The Physical Basis of Soil/Water Relationships

W. Burke, An Foras Taluntais, Land Reclamation Seminar Oct. 24 – 26, 1978

Soil is regarded as a 3 phase system i.e. solids, water and air. The physical properties of soils depend on the nature of the solids and/or the amounts of water and air in the soil. The solid phase of the soil is relatively constant and the water and air phases are complimentary and occupy the pore spaces. A saturated soil has all its pores filled with water and at the other extreme a dry soil has all its pores filled with air. The normal condition in the field is somewhere between these two extremes.

A "good soil" will normally have 50 to 60 per cent of its volume consisting of pore space. And ideally about half of this pore space will be filled with stored water i.e. water that will not drain away. These are idealized values and there is considerable scope for variation. Many crops can do well with as little as 9 % air filled pores. A reduction in porosity means an increase in compaction. When a soil has most of its pores filled with air it has poor drought resistance and when most of pores remain filled with water it is wet, cold and water logged.

Soil solids

The solids in a soil consist of mineral and organic materials. When organic matter is dominant the soil is peaty and a raw bog has almost 100 % organic matter in its solids. In a normal tillage soil organic matter will be no more than 3 to 4 % by weight and often less. In pasture soils it will generally range upwards from this value. Organic matter is useful in a soil as a conditioner for soil structure and as a storage facility for water and nutrients. As the amount increases it causes problems associated with weakness, because of the low strength of organic matter, and wetness, because of its ability to absorb and retain water. The ultimate condition is a wet bog but heavy pasture soils often have a peaty layer on the surface. This condition is widespread in Ireland and the layer can vary from a few centimetres to any depth. It is the cause of widespread poaching problems. In most soils the most important material is the mineral portion. Its properties largely depend on two factors, texture and structure.

Soil texture

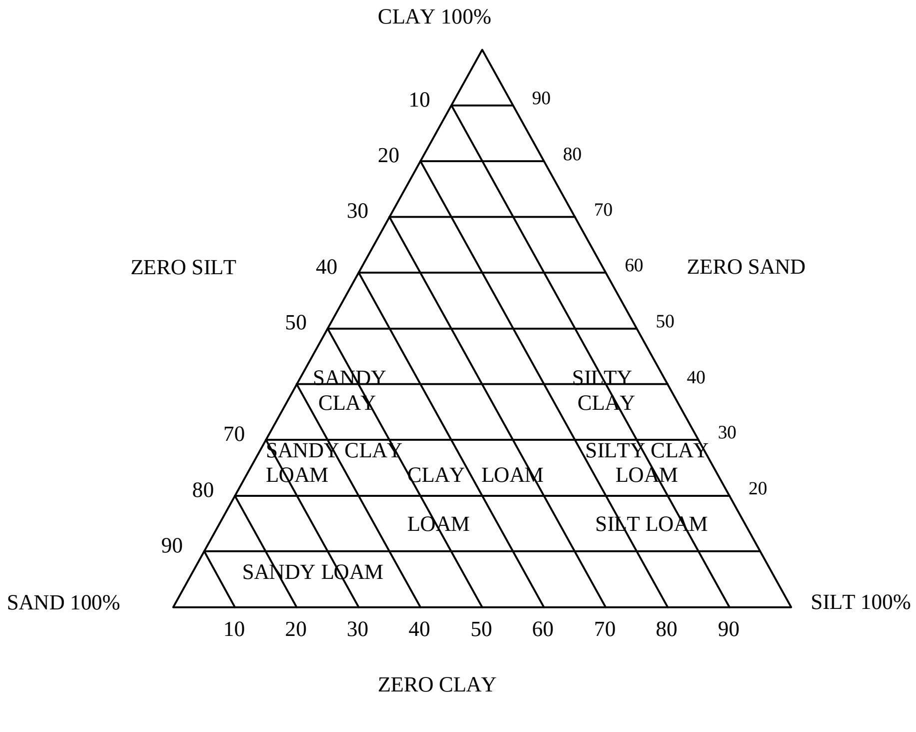
The individual particles of a soil are called textural separates and are classified on the basis of size. If the majority of the particles are coarse (gravelly or sandy) the soil is coarse textured. Soil particles are classified according to different systems. While the systems differ in detail they are in general agreement. Thus particles larger than 2 mm are classified as gravel. In general particles between 2 mm and 0.6 to 0.2 mm are called coarse sand; fine sand ranges downward in size to .06 to .02 mm, particles from this size down to .002 mm are called silt and particles smaller than .002 mm in diameter are called clay. Three systems of classification are given in Table 1.

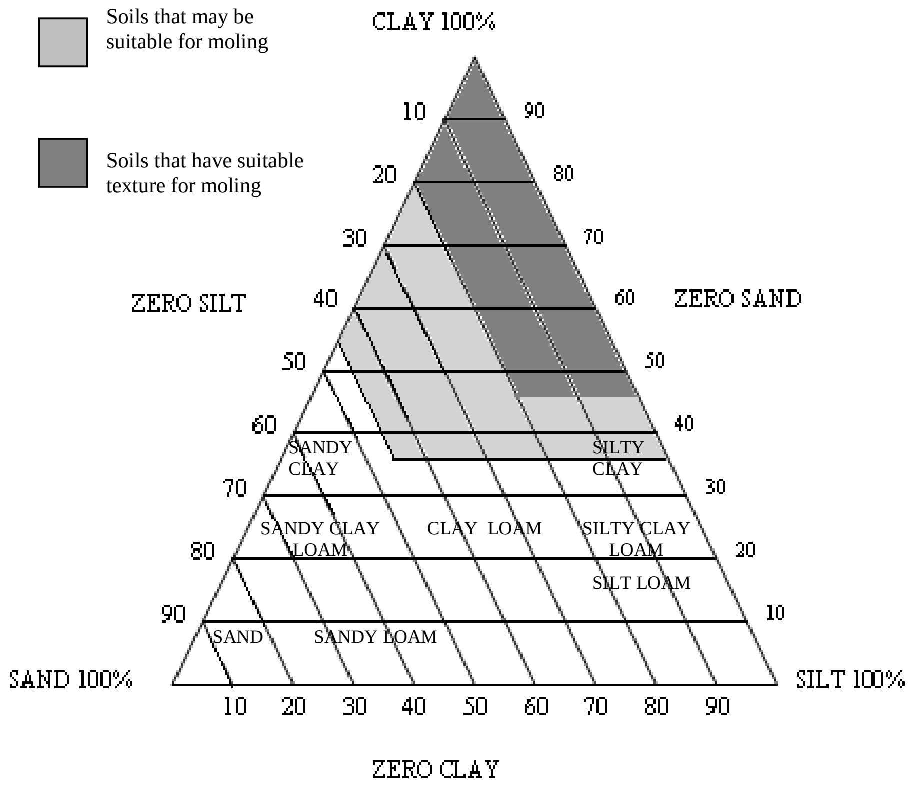
Table1. Classification system of soil particles of different sizes

	B.S. System	International System	U.S.D.A. System
Coarse Gravel	-	> 2 mm	> 2 mm
Gravel	60 – 2.0 mm		
Fine Gravel	-		2.0 – 1.0
Coarse Sand		2.0 – 0.2	1.0 - 0.5
Medium sand	2.0 – 0.6		0.5 – 0.25
Fine Sand	(Sand)	0.2 - .02	0.25 – 0.1
Very fine sand			0.1 – 0.05
Silt	0.06 - .002	0.2 - .002	0.05 - .002
Clay	<.002	<.002	<.002

When moist soil is rubbed between the thumb and forefinger the sandy part feels gritty, silt feels floury and clay feels sticky. With practice it is possible to make a reasonable assessment of the texture of a soil in the field by feel.

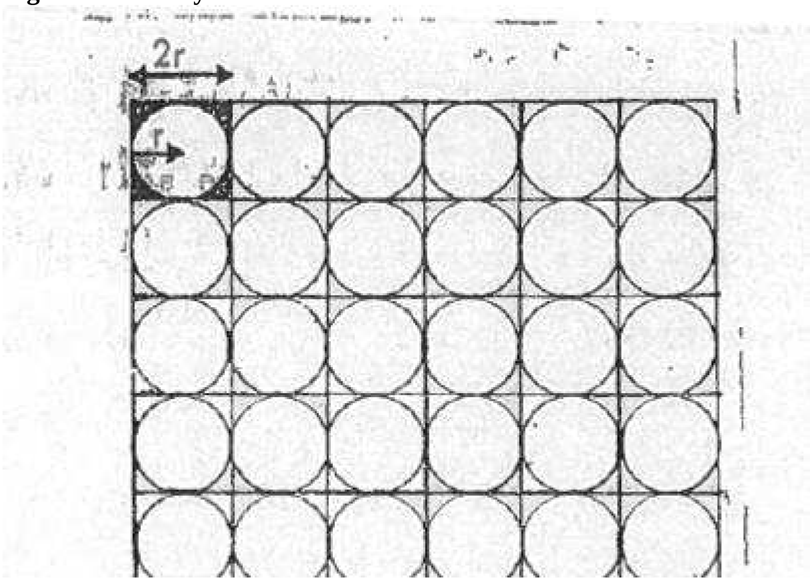
Obviously textural analysis permits us to classify soils according to the coarseness or fineness of the materials of which they consist, and this is very important. Textural analysis permits the classification of soils into different textural groups. An example of a chart for this purpose is given below left. An example of one use of this chart is shown on the second chart. An old rule of thumb to determine if a soil was suitable for moling was: if the clay content was less than 35% and the sand content greater than 45% the soils were unsuitable. Soils having 45% clay and not more than 20% sand were considered to be very suitable while soils in between were considered to have potential for moling. The textural ranges of the three classes are shown in the chart. While this test is not absolute it is a useful guideline and when used in conjunction with the USDA ball test it can be vey helpful.





The next aspect to be considered is how texture affects porosity (porosity itself will be discussed later). Initially we assume that the soil consists of uniform spherical particles, arranged uniformly side by side on top of each other.

Figure 1 Porosity



In effect the soil now consists of a series of cubic boxes of side 2r, each which contains a uniform sphere of radius r. The porosity of each box is equal to the volume of the box minus the volume of the contained sphere.

If the radius of the sphere = r

The volume of each box
(side = 2r) $= 8r^3$

The vol. of each sphere $= 4/3\pi\ r^3$

and the porosity $= 8r^3 - 4/3\ \pi\ r^3$ (Vol. of box – Vol. of enclosed area)

and the porosity % $= 8r^3 - 4/3\ \pi\ r^3 * 100 = (8 - 4/3\ \pi) * 100\% = 47.64\%$

Since the porosity of "each box" is the same the total porosity (per cent) of the soil is 47.64%

It is to be noted that the dimensions of r has disappeared and this tells us that for uniform spheres that the % porosity is the same irrespective of the size of the spheres. It is also obvious that for large spheres the individual pores are large and for small spheres the individual spheres are small. Soils do not consist of uniform spheres but the similarity holds. Thus for soils with uniformly sized particles the percentage of pore space will tend to be the same irrespective of whether the texture is coarse or fine, but the pores in the coarse textured soil will be large, and in fine textured soil, small.

The pattern of packing already considered is a loose one and other forms are possible. In the closest possible packing for spheres the porosity is reduced to 26%.

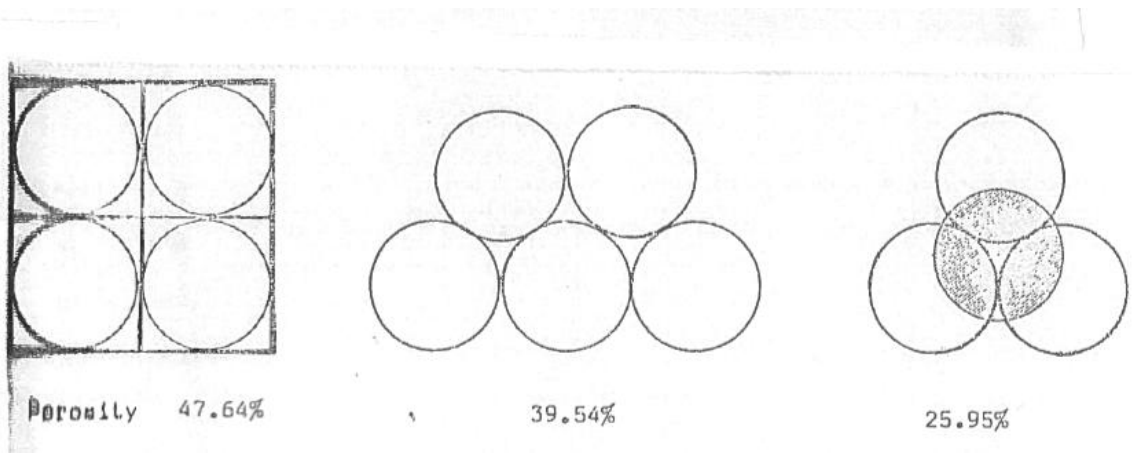


Fig. 3 Porosity depends on the arrangement of particles

The corresponding condition in a soil occurs when the soil is compacted. Compaction is accompanied by a re-arrangement of the particles to give a denser soil with less pore space and usually a reduction in the size of the individual pores. Soil particles are not uniform in size or shape. Thus smaller particles can fit in between larger ones and in effect a compact soil can be very dense with very little pore space. Compaction can occur naturally due to soil forming processes. It is also often man made by such practices as tilling wet soil, ploughing always at the same depth, heavy machinery etc. The heaviness in soil caused by compaction should not be confused with the heaviness resulting from small pores (to be discussed later).

Fig. 4 Loose and compacted soil

Such soils require sub-soiling or ripping to re-arrange the particles in a looser pattern and thus improve the porosity and they cannot be properly reclaimed without this treatment. Another very important attribute of texture is the total surface area of the individual particles. With the exception of clay minerals all soil chemical reactions must occur on particle surfaces. Similarly physical processes such as cohesion and plasticity depend on contact area between surfaces .In general the larger the surface area the more active the soil both chemically and physically. Similarly contact is better between flat surfaces and uneven ones.

If we start with a cubic particle of side 2 mm i.e. large grain of coarse sand. It has 6 sides each $4mm^2$ in area and its total surface area is 24mm.

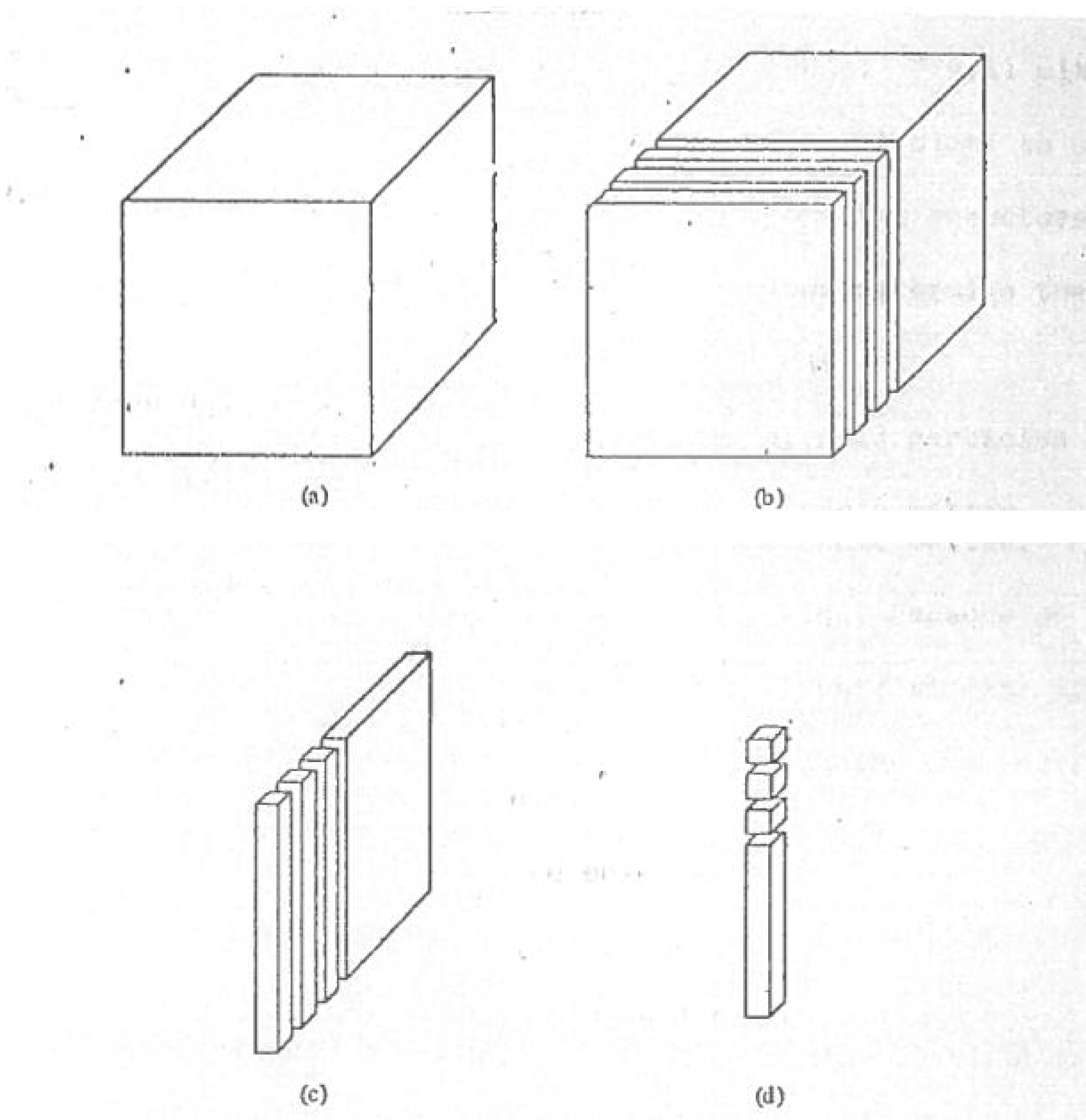


Fig. 5 Increase in surface area which accompany a decrease in particle size.

If this sand grain is divided into smaller cubes of clay size each with a size of .002 mm there are now 1,000,000,000 particles. The surface area of each particle is 6 * (.0002) mm^2. = 6 * .000004 = .000024 mm^2. But there are 1,000,000,000 particles and the total surface area is 24,000 mm^2. What this means is that the clay size material has an average of 1,000 times as large a surface area as the same volume of coarse sand. This explains why clay dominates both physical and chemical properties of soils. Referring back to the “feel” of texture. Clay is sticky because of the enormous surface area that it has for contact. Silt is floury but its surface area is not large enough to determine its other physical properties. Sand particles lack cohesion as their relative surface area is small. This is the main reason why we consider soils with a high clay content to be suitable for mole ploughing and other soils to be unsuitable. Clayey soils have a high cohesion i.e. the particles stick to each other and thus the mole stays open. Other soils lack cohesion and moles in them are not stable.

Conversely clayey soils are seldom suitable for ripping or sub-soiling because they tend to be too sticky to shatter unless they are very dry (cohesion is too high).

An important physical property of soils is its plasticity characteristics. By definition plasticity is the property that enables a soil to be deformed and to retain its deformed shape. Thus silt and clay are dominant in determining plasticity. The next diagram shows why fine grained soils are plastic.

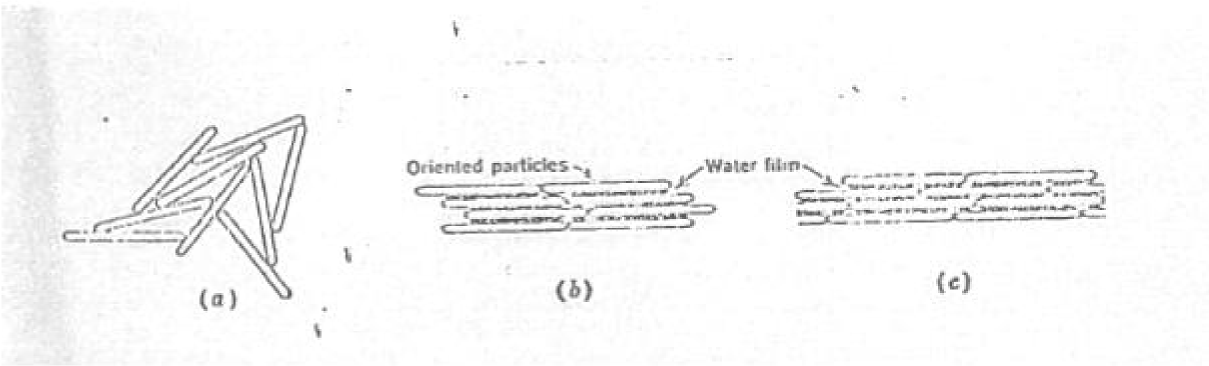


Fig. 6 Orientation of particles as a cause of soil plasticity

A soil with a lot of silt may be plastic and therefore can be moled but unless it has enough clay to have good adhesion the moles will not persist. Sand is neither cohesive nor plastic and moling a soil with much sand is generally of little use.

Soil structure

Up to this we have been examining the properties of the textural units of soil particles. The manner in which these particles are aggregated and built together is referred to as soil structure. If soils did not have structure they would invariably be very dense and compact. Finer particles would occupy the spaces between larger ones with clay material ultimately sealing most of the very small pores.

A soil with “good” structure has adequate porosity in both amount and number of pores. It is useful to compare it to a well constructed and well designed house. The house has a variety of rooms of different sizes to suit the needs of the occupants and the structure itself is stable. (It will be seen later on that pore sizes determine the movement and retention of water in the soil).

The bonding materials that keep the coarser soil particles arranged in a good structure are usually clay particles and organic matter. Clay mineralises by their large areas for surface contact, but mainly because of the electrical charges they carry. Organic matter behaves in a very similar manner. Iron oxides are also good bonding materials. This explains why reddish soils usually have an excellent structure. The red colour comes from an abundance of iron oxides.

Soil water

The water molecule consists of two atoms of Hydrogen and one of Oxygen. The configuration of the molecule gives water special properties.

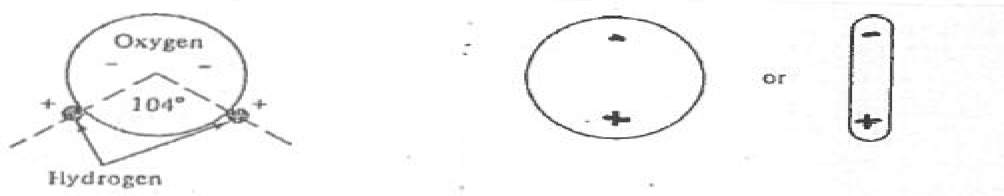


Fig. 7 Structure of water molecule

The two H atoms are not located on opposite sides of the atom but are both on the same side thus creating a positive end. This causes one end of the molecule to carry a positive charge and the other a negative one. Positive and negative charges attract each other and they are also attracted to other positive and negative surfaces. These forces and other interactions between the molecules produce an effect called surface tension, which creates a pull between molecules at the surface of a fluid. We will not develop the theory of surface tension here but because of its dominance in soil water interactions it must be introduced. It can be regarded simply as a force which produces a tension in the surface of liquids. The result of this is that a water surface behaves as if were covered by a thin skin. One consequence of surface tension is that if an open ended tube of a small bore is placed in water, the water will rise in it to a specific height. The relationship is approx.

$$H = 0.15 \text{ cm}/r$$

Where h is the height the water rises and r is the radius of the tube.

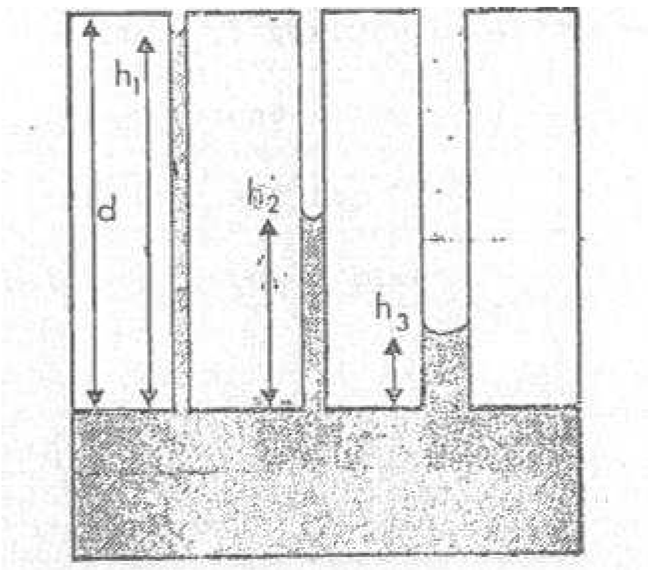


Fig. 8 The relationship between capillary rises (h) and capillary radius (r)

Thus the wider the bore the smaller the capillary rise. We can immediately apply this principle to soils. If a soil has a water table at a depth of 60 cm below the surface the principle of capillary rise lets us calculate what size pores remain full of water.

H = 0.15/r or r = 0.15/h but h = 60 cm

0.15 cm/60 = 0.0025 r = 0.025mm

This shows that water will stand at a height of 60 cm in a capillary of radius 0.025 mm above an open water surface. It stands at lower levels in pores and the upper parts of these pores will be filled with air. This is the reason why the pore space in a soil in the field is normally partly air filled and partly water filled. It is this stored water that keeps crops growing in drought conditions. Similarly different porosity patterns result in different ratios of air and water filled pores in different soils. One consequence is that if all the pores in a soil are smaller than 0.0025 mm radius, drains in at a depth of 60 cm will not remove any water from the soil. The effect of deepening the drain to 90 cm would in theory lower the water in the pores by 30 cm but would not remove any water from pores of radius 0.017 mm, calculated as above. The conclusion that must be drawn is that the installation of drains per se does not ensure that any drainage will occur. In fact the radius of pores occurring in silt size material 0.0025 mm, or 1/10 the size that would be drained by a drain of 60 cm and in theory drains should be installed at a depth greater than 6 metres to drain silt. However experience has shown that pores of smaller radius than about 0.025mm tend to stay full of water irrespective of what depth drainage is
provided.

PAPER 2

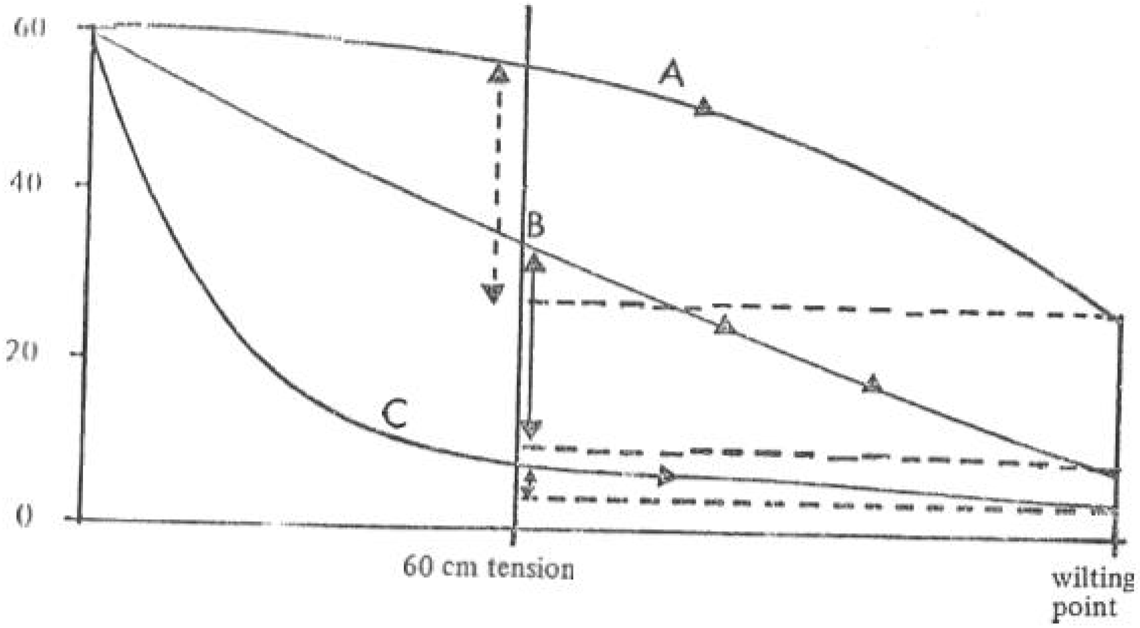


Fig. 9 Moisture characteristic curves of 3 soils

In Soil A (which could resemble a heavy wet soil of the type found in drumlins) almost all of the pores are very small and undrainable by ordinary field drains.

In Soil B nearly half of the soil water is drained away by field drains or natural drainage but soil still has good reserves of water against drought. This would probably be a good soil of medium texture and have a good range of pores of different sizes.

In Soil C almost all of the water is removed by drainage. This could be a sandy, coarse textured soil and very subject to drought. The only means of draining soil A is to alter the pore configuration by some means suited to the soil texture e.g. deep ploughing, sub-soiling, ripping etc, thereby creating larger pores. In theory moling soil A would not be of much benefit because the pores are too small. In practice the disruption caused by the mole plough to soil would be of considerable benefit.

Soil water movement

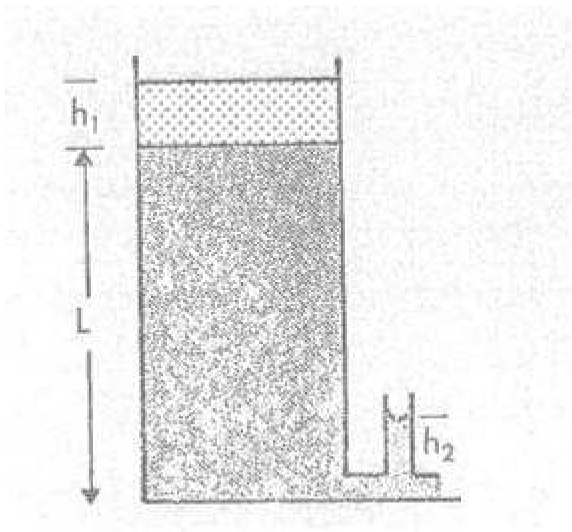
For the purpose of discussing the movement of soil water we need to consider the energy status of the water in the soil. Here we will consider three simplified conditions. If we select a particular reference level in the soil e.g. the depth of the bottom of the drain (for the moment we will ignore surface tension effects) water at elevation above the drain bottom will flow downwards towards it and we say it has potential energy due to its elevation, water at the bottom of the drain does not move, we say it has neutral or zero energy, but water below the drain bottom must be worked on to raise it to the drain bottom.. It has negative energy. Water will always flow from a position of higher energy to a lower one, and this difference in energy is referred to as head (H) where drainage is concerned. Here, head is simply the difference in height between the position at which water is and the position to which it is going.

One important consequence of this energy concept of water flow is known as Richard's Outflow Law which states that "outflow of free water from soil occurs only if the pressure in the soil water exceeds atmospheric pressure". This law explains why water flowing in soil will not get into drains. Since the outlet of a land drain is open to the atmosphere it follows that pressure along the perimeters of all drains in the system is atmospheric pressure. Similarly by definition the pressure at water table is also atmospheric pressure. When the water table in a soil is below the drain bottom and water moving vertically downwards towards the water table all of this water is in tension (less than atmospheric pressure) i.e. it is at a lower energy status than the water around the drain perimeter and it is physically impossible for such water to get into the drain. Thus a drain installed above a water table will normally carry water only when the water table rises above the drain bottom. Drains installed in the vicinity of a fluctuating water table will run only intermittently. Some water may enter these drains through long cracks in the soil, but in general they are not taking any part in the dewatering or drainage of the soil mass.

Darcy's Law

If we measure the quality of water flowing through a block of uniform soil for a specified time we get some particular value.

Fig. 10 Darcy's Law



If we then measure the flow through a similar block with a cross section half that of the first we find that the original flow is halved That is, the flow is proportional to the cross sectional area. Similarly if we keep the cross sectional area constant but double the length of the block in the direction of the flow without changing the head or water pressure we find that the flow is reduced to half the original. That means that the flow is inversely related to the distance to which flow takes place (because it has to travel twice as far the resistance is doubled). In 1856 a French engineer called Darcy summarised all of this in what is known as Darcy's law which can be written simply as Q/T = K (AH/L). Darcy's law can be stated in other forms also).

Q = Quantity of water flowing through the soil in time t
t = Time
A = Cross section through which water flows
H = The Head which is causing the flow = h1 + L – h^2 in Fig.10
L = The distance through which water is flowing
K = Is a coefficient which is specific for any soil and is called the hydraulic conductivity or the soil water permeability.

For soils with small pores K is small, for soils with large pores K is large. In the field, soil pores vary in size and K is dependant on the pore size distribution.

Darcy's Law is the cornerstone on which all the theory of water flow in soils has been based and the K derived from it is also used in the development of all the formulae used to predict the depth and spacing of drains.

We will next consider the flow through an individual pore. For this purpose we can regard the pore as a very narrow cylinder of radius r. It can be shown that the flux in the pore (i.e. the amount of water flowing in unit time) is proportional to the 4th power of the radius.

$$Q/t \;\alpha\; r^4$$

Assume that flow through a cylinder (pore) of radius 1.0 mm is equal to one unit of water per minute. (Cross sectional area = 3.14 mm^2). Replace this cylinder (pore) with 10 cylinders each with a cross sectional area of 0.314 mm^2). Replace this cylinder (pores) with 10 cylinders each with a cross sectional area of 0.314mm^2 = 1/10 of the original area of 3.14 mm^2.

The radius of each new cylinder = 0.32mm and the ten together have the same cross sectional area as the single original cylinder.

Flux through the cylinders is proportional to r^4
Flux through the original cylinder = 1 unit
Flux through the 10 smaller cylinders = 10 $(0.32)^4$ units or 0.10 units

Thus while we have the same cross sectional area of pore space for flow, the total flux through the 10 smaller pores is only 1/10th that through the large one i.e. K is reduced to1/10th of its original value. As the pores get smaller the value of K falls off very rapidly. Halving the pore size reduces flow by $(1/2)^4$ or to 1/16th.

When all this is put together it explains why a soil with small pores drains very slowly and still remains wet when drainage has ceased. It also shows why it is necessary to install drains much closer in a soil with small pores than in a coarse soil. Very often heavy wet soils have as much, or more total pore space than well drained soils – the difference is in the size of the individual pores. The term "heavy" as applied to soils is based on the theory that because such a soil has a large percentage of very small pores it holds a lot of water and therefore is actually "heavy". Similarly a "light" soil has larger pores, does not retain water and therefore is "light".

Evaporation

The only other drying factor to be considered for Irish soils is evaporation or evapotranspiration. This is the only process to remove water from the soil after drainage ends. Evaporation or evapotranspiration is a physical process involving a change of water from a liquid in the soil to a vapour in the atmosphere. It is a well known physical concept that it takes 590 calories of energy to change 1 gram of liquid water to 1 gram of water vapour, which diffuses into the atmosphere. The only source of this energy is the sun. Measurements have shown that Ireland gets about 70,000 calories of solar energy per cm^2 per annum. If all this went to evaporate water then the total amount of water that would evaporate would be about 1250 mm, which is more than the annual rainfall in most places. In reality the theoretical possibility for evaporation for grass is about 450mm – 500 mm. Recent English findings have shown that it is possibly as high as 875mm from a fully grown forest in Ireland. In reality, evaporation from grass in Ireland accounts for some 375mm – 450 mm each year and almost all of this takes place from April to September inclusive, but mainly from May to August.

This concept is important for very large areas of Irish soils. Soils that cannot be drained or that have not been drained are dependent on this evaporation and these soils are suitable only for summer grazing.

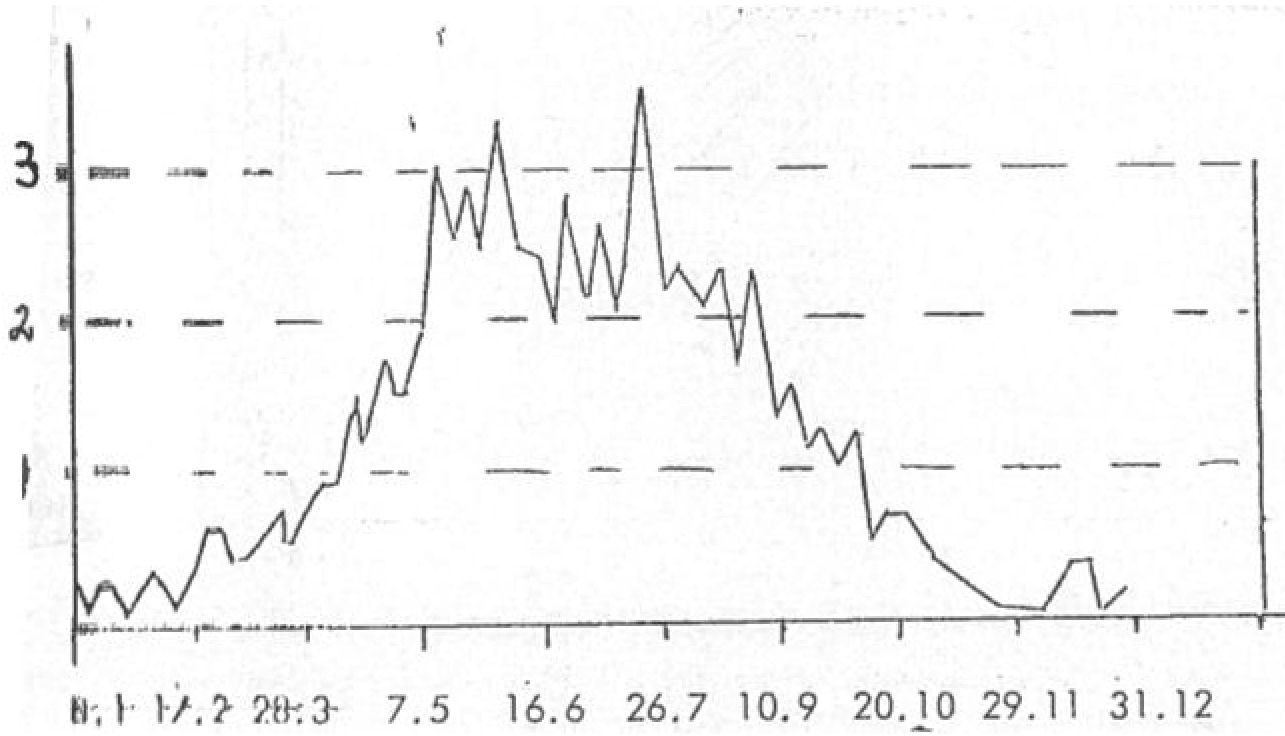


Fig. 11 Daily rates of evaporation (mm)

Summary

1. Soil consists of solids water and air.
2. The mineral part of the solids is composed of particles of different sizes.
3. Smaller particles dominate the physical properties due mainly to: (a) The relatively large surface area of small particles. (b) The effects of particle size on porosity and pore size distribution. (c) Some clay particles (clay minerals) have special properties.
4. The manner in which the soils individual particles are aggregated is called soil structure. A good soil structure has a range of pores of different sizes and the structure is stable.
5. Surface tension which causes water to rise in a capillary tube is responsible for the retention of water in small pores. Pores with radii less than 0.025mm do not normally dry out. Therefore soils with a lot of small pores will not drain.
6. Darcy's law is the fundamental law governing flow of soil water. The permeability coefficient or Hydraulic Conductivity K arises from Darcy's law and describes the drainage status of soil.
7. Flow is much slower through small pores than through large ones. The soils with very small pores have low permeability.
8. Water not removed from soil by drainage can be removed only by evaporation.