-third atmosphere percentage values obtained with pressure-plate and suction-plate apparatus [From Richards and Fireman (35)].

Soil Sample Number	Pressure-Plate Data	Suction-Plate Data
A1	9.16	9.16
A2	9.10	9.02
A3	<u>9.10</u>	<u>9.11</u>
Average for A	9.12	9.10
B1	40.49	40.70
B2	41.57	40.58
B3	<u>40.32</u>	<u>41.46</u>
Average for B	40.79	40.91

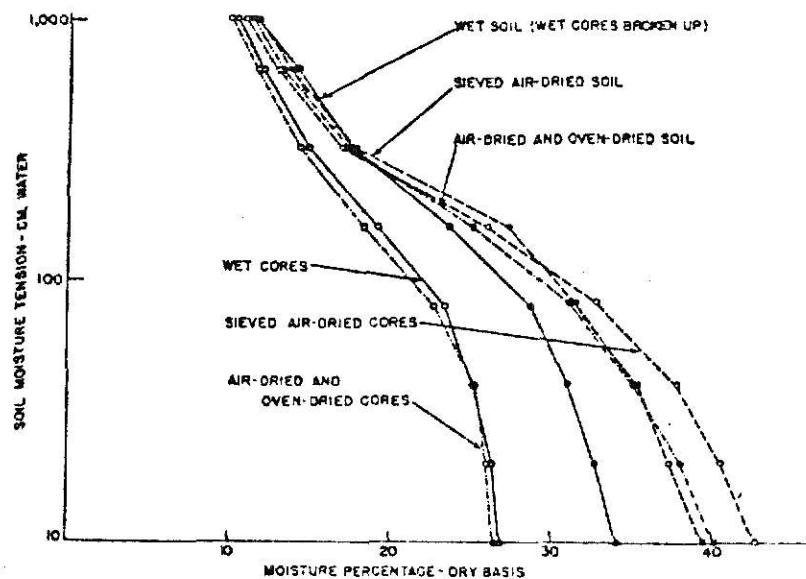


Figure 13. Comparison of moisture-retention curves for Fallbrook loam having disturbed and undisturbed field structure [From Richards and Fireman (35)].

left-hand curves in this figure indicate that neither air nor oven drying of the cores significantly changed the moisture retention as compared with unaltered wet cores. Thus, drying alone did not appreciably change the pore-space relations concerned with moisture retention. These four curves at the right show the effect of other treatments as follows: wet cores broken up by hand, dried soil broken by hand, dried cores broken up and sieved, and dried soil sieved.

As can be seen from Richards and Fireman's curves, any manipulation of the soil in either the wet or the dry state, such as breaking up the cores or sieving the soil, significantly increased the moisture retention throughout the 1-atmosphere tension range. The wet cores that were lightly broken up by hand, and therefore were the least disturbed, were intermediate between the undisturbed cores and the sieved cores in the lower tension range. In the higher tension range they all held approximately the same amount of water.

In a study conducted by Salter and Haworth (36) to determine the upper limit of available water, they concluded that in determining field capacity the suction plate method using undisturbed cores of soils gave satisfactory results where only a rough estimate of soil moisture content was required. For more critical work, the use of the direct sampling method was essential. (The direct method was determining the moisture content of a sample by drying to constant weight at 105°C.

Another study, on the upper limit of available water, conducted this time by Salter and Williams (37) found that all the one-third atmosphere percentages using the pressure membrane apparatus were lower by approximately five percent on the absolute scale and, in the majority of instances, significantly lower than the corresponding moisture contents at the corresponding moisture contents at field capacity determined by the direct method as described by Salter and Haworth (36).

Salter and Williams also conducted some experiments on the lower limit of available water (15 atmosphere range). Their results were quite different from Richards and Fireman (35). They used the following techniques to determine the lower limit of available water:

1. For the permanent wilting percentage of undisturbed soil, the sunflower method presented by Salter and Haworth (36) was used. (The permanent wilting point or percentage of a soil is defined as the water content of a soil at which plants will wilt and do not recover turgidity when placed in a humid atmosphere over night.)

2. For the permanent wilting percentage of disturbed soil, the sunflower method was used again but this time with a disturbed soil.

3. For the 15-atmosphere percentage of undisturbed soil, cores of soil were equilibrated at a pressure of 15 atmospheres in a pressure-membrane apparatus and the moisture contents determined.

4. For the 15-atmosphere percentage of disturbed soil, 50 gram soil samples were air-dried, passed through a 2 mm sieve, subjected to a pressure of 15-atmospheres in a pressure-membrane apparatus, and the moisture contents determined.

Their results can be summarized as follows:

1. In approximately 30 percent of the comparisons, the permanent wilting percentage determined on a disturbed sample of soil differed significantly from that on an undisturbed sample. Significant differences occurred more frequently with the medium- to fine-textured soils than with the coarser-textured soils.

2. In about 75 percent of the comparisons, the summer values were higher than the spring values. With the fine-textured soil, half the number of samples taken in the summer had a significantly higher permanent wilting percentage than those in the spring.

3. In general, there was good agreement between the permanent wilting percentage and the 15-atmosphere undisturbed soil samples. The largest differences were found with the medium-textured soils.

4. The 15-atmosphere percentages determined by the two methods differed significantly in 50 percent of the cases. Differences were greatest with the fine-textured soil, but significant differences also occurred with the medium- and moderately coarse-textured soils.

The results are shown graphically in Figure 14. The line drawn at a 45° angle indicates the position where

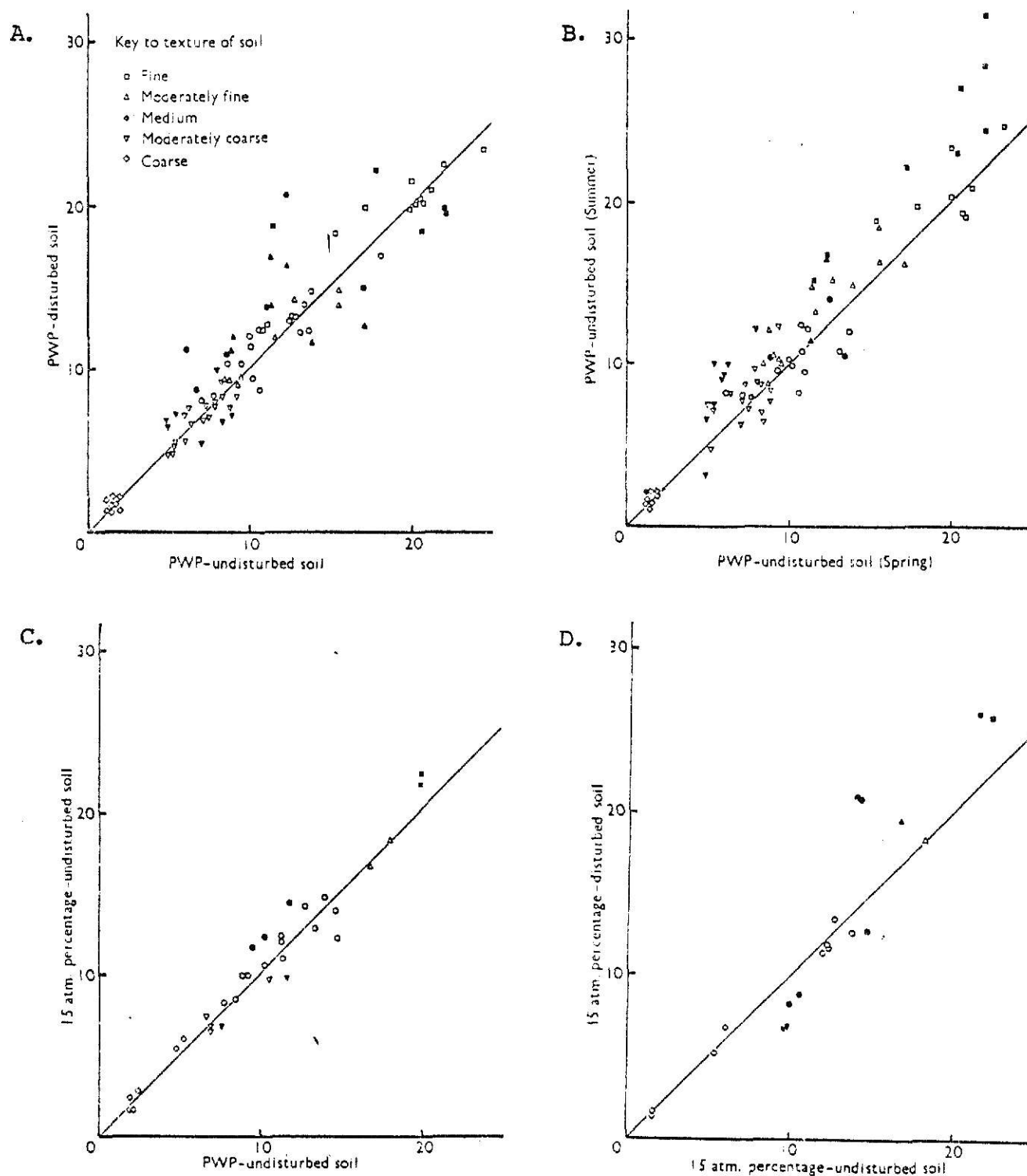


Figure 14. Lower limit of available water

Relationships between (A) Permanent wilting points (PWP) determined on undisturbed and disturbed soil, (B) PWPs determined on undisturbed soil in spring and summer, (C) PWPs and 15 atmosphere percentages, both determined on undisturbed soil samples, (D) 15 atmosphere percentages determined on disturbed and undisturbed soil samples. Each point is mean of three determinations [From Salter and Williams (37)].

identical results from the two methods would be. The open symbols indicate non-significant differences and the closed symbols, significant differences ($P = 0.05$) between the results obtained by the two methods. A different symbol has not been used for each soil; but soils in the five main textural groups (U.S.D.A. Soil Survey Manual, 1951), fine-, moderately fine-, medium-, moderately coarse-, and coarse-textured, are distinguished by different symbols.

Salter and Williams (37) presented five different values of the available water content for 11 soil types. These values were calculated using various combinations of the different measurements of the upper and lower limits of available water. The values are presented in Table 2. When reading the table, it shows that when the direct method was used to measure the upper limit of available water and the 15-atmosphere percentage determined on a soil core for the lower limit, the effect on the values obtained for the available water content was comparatively small--the differences from the standard method never being more than 16 percent for any of the soils. For the majority of soils, the differences were less than 10 percent. When the 15-atmosphere percentage was determined, the differences from the standard were larger for the disturbed samples of soil than for the undisturbed cores of soil.

In another investigation, Salter and Williams (37) showed that the moisture characteristic determined on the air-dried, sieved sample of sandy loam soil was very different from that obtained with undisturbed soil cores of the same soil. These

Table 2. Available-water capacities (in.) of the top 6 in. of 11 soils calculated using the different values obtained for the upper and lower limits of available-water [From Shaykewich (39)].

(Means of six determinations; asterisks indicate statistically significant differences from the standard, *P = 0.05, **P = 0.01, ***P = 0.001)

Upper, limit measurement:		(a) Direct method		(b) $\frac{1}{3}$ atm. percentage		s.e. for comparison between means
Lower limit measurement:		(c) 15 atm. % (undisturbed)	(d) 15 atm. % (disturbed)	(c) 15 atm. % (undisturbed)	(d) 15 atm. % (disturbed)	
Group	Soil texture No.	(a) PWP (undisturbed)	(a) Direct method	(c) 15 atm. % (undisturbed)	(d) 15 atm. % (disturbed)	
Coarse-textured soils	Sand 8	0.42		0.10***	0.10***	0.014
	Loamy sand 13	1.03		0.75***	0.72***	0.042
	Sandy loam 9	0.70		0.53***	0.62***	0.031
	Sandy loam 23	1.57		0.76***	0.81***	0.049
Moderately coarse-textured soils	Loam 14	1.61		1.22***	0.85***	0.046
	Loam 19	1.10		0.89***	0.85***	0.039
Medium-textured soils	Very fine sandy loam 20	1.29		0.80***	0.93***	0.022
	Silt loam 22	1.60		1.44	1.46	0.082
	Silt loam 10	2.02		1.04***	1.08***	0.081
Moderately fine-textured soils	Silty clay loam 18	1.04		0.82*	0.73*	0.080
	Clay 3	0.83		0.42***	0.21***	0.030

samples of the sandy loam soil were prepared in five ways:

1. Undisturbed and stored in a water-saturated atmosphere (method a),
2. A disturbed sample [50 gram air-dried, sieved (2 mm)] saturated in water for 24 hours (method b),
3. Same as 2 except sample was wetted slowly (method c),
4. Samples were air-dried but not sieved, then wetted slowly as in 3 (method d), and
5. Samples of unsieved, moist soil reformed into cores wetted from below (method e).

By methods (a) and (e) the relationship between the percentage soil moisture and log tension was found to be linear but these linear moisture characteristics differed significantly from one another. Using methods (b), (c), and (d) the relationships obtained were curvilinear and at almost all tensions the moisture contents differed significantly from those obtained from (a) which was regarded as the standard method. These results are shown in Figure 15.

Another investigation by Salter and Williams (37) was made between the moisture characteristics determined by methods a and b of the preceeding investigation for five different soils. The results (Figure 16) show that moisture characteristics differed significantly from one another.

As stated earlier in this paper, the degree of availability of soil water and the form of its movement in soil is determined by the interrelationships that exist between water and the solid and gaseous phases of the soil. The major discrepancy between the results as derived by Richards

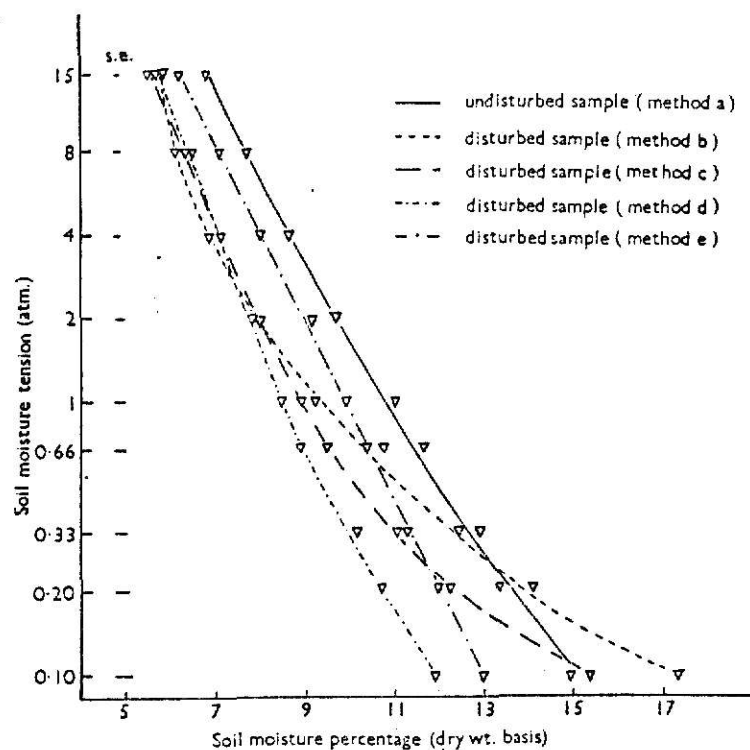


Figure 15. Moisture characteristic of a sandy loam soil determined on samples of soil prepared by five different methods [From Salter and Williams (37)].

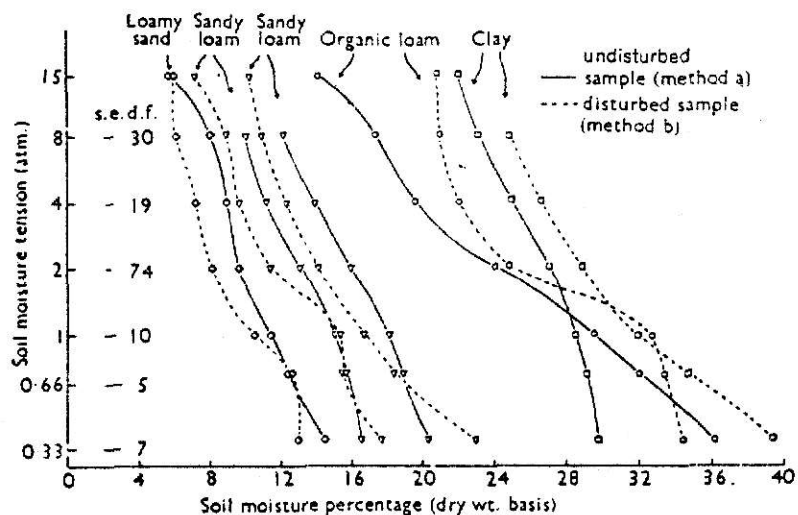


Figure 16. Moisture characteristics of five soils determined for undisturbed and disturbed samples of soil [From Salter and Williams (37)].

and Fireman (35), and Salter and Williams (37) is that of disturbed soils versus undisturbed soils.

The hydraulic properties of disturbed and undisturbed soils were studied by Shaykewich (39). Initially, property differences between disturbed and undisturbed soils were given (Table 3). The results obtained were that in most of the soils used, water content at low suction was greater in disturbed than in undisturbed samples (Table 4). At high soil suctions, pF 3.85 and 4.20, there were significant effects of sample disturbance on water retention. Also with respect to the lower limit of available water, in two cases out of seven, soil disturbance had a significant influence (Table 5). This agreed with the 30 percent found by Salter and Williams (37).

When Shaykewich (39) looked at hydraulic conductivity, he found for most of the soils the hydraulic conductivity for disturbed samples was greater than that for undisturbed samples at low suctions ($pF < 3$). At high suctions ($pF > 3.5$), the opposite was true (Figure 17).

In considering how sample disturbances might influence hydraulic conductivity, two key factors are believed to control the area through which water can flow and the length of the path that water must flow. It is known that in many soils a considerable portion of the water is held by swelling forces associated with diffuse ion layers of clay particles (1, 4, 21, 34, 36). In relatively dry soils (e.g., $pF = 4.0$), surface forces are probably more important than

Table 3. Properties of soils used
[From Shaykewich (39)].

<u>Soil and Horizon</u>	<u>Bulk Density</u>		<u>% OM</u>	<u>% Sand</u>	<u>% Silt</u>	<u>% Clay</u>	<u>Particle Density</u>
	<u>Undisturbed</u>	<u>Disturbed</u>					
Plum Ridge Ah	1.27	1.05	5.39	73.7	15.5	10.8	2.42
Pine Ridge Ah	1.53	0.99	4.87	66.6	17.0	16.4	2.45
Morton Ah	1.51	1.10	3.66	48.1	33.8	18.1	2.55
Wellwood Ah	1.12	0.93	5.76	44.9	28.2	26.9	2.38
Wellwood Bm	1.27	0.94	2.17	33.0	37.0	30.0	2.51
Wellwood C	1.44	0.96	1.05	8.4	49.4	42.1	2.54
Red River Ah	1.25	1.01	2.69	3.7	17.9	78.4	2.23

Table 4. Gravimetric water content at $pF = 2.45$
[From Shaykewich (39)].

<u>Soil and Horizon</u>	<u>Undisturbed</u>	<u>Disturbed</u>
Plum Ridge Ah	24.11	23.75
Pine Ridge Ah	19.82	25.55
Morton Ah	23.28	26.40
Wellwood Ah	22.86	33.61
Wellwood Bm	16.39	18.61
Wellwood C	19.88	23.47
Red River Ah	51.05	46.60

Table 5. Gravimetric Water Content at $pF = 4.20$
 [From Shaykewich (39)].

<u>Soil and Horizon</u>	<u>Undisturbed</u>	<u>Disturbed</u>
Plum Ridge Ah	8.13	11.91
Pine Ridge Ah	9.88	10.35
Morton Ah	10.50	8.62
Wellwood Ah	13.39	13.72
Wellwood Bm	10.54	10.38
Wellwood C	11.33	15.00
Red River Ah	28.67	29.75

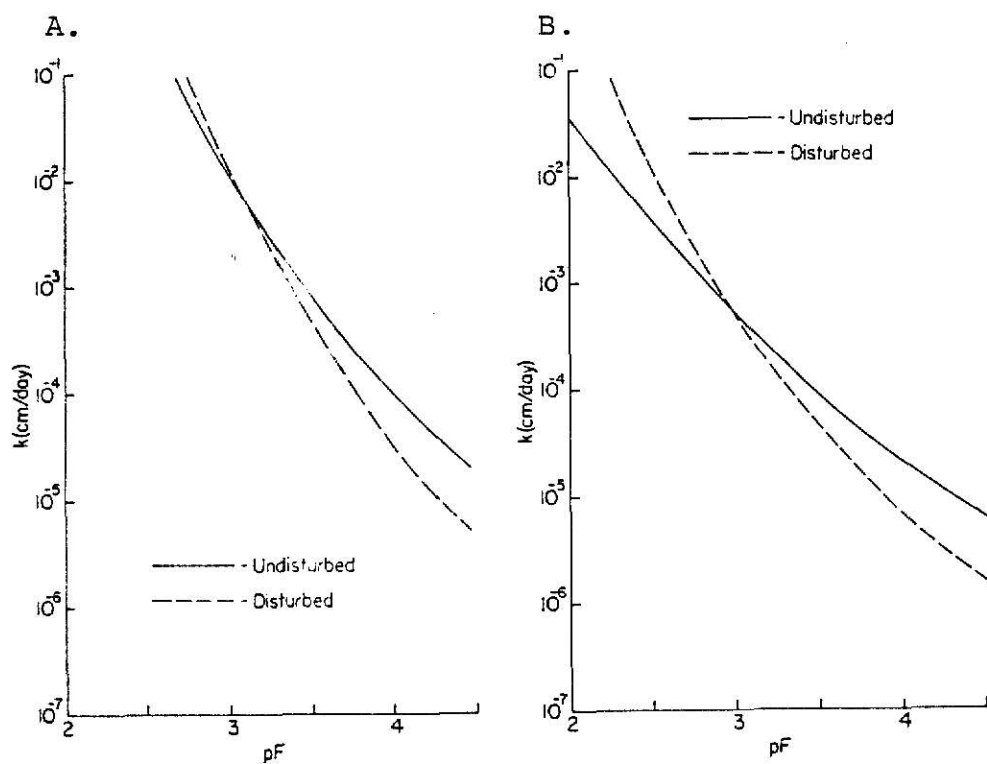


Figure 17. Hydraulic conductivity - pF relationships
 (A) for Morton Ah (B) for Wellwood Ah
 [From Shaykewich (39)].

capillary forces even in granular soils. Therefore, it follows that at low pressure the flow is in the liquid phase while in dry soils, the movement of water in the vapor phase is probably relatively important.

At the outset, Shaykewich's data exhibited soil property difference between disturbed and undisturbed soil. Table 3 presents these results. When water content at low suction was analyzed, the results showed that in most of the soils used the water content was greater in disturbed than in undisturbed samples (Table 4). This agrees with the premise on which the pressure plate or pressure-membrane apparatus was established for determining soil water potentials. When referring to the principles of soil moisture retention, it was mentioned that the amount of water retained by a soil at any particular suction depends on the particles which compose it and the arrangement of those particles. Here, as was described, the larger pores empty first followed by progressively smaller ones until an ill-defined point where adsorption forces hold the remaining water. According to Marshall (24), the actual amount of water available depends on the structure rather than texture.

Kemper (19) agreed with Marshall (24) that the structural stability of the matrix itself may hold water. Such structure would resist pressure and surface tension preventing the removal of water from the interior of the matrix. At the same time, however, applied pressure and the removal of water result in a breakdown of soil structure thus forcing water out.

Rode (29) compared two soils of similar texture but different structure. One was a powdery, structureless soil, the other a fine, lumpy structure (lumps of sizes 1 - 10 mm). He found that the structureless soil easily loses a considerable part of its moisture through physical evaporation because of circulation between particles under the action of capillary and absorption forces. In the structured soil, moisture is contained as "suspensional within aggregates". As was discussed earlier, no capillary circulation is possible in the intervals between aggregates because such intervals are (relatively) wide; therefore, at 15 atmospheres of tension, vapor pressure is of primary importance, affected both by temperature and pressure.

The relationship between moisture tension and temperature is evident from a consideration of the free energy equation and matrix potential (13). This potential, which is numerically equal to the moisture potential, is defined as the work involved in transferring a unit of moisture from a point in question in the soil mass to a reference point considered as zero potential. It is evident that the term "pv" in the free energy equation of $f = pv + e - Ts$, is a measure of the work involved in the process. Since $p v = nRT$, where n is the number of moles of gas occupying a volume v at an absolute temperature T and pressure P , and R is the universal gas constant, soil moisture in the vapor form is a function of temperature. Any increase or decrease in temperature from one moisture determination to another moisture determination will

cause a difference in the result. In the various data presented in this paper, the writers did not give the temperature at which the experiments were run.

Pressure was also mentioned as having an effect on the determination of soil moisture. When the total pressure is increased, the vapor pressure also increases. That is, as more of an indifferent gas is pumped in, more of the liquid evaporates. The partial pressure of the vapor phase by itself is unaffected by the addition of the indifferent gas; only the liquid phase feels the additional pressure causing the liquid phase to evaporate (38). When comparing 1 atmosphere pressure to a 15 atmosphere pressure, at a temperature of 300K, an increase in vapor pressure of 1446 percent (38) results. Referring back to Table 2, this difference may account for a portion of the differences between disturbed and undisturbed samples. The remaining difference, as pointed by Kemper (19), Marshall (24) and Rose (29), is possibly due to the structure. When a structured soil is given a structureless characteristic, allowing moisture vapor to follow a completely different path to reach equilibrium, the increase in vapor pressure may give a much higher removal of moisture.

SUMMARY AND CONCLUSION

This report presents two methods for determining soil moisture retention properties of a soil. The first method has a pressure range of 0 to 2 atmospheres, while the second method has a pressure range of 1 to 15 atmospheres.

When the external pressure force is first applied, water, which is retained by gravitational and/or matrix forces, begin to empty from the larger pores. As the pressure increases progressively small pores empty until an ill-defined point is reached when adsorption forces retain the water. Still a greater increase in pressure will begin the removal of adsorbed water through the water vapor form.

Because retained water contains different quantities and forms of energies, a relationship was set up between the retained water and the type of potential energy attributed to retaining that particular water. This assignment of potential energies provided a basis for a quantitative figure of identifying the external force associated with retained water that is available to plants. This is particularly important because a value of 15 atmosphere pressure has been designated as the permanent wilting point, widely used (especially in irrigation farming) to represent the lower limit of water available to the crop.

Soil moisture retention values as determined by the methods presented in the section on Materials and Methods will provide accurate data that is repeatable. However, as

can be seen by this discussion, when a disturbed sample is used, the accuracy of the data as compared to the actual value is questionable. There is no question that errors will result when analyses are conducted in the pressure range up to a pF value of 2.45. The controversy begins when the pressure range is in the order of pF 3.85 and 4.20. At this point, authors differ.

The reason for the differences can be many. It was pointed out that running the analysis at a different temperature has a direct influence on the results. However, this difference is minor when considering the slight temperature differences in room temperatures. Pressure differential, which is inherent in the procedure itself, provides a source of error when comparing the differences between structures of a disturbed sample and an undisturbed sample.

Other effects based on soil properties concerned with the amount of clay, organic matter, silt, and salt concentrations are speculated upon but not shown as to what effect they have when comparing a disturbed sample to an undisturbed sample. Also, what effect entrapped air has is only theorized.

All these questions need to be resolved before an accurate picture can be obtained when concerned with determining soil moisture retention properties at the permanent wilting point.

The purpose of this report is to provide a method using the available equipment as supplied by Soilmoisture Equipment Corporation. It is to be noted the person using the equipment must keep in mind the inherent problem of the equipment and the accuracy that may be obtained.

REFERENCES

1. American Society of Agricultural Engineers, Nomenclature Committee, Soil and Water Division, Glossary of Soil and Water Terms, Special Publication SP-04-67. St. Joseph, Michigan, January 1967.
2. American Society of Testing and Measurement, "Standard Test Method for Capillary-Moisture Relationships for coarse-and Medium-Textured Soils by Porous-Plate Apparatus." Standard ASTM D 2325-66 (Reapproved 1974), 1979 Annual Book of ASTM Standards, Part 19, pp. 344-350.
3. American Society of Testing and Measurement, "Standard Test Method for Capillary-Moisture Relationships for Fine-Textured Soils by Pressure-Membrane Apparatus." Standard ASTM D 3152-72 (Reapproved 1977), 1979 Annual Book of ASTM Standards, Part 19, pp. 478-485.
4. Archer, J. R. and P. D. Smith. "The Relation Between Bulk Density, Available Water Capacity, and Air Capacity of Soils." Journal of Soil Science. Vol. 23, No. 4, Dec. 1972, pp. 475-480.
5. Basak, P. "Soil Structure and Its Effects on Hydraulic Conductivity." Soil Science. Vol. 114, No. 6, Dec. 1972, pp. 417-422.
6. Baver, L. D., W. H. Gardner, and W. R. Gardner. Soil Physics. John Wiley and Sons, Inc., New York. 4th Ed., 1972.
7. Chahal, R. S. "Effects of Entrapped Air and Pressure on Matric Suction." Soil Science. Vol. 102, No. 2, Aug. 1966, pp. 131-134.
8. Chahal, R. S. "Effects of Temperature and Trapped Air on the Energy Status of Water in Porous Media." Soil Science. Vol. 98, No. 2, Aug. 1964, pp. 107-112.
9. Childs, E. C. "Concepts of Soil Water Phenomena." Soil Science. Vol. 113, No. 4, April 1972, pp. 246-253.
10. Childs, E.C. Soil Water Phenomena. John Wiley & Sons, Ltd., New York, 1969.
11. Collis - George N. "Free Energy Considerations in the Moisture Profile at Equilibrium and Effects of External Pressure." Soil Science. Vol. 91, No. 5, May 1961, pp. 306-311.

12. Corey, A. T. Mechanics of Heterogenous Fluids in Porous Media. Water Resources Publications, Fort Collins, Colorado. 1977.
13. Gardner, R. "Relation of Temperature to Moisture Tension of Soil." Soil Science. Vol. 79, No. 4, April 1955, pp. 257-265.
14. Groenevelt, P. H. and G. H. Bolt. "Water Retention in Soil." Soil Science. Vol. 113, No. 4, April 1972, pp. 238-254.
15. Hillel, D. Soil and Water. Academic Press, New York, 1971.
16. Hillel, D. and J. Mottes. "Effect of Plate Impedance, Wetting Method, and Aging on Soil Moisture Retention." Soil Science. Vol. 102, No. 2, August 1966, pp. 135-139.
17. Jensen, R. D. and A. Klute. "Water Flow in an Unsaturated Soil with a Step-Type Initial Water Content Distribution." Soil Science Society of America Proceedings. Vol. 31, No. 3, May-June 1967, pp. 289-296.
18. Kauzman, W. Kinetic Theory of Gases. W. A. Benjamin, Inc. 1966.
19. Kemper, W. D. "Structural Implications of Moisture Retention by Clay-Size Soil Materials." Soil Science Society of America Proceedings. Vol. 22, No. 1, January - February 1958, pp. 5-8.
20. Laliberte, G. E. and R. H. Brooks. "Hydraulic Properties of Disturbed Soil Materials Affected by Porosity." Soil Science Society of America Proceedings. Vol. 31, No. 4, July-August 1967, pp. 451-454.
21. Lambe, T. W. and R. V. Whitman. Soil Mechanics. John Wiley and Sons, Inc., New York, 1969.
22. Lee, I. K., ed. Soil Mechanics, New Horizons. Fletcher and Sons, Ltd., Nowrich, England, 1974.
23. Low, P. R. and J. F. Margheim. "The Swelling of Clay: I. Basic Concepts and Empirical Equations." Soil Science Society of America Journal. Vol. 43, No. 3, May-June 1979, pp. 473-481.
24. Marshall, T. J. 1959. "Relations Between Water and Soil." Harpenden: Commonwealth Bureau of Soils. Technical Communication No. 50.
25. Mitchell, J. K. Fundamentals of Soil Behavior. John Wiley and Sons, Inc., New York, 1976.

26. Parlange, J. Y. and D. E. Hill. "Air and Water Movement in Porous Media: Compressibility Effects." Soil Science. Vol. 127, No. 5, May 1979, pp. 257-263.
27. Peck, A. J. "Change of Moisture Tension with Temperature and Air Pressure: Theoretical." Soil Science. Vol. 89, No. 6, June 1960, pp. 303-310.
28. Powers, W. L. Laboratory Exercise to Determine Soil Moisture Retention, Dept. of Agronomy, Kansas State University.
29. Rode, A. A. Soil Science, published for the National Science Foundation, Washington, D.C. by the Israel Program for Scientific Publ. Jerusalem, 1962.
30. Rode, A. A. The Moisture Properties of Soils and Underground Strata. Published for the National Science Foundation. Washington, D.C. by the Israel Program for Scientific Translations, Jerusalem, 1960.
31. Rode, A. A. Theory of Soil Moisture. Vol. 1. Published for the National Science Foundation. Washington, D.C. by the Israel Program for Scientific Translations, Jerusalem, 1969.
32. Rolfe, P. F. and L. A. G. Aylmore. "Water and Salt Flow Through Compacted Clays: I. Permeability of Compacted Illite and Montmorillonite." Soil Science Society of America Journal. Vol. 41, No. 3, 1977, pp. 489-495.
33. Rose, D. A. "Soil Water: Quantities, Units and Symbols." Journal of Soil Science. Vol. 30, No. 1, March 1979, pp. 1-15.
34. Richards, L. A. "Pressure-Membrane Apparatus--Construction and Use." Agricultural Engineering. Vol. 28, October 1947, pp. 451-454. 460.
35. Richards, L. A. and M. Fireman. "Pressure-Plate Apparatus for Measuring Moisture Sorption and Transmission by Soils." Soil Science. Vol. 56, No. 6, December 1943, pp. 395-404.
36. Salter, P. J. and F. Haworth. "The Available-Water Capacity of a Sandy Loam Soil." Journal of Soil Science. Vol. 12, No. 2, September 1961, pp. 326-334.
37. Salter, P. J. and J. B. Williams. "The Influence of Texture on the Moisture Characteristics of Soils." Journal of Soil Science, Vol. 16, No. 1, March 1965, pp. 1-15.

38. Sears, F. W. and G. L. Salinger. Thermodynamics, Kinetic Theory, and Statistical Thermodynamics. Addison-Wesley Publ. Comp., Reading, Massachusetts, 3rd Ed., 1975.
39. Shaykewich, C. F. "Hydraulic Properties of Disturbed and Undisturbed Soils." Canadian Journal of Soil Science. Vol. 50, No. 3, October 1970, pp. 431-437.
40. Singh, A. Soil Engineering in Theory and Practice. Vol. 1, Asia Publishing House, New York, 2ed. 1976.
41. Soilmoisture Equipment Corporation. "Operating Instructions for the 15 Bar Ceramic Plate Extractor. Cat. No. 1500." Santa Barbara, California.
42. Soilmoisture Equipment Corporation. "Instruction for Setup of the Cat. No. 700-23 Mansfold." Santa Barbara, California.
43. Tschapek, M., C. O. Scoppa, and C. Wasowski. "The Surface Tension of Soil Water." Journal of Soil Science. Vol. 29, No. 1, March 1978, pp. 17-21.
44. United States Department of Agriculture, Agricultural Handbook No. 60. February 1954.
45. Vilenskii, D. G. Soil Science. Published for the Nat. Sci. Foundation, Washington, D. C., by the Israel Program for Scientific Translations. 1960.
46. White, N. F., H. R. Duke, D. K. Sunda, and A. T. Corey. "Physics of Desaturation in Porous Materials." Journal of the Irrigation and Drainage Div. Proceedings of the American Society of Civil Engineers. Vol. 96, No. 1R2, June 1970, pp. 165-191.

APPENDIX A

The following data was obtained on a loam clay soil using the methods as described in section Materials and Methods.

<u>Soil Sample Number</u>	<u>2-Bar Determination percent by weight</u>	<u>15-Bar Determination percent by weight</u>
1	22.00	18.20
2	27.71	18.12
3	22.68	17.70
4	26.71	18.07
5	27.64	19.35
6	20.45	18.34
7		18.23
8		18.78
9		17.09
10		18.45
11		18.70
12	<hr/>	<u>18.66</u>
Average	24.53	18.31

METHODS FOR DETERMINING SOIL MOISTURE RETENTION

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ABSTRACT

The primary purpose of this report was to present a method for determining soil moisture retention properties of a soil using pressure plate apparatus. Two methods were required: the first had a pressure range of 0 to 2 atmospheres; the second, a pressure range of 1 to 15 atmospheres. Following a literature search, a brief discussion was developed on how water is retained by soils, the soil water potentials, and the determination of soil water. Also within the text, results of different research were discussed highlighting the controversy between disturbed versus undisturbed samples.