Water Diffusivity and Capillary Conductivity Studies of Some Libyan Soils: Valley Soil in Sidi El-Mesri in the Jaffara Plain

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INTRODUCTION

The amount of water available for plant growth per unit volume of soil is determined by the relation between the soil suction and the soil water content. However, the availability of water to plants not only depends upon the energy with which it is held by soil, but also on the rate of water movement in the soil in the direction of plant roots. Soil water movement in soil will occur when there are potential differences between different points in soil. The water tends to move from a position of higher to one of lower potential. The ability of soil to transmit water under a given potential gradient is determined by its hydraulic conductivity or diffusivity coefficient. In an unsaturated soil a part of the void space is filled with air. This reduces the volume of the medium that is available for the flow of water. Hence the hydraulic conductivity of an unsaturated soil depends on the moisture content. It is more often the case in arid and semi-arid regions as in Libya that the soil pores are not completely filled with water and one is concerned with the unsaturated water movement. A knowledge of the hydraulic conductivity and diffusivity of unsaturated soil is needed for any scientific prediction of infiltration, distribution and storage of moisture within the soil, evaporation and drainage from the soil.

Several techniques have been described for the measurement of the unsaturated hydraulic conductivity and diffusivity of soils, (2,3,5,6,7).

The objective of this research is to study the relationship between the water present in the soil and the energy with which it is held in the soil at three different depths in the valley area of the Jaffara plain soil. The soils are level soil, which have been under extensive cultivation, and the soil profile shows a little development, and soil texture is sandy loam, (1) Another objective of this study is to use the ouflow method first described by Gardner (3) and later refined by Miller and Elrick (8) to study diffusivity and unsaturated hydraulic conductivity as a function of both tension and moisture content for this valley soil at three different depths.

The above study is sorely needed for such soil in Sidi El-Mesri area since there is not

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any work in the literature about that soil and also it is needed for the prediction of infiltration and water distribution and movement of water to plant roots, in such soil (4,9, 10).

METHODS AND MATERIALS

The soil samples were collected from three depths of the soil in the valley area at Sidi El-Mesri in the Jaffara plain. The soils where the samples were collected have been under extensive cultivation for a long time and the profile shows some variation with depth. The samples were taken at 0–30, 30–60, and 60–90 cm. Depths with an undisturbed soil sampler which yields a core of soil 7.6 cm in diameter and 6.5 cm long. The undisturbed samples were carefully taken to keep soil structure and pore size distribution as in the field condition. The core samples were placed on the porous plate in the pressure chamber in the apparaturs. The essential parts of the apparatus used in this research is shown in Figure 1. The essential parts of this apparatus are (1) a pressure chamber with a porous plate, (2) an outflow volume measurement system, (3) a compressor as a source to supply pressure, (4) a system for control of the gas phase pressure in which gas pressure control was achieved with standard pressure regulators. A mercury manometer was connected to the pressure control system to measure the exact pressure applied in the pressure chambers. The porous plate was saturated with deaerated water by soaking it with water. The core samples were placed upon the porous plate in the pressure chamber and were saturated by soaking in water. After saturation the lowest gas-phase pressure desired was applied. In this research the pressure increments 50, 100, 150, 200, 250, 300, 400 and 500 millibars (cm of water) were applied. The flow was recorded for each pressure increment until equilibrium was attained. This equilibrium was reached when the flow of water was stopped for a given applied pressure increment. For each pressure increment applied, values of flux versus time were obtained and also the total volume of water removed from the sample as a result of the application of the pressure increment was measured. The resistance to flow in the porous plate is assumed regliqible in this research because the porous plate used has a low bubbling pressure (5).

RESULTS AND DISCUSSION

Figure 2 shows the relationship between the water present in the soil and the energy with which it is held or soil tension. There is seen to be a hyperbolic relation between the moisture content in soil and suction. The surface 0–30 cm depth holds water with comcomparatively lower tension compared to subsoil. For the 0–30 depth it is seen that as the suction is increased from zero to 100 cm water (zero to 100 millibars) the moisture percentage by volume changes from a possible maximum 41 at saturation to 14 at a suction of 100 millibars, while for the 60–90 cm depth it drops from a possible maximum 42.5 at saturation to 23.5 at 100 millibar tension. If we look at the value of retained water at 344 millibars which is considered the value of tension at which soil is at the field capacity moisture content, for 0–30 cm depth the moisture percentage is 7 while for 60–90 cm depth the moisture percentage is 11. However the United States Bureau of Reclamation has reported (10) extensive measurements of the moisture retention characteristics of soil, and they concluded that for sandy soils the 1/10 atmosphere retentivity is a satisfactory index of the upper limit of the available water. For the soil analysed in this research, if we apply this phenomenon and take 1/10 atmosphere as the upper limit for

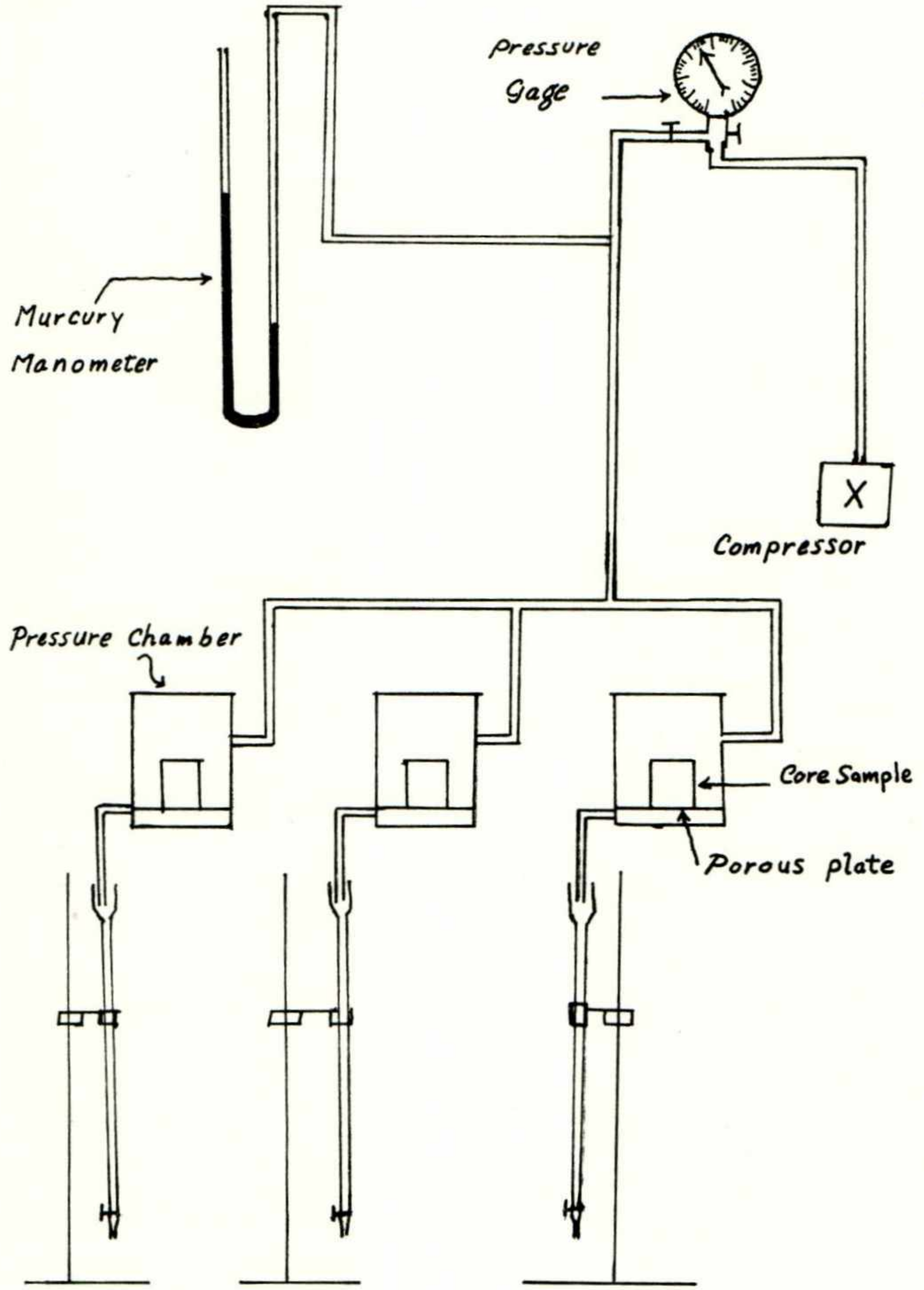

Fig. 1. Diagram of the apparatus constructed for the outflow method of soil water diffusivity and capillary conductivity determination.

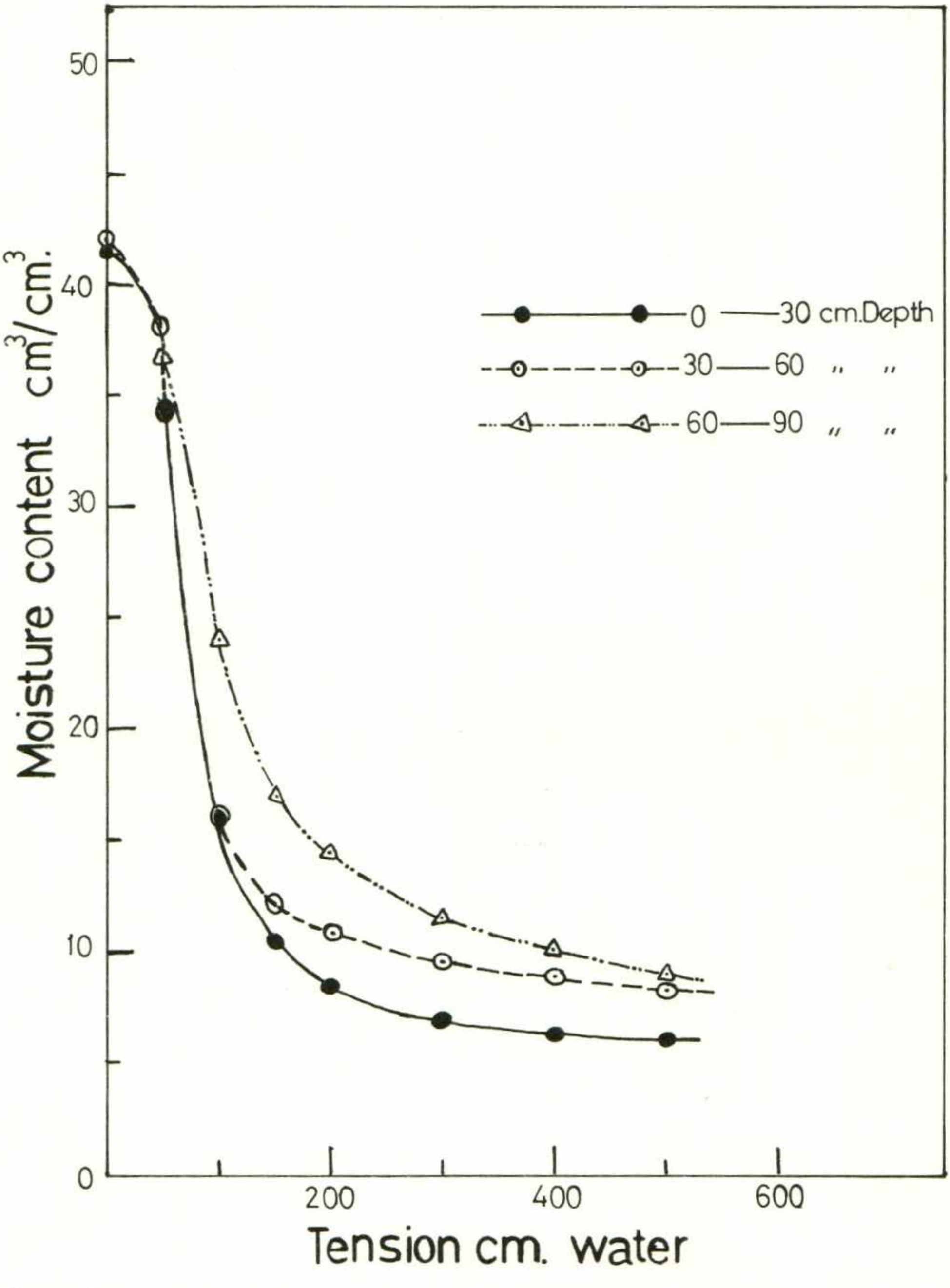

Fig. 2. Soil–water characteristic curves for three depths of soil in the valley area of the Jaffar Plain.

available water in soil, the 0–30 cm depth will contain 14 % of moisture as the upper limit of the available water while for 60–90 cm depth this moisture percentage is 23.5.

Relatively speaking as we can conclude from the three moisture tension curves, the curves for the depth 30–90 cm are seen to represent much more desirable moisture retention characteristics than the curve for 0–30 cm depth.

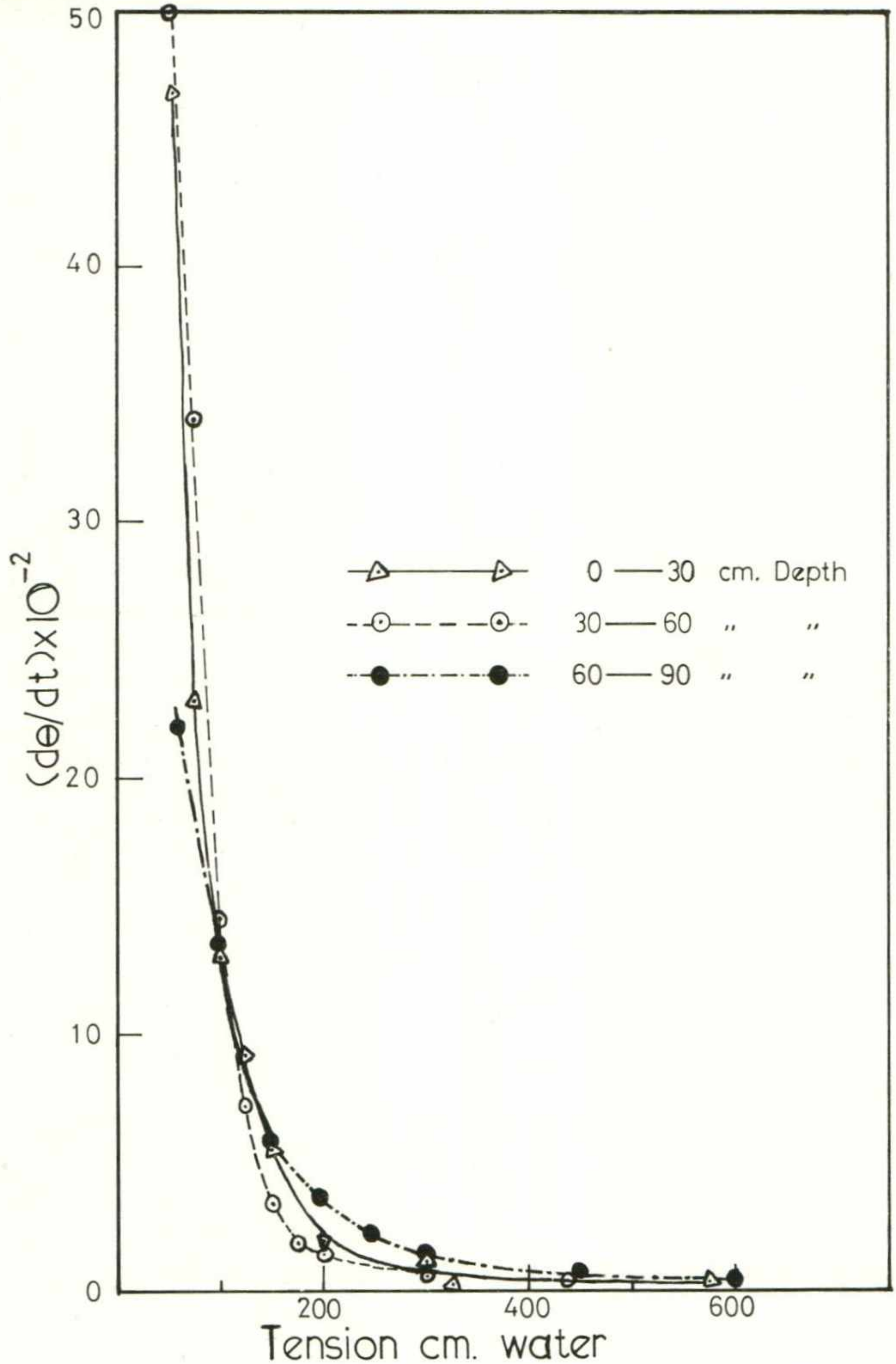

Fig. 3. Water capacity dθ/dT versus soil tension for three depths of soil.

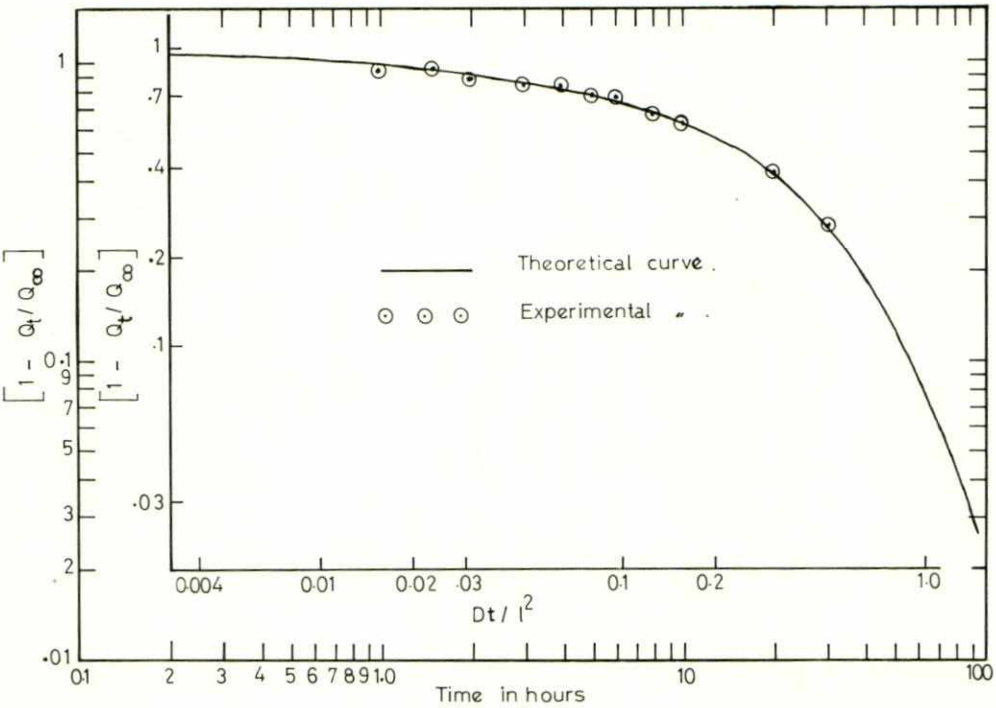

Fig. 4. An example of the overlay fitting of experimental data with the theoretical curve. D. is diffusivity and L is the length of core sample.

Figure 3 shows the relationship between water capacity and the tension in soil. The water capacity $d\theta/dt$ (where θ is the volumetric moisture content and t is the tension) is the change in water content of the soil per unit pressure head change (or per unit suction change). This water capacity tells at a given moisture content how much water the soil will release or absorb per unit change in suction. The values in figure 3 were obtained experimentally by measuring the slope of the moisture characteristic curves at different values of tension. As shown in the figure the three curves for the three depths examined, are close to each other. We can see that the value of the water capacity decreases at a rapid rate when the tension is increased; then the curves level up. This means that the soil releases moisture rapidly at the initial application of pressure and this rapid initial release of moisture will result in emptying the pores. This indicates that a large portion of the soil pore spaces are large in size and they are not capable of holding moisture at high tension.

Figure 4 shows an example of the fitting of experimental outflow data with the theoretical curves for the determination of water diffusivity. The experimental value of flux Q(t) versus time was obtained during each pressure increment applied on the soil samples inside the pressure chambers while $Q(\infty)$ is the total amount of water released from the soil sample during a given pressure increment applied on soil. Experimental data was plotted on translucent log-log graph paper used as an overlay, which is then matched by horizontal and vertical translation to an underlay plot of the diffusivity equation prepared on the same kind of log-log graph paper. The diffusivity equation which is used in this analysis is of the form

$$1 - \frac{Q(t)}{Q(\infty)} = \frac{8}{\pi^2} \sum_{m=0}^{\infty} \frac{1}{(2m + 1)^2} \exp\left[\frac{-(2m + 1)^2 \pi^2 Dt}{4L^2}\right]$$

where Q(t) is the volume of outflow at time t, and $Q(\infty)$ is the total volume of outflow occurs because of the applied pressure increment, L is length of the core sample, and D is diffusivity. **A theoretical plot of the quantities $(1 - Q(t)/Q(\infty))$ versus log (Dt/L^2) was** constructed. With this theoretical curve a plot of experimental values of log $(1 - Q(t)/Q(\infty)$ versus time was matched. In general the fitting of experimental data with the theoretical curve was good, and no difficulty was encountered in the present research. Fitting difficulty has been reported by some investigators, (2,7). From fitting experimental data with theoretical curve, water diffusivity at different values of tension was obtained. Once the diffusivity was obtained the relation.

$$D(\theta) = \frac{K(\theta)}{C(\theta)}$$

(where $D(\theta)$ is the diffusivity coefficient and is a function of either tension or moisture content, $K(\theta)$ is the unsaturated hydraulic conductivity coefficient and is also a function of moisture content or tension, and $C(\theta)$ is the water capacity coefficient usually expressed as $d\theta/dt$ as was explained earlier), was used.

Figure 5 shows the relationship between diffusivity and moisture content in soil for the three depths studied. The diffusivity curves are particularly interesting. After a rapid initial decrease with decreasing moisture content, a plateau occurs over which the diffusivity is more pronounced in the coarse textured soil than the ones on which this research was conducted. In this region where the plateau occurs, the increase in the slope of the moisture tension curve is sufficient to more than counteract the decrease in conductivity as the suction increase.

Figure 6 shows the relationship between the capillary conductivity and the value of tension in soil. The curves were fitted to the data points. It is seen in the figure that with increasing suction there is a very rapid decrease in the capillary conductivity of soil for the three depths studied. For example for 30–60 cm depth the value for K (capillary conductivity) at a suction equal to 100 millibars (100 cm of water tension) $= 0.26$ cm/hour while at a suction equal to 300 millibars (300 cm of water) the value for $K = 0.001$ cm/hour, a change which has the ratio $0.260/0.001 = 260$. This rapid decrease is due to rapid emptying of soil pores of water with increasing suction in such coarse soil. Figure 7 shows the relation between capillary conductivity and moisture content in soil. The three curves for the three depths fall close to each other and they follow the same trend. This indicates that as far as the capillary conductivity of the soil is concerned, the soil is homogeneous for the property of transporting water under the unsaturated condition. As is shown in the curves there is a rapid decrease in the value of capillary conductivity for a small change in the moisture content. For example, if we look to the curve for the depth 30–60 cm we find that at moisture content equal to 40% by volume, which is close to saturation condition of the soil, the capillary conductivity is 0.8 cm/hr, which indicates that the soil is a good conducting medium for moving water when all the pores are involved in this conduction at saturation. If the moisture content decreases to 20% by volume, the value for capillary conductivity is equal to 0.3 cm/hr, or $(K_{40}/K_{20}) = 0.8/0.3 = 2.7$ or K at 40% moisture content is 2.7 times the hydraulic conductivity at 20% moisture content. If we look to a change in capillary conductivity between a moisture content equal to 20% and a moisture content equal to 10%

$$(k_{20}/k_{10}) = \frac{0.3}{0.0003} = 1{,}000$$

we find that a 1/1000 reduction in the value for capillary conductivity occurs when the moisture content decreases from 20% to 10% on volume basis. The 10% moisture con-

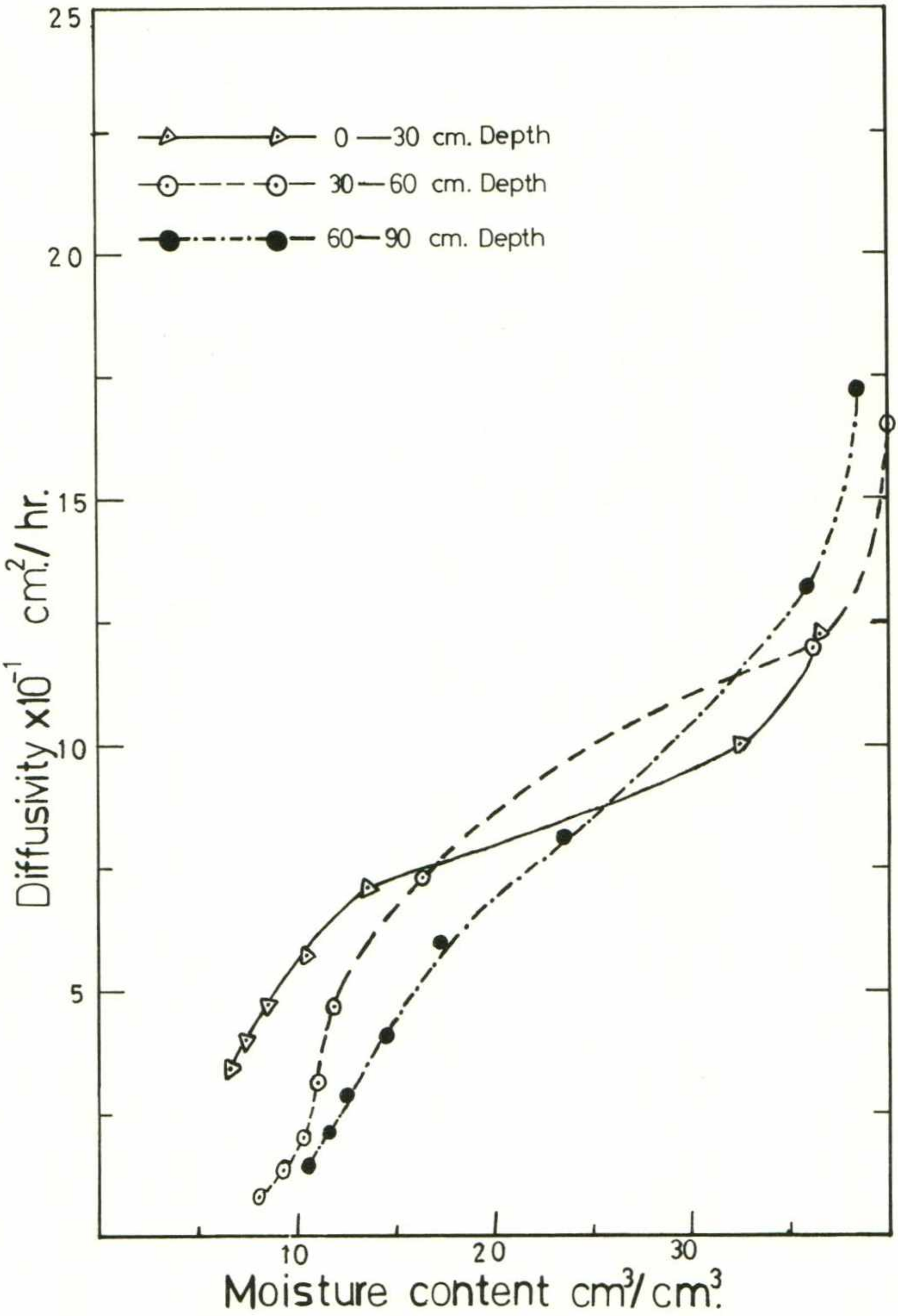

Fig. 5. Diffusivity plotted as a function of moisture content for three depths of soil.

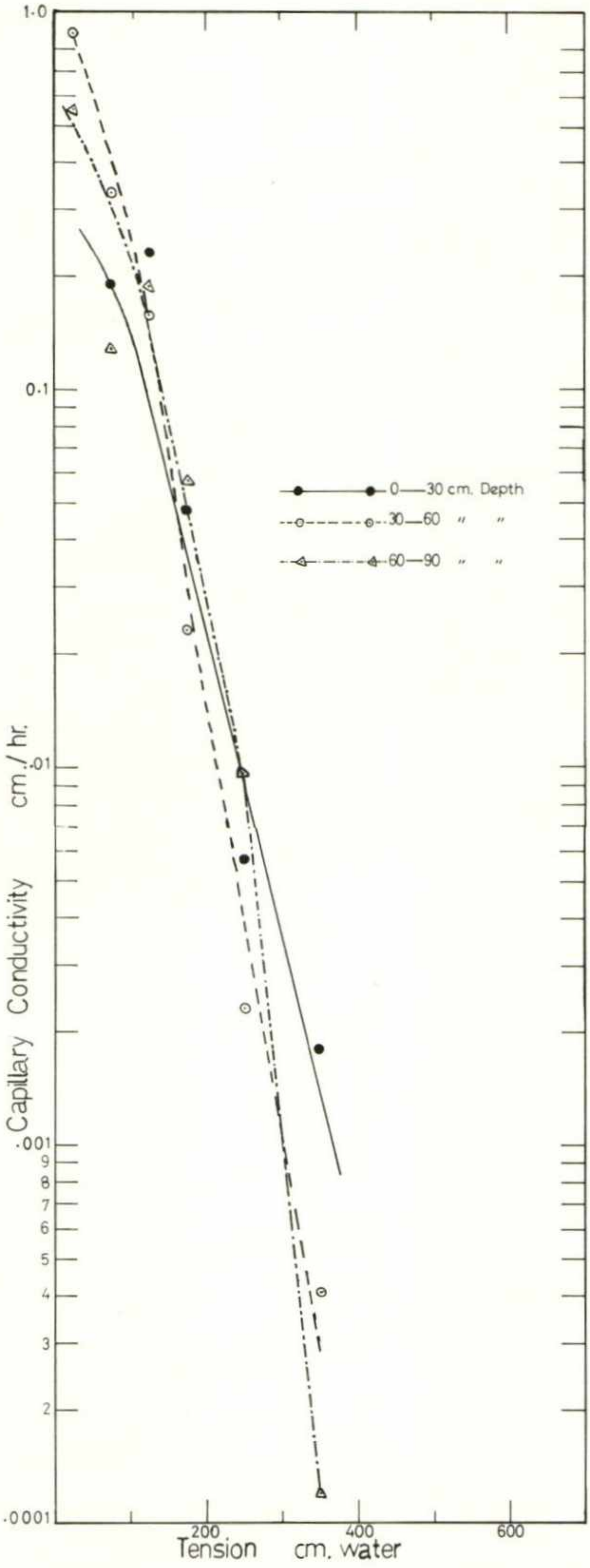

Fig. 6. Capillary conductivity plotted as a function of soil-water tension for three depths of soil.

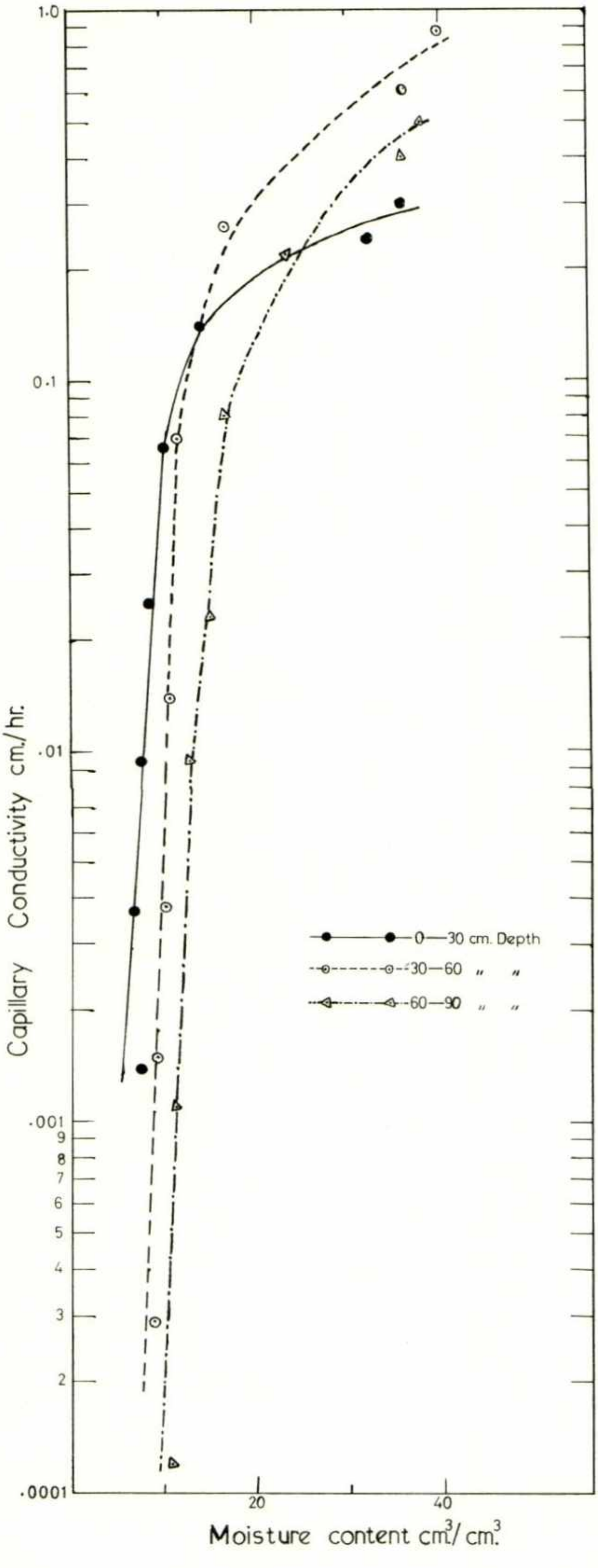

Fig. 7. Capillary conductivity plotted as a function of moisture content on volume basis for three depths of soil.

tent represents approximately, the moisture content at field capacity, if we take the value of moisture content at a tension equal to 340 millibar as the value of the moisture content at field capacity.

This explains in part why crop plants in such coarse textured soils show drought symptoms so readily on hot dry days. Not only is the amount of water present in such soil less compared to fine textured soils, but also when the suction is appreciable or in turn the moisture content is low, the moisture movement to the roots is limited by low capillary conductivity. The values in Fig. 7 could be used to calculate the velocity of water movement to the roots of plants under a given potential gradient. It also has been frequently observed and reported that a day or two after irrigation, the rate of drainage of water from the wetted portion of the soil materially decreases. In view of the capillary conductivity data in Fig. 7, this is easily explained by the fact that the drainage rate becomes low as the capillary conductivity attains low values.

The relation of soil moisture and capillary conductivity to suction are measureable soil moisture characteristics that have practical usefulness. Given these characteristics along with the initial conditions and boundary conditions, it is possible to calculate, at any later time, the rate of flow and distribution of water in any given field situation.

SUMMARY

For soils in the valley area in Sidi El-Mesri in the Jaffara Plain, moisture characteristic curves were obtained at three depths. Using undisturbed core samples for these three depths water flux versus time curves were matched with the theoretical curves of the solution of the flow equation. From this matching process values of diffusivity and capillary conductivity of soil were calculated. The relation between the capillary conductivity and both tension and moisture content for the soils was obtained.

It was found that the soil at the three depths studied releases moisture rapidly with the increasing tension. The surface soil is faster in that respect than the subsoil. If we consider the value of tension = 340 millibar as the value of water at field capacity, the field capacity of surface soil was about 7 % moisture content on volume basis, while for the subsoil the field capacity was about 11.5 %, both values are low values for retaining water in soil for growing plants. For this reason irrigation between short intervals is needed to always supply growing plants with ample amount of water.

The capillary conductivity versus both tension and moisture content curves for the three depths studied are close to each other. The general conclusion from the capillary conductivity data is that when the soil contains a high amount of water, the capillary conductivity is very high, which indicates that these soils transport water at a high rate when they are close to saturation. When the moisture content decreases in soil a very rapid decline in the value of the capillary conductivity takes place. A 1/1,000 reduction in the value for hydraulic conductivity was obtained when the moisture content in soil was changed from 20 % on volume basis to 10 %. It is concluded that this soil is a very slow medium for transporting water under low water content. This conclusion in part explains why crop plants in such soil show drought symptoms on hot dry days because movement of water in the direction of roots is limited by these low values of capillary conductivity.

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