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Determination of Unsaturated Hydraulic Conductivity and Diffusivity as a Function of Moisture Contents and Soil Suctions

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***Abstract*- This study on unsaturated hydraulic conductivity and diffusivity of a soil was conducted at Agricultural engineering experimental plot, Ahmadu Bello University, Zaria. Experimental conductivity was carried out from five profile pits with samples taken from (15, 30, 45 and 60cm) depths. The saturated conductivity (Ks) was first determined in the laboratory using the constant head method, the gravimetric moisture contents were estimated in the laboratory using the pressure plate extractor by applying the required suctions at (0, 0.1, 0.3,1,5,10 and 15) bars. The bulk densities of the samples collected were also estimated. The volumetric moisture contents were determined by multiplying the gravimetric moisture contents with their corresponding bulk densities. Jackson's model of 1973 was applied to determine the unsaturated hydraulic conductivity at each moisture content using the formula $Ki = Ks(\theta i/\theta s)\ (\sum_{j=i}^{m}[(2j+1)-2i)\varphi j-2])/(\sum_{j=1}^{m}[(2j-1)\varphi j-2])$. The soil suction and the volumetric moisture contents were related to $K(\varphi)=[a\varphi]^{m}m$ and $K(\theta)=b\theta^{m}$. Where K is the degree of saturation or unsaturation. φ is the volumetric moisture content and θ is the soil suction head, a, b are the empirical constants while m and n are constants for the measure of the steepness. Mualem Van Gunatchen model of 1976 predicted a formula which was used in determining the hydraulic diffusivity by multiplying the conductivity to the differential of this relation$\varphi=a\theta^{m}$. Major findings of this study revealed that the value of the diffusivity as a function of volumetric moisture content decreases down the profile pit, this could be as a result of the existence of materials in the soil with increase in the suction. The coefficient of determinant (R^2) decreases down the profile, it was also observed that the bulk density (B) and Porosity affect the hydraulic conductivity (Ks) and diffusivity (D) of the soil on site.**

***Keywords*- Unsaturated hydraulic Conductivity, Diffusivity, Moisture Contents, Soil Suction, Zaria.**

I. INTRODUCTION

Hydraulic conductivity of a soil refers to the measure of how easily water passes through the soil and unsaturated hydraulic conductivity is a measure of soil's water-retaining ability. When soil pore space is not saturated, it infiltrates into the true soil matrix (James et al., 1995). The basic purpose of cover lining is to minimize fluid flow and contain liquid that might contaminate the surface soil and the water table. One most important factor governing the performance of these containment systems is the hydraulic conductivity (Fredlum, 1995), which mainly depend on the water content, dry density, and degree of saturation (i.e. the compaction state) of the soil the movement of moisture and hence the spread of the contaminated that takes place in the region surrounding the water containment area, which is mostly unsaturated (Grosy, 1995).

Hydraulic conductivity is classified as direct and indirect method. The direct method is quite tedious and time consuming and requires expensive set up. The direct methods for measuring involve paired measurements of water content and metric potential (Farimah et al., 2008). Several methods have been reported, e.g., tensiometer method pressure plate technique, hanging water column method, and psychrometer method broadband dielectric spectroscopy and magnetic resonance sounding (Steven and Ugur, 2013). Indirect method provides a measure of the quality of water in the soil which can be used to estimate the hydraulic conductivity (Donghao et al., 2017). Dynamics of the quality of water in unsaturated soil system can be described by various differential equations derived from the combination of Darcy's law and conservation of mass of principle. Derivation of such equation under varying boundary and initial condition require knowledge of volumetric water content in soil(θ),

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soil water suction(φ), rate at which water flows in the soil (K) (Marco et al.,2010). Therefore, the Hydraulic Conductivity equation can be expressed as;

$$K(\theta) = d\varphi/d\theta \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Unsaturated hydraulic conductivity at each moisture content were estimated using the formula;

$$K_i = Ks\left(\frac{\theta i}{\theta s}\right)\frac{\sum_{j=i}^{m} |(2j+1)-2i)\varphi j-2|}{\sum_{j=1}^{m} |(2j-1)\varphi j-2|} \ldots\ldots\ldots\ldots (2)$$

The soil suction and the volumetric moisture contents were related to;

$$K(\varphi) = a\varphi^m \text{ And } K(\theta) = b\theta^m \ldots\ldots (3)$$

Saturated and unsaturated soil hydraulic conductivity is one of the most important hydraulic properties, which affects water flow and solute transport. Many part of the world, most land slope influences the soil properties, such as mixture distribution, infiltration rate and cumulative sorpivity, (Safar and Majid 2009) other factors affecting saturated and unsaturated hydraulic conductivity are pore size distribution, pore shape, porosity, specific surface tension, soil structure, bulk density of the soil and organic matter of the soil (Sean et al., 2007). Porosity which is the major factor for determining the hydraulic conductivity and diffusivity can be expressed as;

$$\text{Porosity (F \%)} = 1 - \frac{BD}{2.65} \ldots\ldots\ldots\ldots (4)$$

Where BD is the bulk density of the soil samples and F is the porosity.

Hydraulic diffusivity gives a measure of diffusion speed of pressure disturbances in groundwater system; large values of hydraulic diffusivity leads to fast propagation of signals in aquifers soil water diffusivity (Ds), change in soil water content per unit in suction(φ), and the relationship among them (Timms et al., 2014). The soil water diffusivity, which is the ratio of the hydraulic conductivity to the differential of water capacity, may be used to analyze the behavior of a soil water system which can be expressed as the product of the hydraulic conductivity by the slope as given in equation 5 below (Klute and Dirksen, 1986)

$$D(s) = K(\theta)\frac{d\varphi}{d\theta} \ldots\ldots\ldots\ldots (5)$$

The hydraulic diffusivity of unsaturated and saturated soil with different salt contents, saline concentration and dry densities is studied by means of wet front, and advancing in a horizontal soil column (Maritxell et al., 2011). It is found that the hydraulic diffusivity of water or saline is an exponential function of water moisture content and decreases with water content. For the same type of soil. When dry density and water contents are the same, the hydraulic diffusivity of the soil water increases with salt content, especially the coarse grained (Jidong et al., 2019).

As saline migrates in the soil, the hydraulic diffusivity of saline decreases with saline concentration (Deng, 2006). Kool et al., 1985 stated that the importance of hydraulic diffusivity is to determine the accurate hydraulic properties for field soil, the component of regional scale climate model, to enables simultaneous determination of unsaturated hydraulic conductivity and to determine the soil water characteristics. These necessitate the above research topic for accurate determination of the soil water infiltration and the rate at which water diffuses into the soil.

II. BACKGROUND OF THE STUDY AREA

This research work on the determination of unsaturated hydraulic conductivity and diffusivity was carried out on Experimental plot of Agricultural Engineering in the month of August 2012 with other supporting laboratory work done all together. The constant head permeameter was used to determine the saturated hydraulic conductivity and pressure plate apparatus was used to determine the suction and the moisture contents.

1. Site Description and Survey:

The study area is the Agricultural Engineering experimental plot just behind the Department of Agricultural Engineering, Ahmadu Bello University, Zaria-Kaduna.(Latitude 11^0 11"N Longitude 7^0 38"S and an altitude of 686m above sea level).The area falls within the Northern Guinea Savanna ecological zone of Nigeria as shown in figure 1 below.

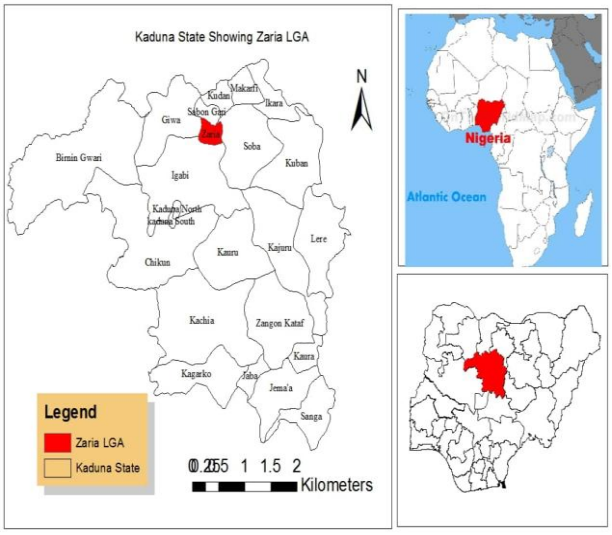

Fig 1. A detailed Map of Kaduna State, Showing Zaria Local Government Area.

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Rainfall for this area is seasonal with an annual mean of 1060mm which falls between the month of April and September. A detailed survey of the area was carried out by Ibrahim (2005).According to Ibrahim's survey; the area is approximately 11712km² which is equivalent to 1.17ha as shown in figure 2.

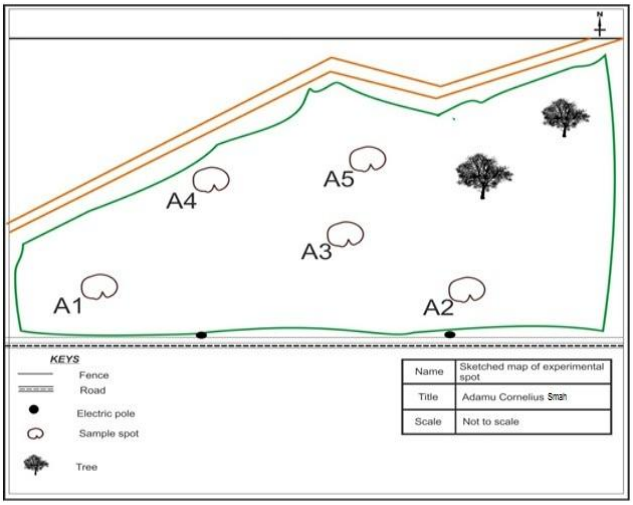

Fig 2. Experimental Field Layout.

2. Experimental Layout:
Random sample technique employed for the collection of samples.

Five locations were dug to a depth of 60cm each. The first, second, third, fourth and fifth locations were tagged as A1, A2, A3, A4, and A5 respectively.

Undisturbed samples were taken at depth of 15cm interval up to 60cm (0-15, 15-30, 30-45, and 45-60) cm at every spot. The total samples collected were 20 for the determination of bulk density, hydraulic conductivity and textural class.

3. Equipment Used in the Field:
Equipments used in collection of samples at the field for constant head permeameter are. Digger, Small hoe, Measuring tape, Bucket, Shovel, Core samplers, Polyethene bags, Pen, Papers, and Masking tape

Fig 3. Soil Samples.

III. RESULTS AND FINDINGS

1. Results:
From the methods used in calculating unsaturated hydraulic conductivity and diffusivity as described in chapter three, the following results were obtained, hydraulic conductivity as a function of suction, hydraulic conductivity as a function of volumetric moisture content. The hydraulic conductivity as function suction and hydraulic conductivity as a function of volumetric moisture content are shown in table 1, while hydraulic diffusivity as a function of volumetric.

Table 1: Hydraulic Conductivity as a Function of Volumetric Moisture Content (Θ) and Soil Suction (Ψ).

Soil Dept (Cm)	Profile Pit: A_1 A_2 A_3 A_4a_5
0 - 15	$K(\Theta) = 2.27 \times 10^{-7}\theta^{60}$ $R^2 = 0.61$ $K(\Psi) = 9.71 \times 10^{-2}\psi^{-5.6x10^{-2}}$ $R^2 = 0.84$
15 – 30	$K(\Theta) = 4 \times 10^{-10}\theta^{50}$ $R^2 = 0.58$ $K(\Psi) = 6.28 \times 10^{-2}\psi^{-5.9x10^{-2}}$ $R^2 = 0.83$
30 – 45	$K(\Theta) = 4 \times 10^{-9}\theta^{40}$ $R^2 = 0.45$ $K(\Psi) = 6.84 \times 10^{-2}\psi^{-5.96x10^{-2}}$ $R^2 = 0.80$
45 – 60	$K(\Theta) = 2.8 \times 10^{-5}\theta^{33}$ $R^2 = 0.30$ $K(\Psi) = 0.1224\times10^{-5}\Psi^{-6}$ $R^2 = 0.75$

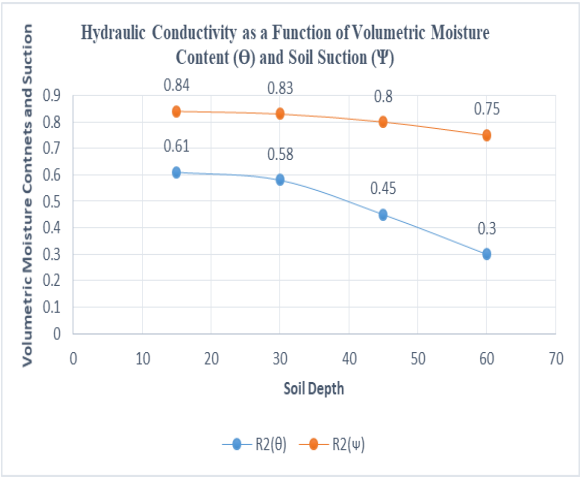

Fig 4. A Graph of Hydraulic Conductivity as a Function of Volumetric Moisture Content (Θ) and Soil Suction (Ψ).

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Table 2. Hydraulic Diffusivity as a Function of Volumetric Moisture Content.

Soil Depth(Cm)	Profile Pit: A_1 A_2 A_3 A_4 A_5
(0-15)	$D(\Theta)=1.06\times10^{-26}\ \Theta^{10\ 20}$ $R^2=0.65$
(15-30)	$D(\Theta)=8.15\times10^{6\ 2}\Theta^{26\ 7}$ $R^2=0.52$
(30-45)	$D(\Theta)=1.96\times10^{18}\ \Theta^{25\ 4}$ $R^2=0.4$
(45-60)	$D(\Theta)=1.7\times10^{6\ 0}\ \Theta^{14\ 2}$ $R^2=0.24$

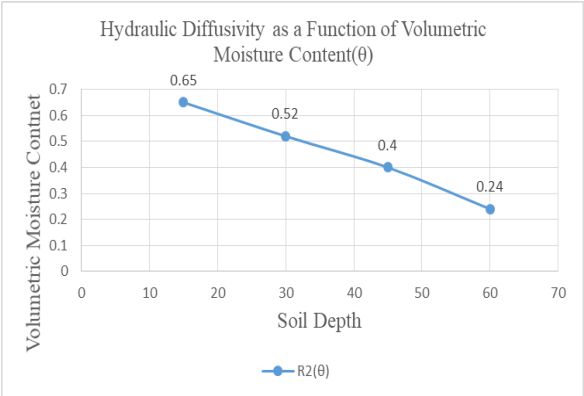

Fig 5. A graph showing the Hydraulic Diffusivity as a Function of Volumetric Moisture Contents.

Table 3. Physical Properties of the Profile Pits.

Soil Depth (cm)	Porosity F (%)	Bulk density (g/cm²)	Hydraulic Conductivity Ks (cm/s)	Hydraulic Diffusivity Ds (cm/s)
0-15	55	1.19	1.56	6.23
15-30	46	1.42	1.25	5.20
30-45	45	1.49	1.20	4.12
45-60	44	1.49	1.18	3.92

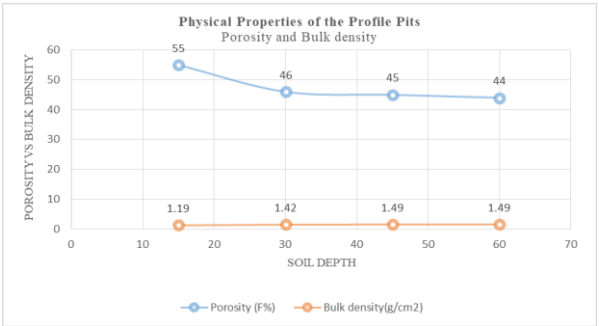

Fig 6. A Graph Showing Porosity and Bulk Density of the Profile Pits.

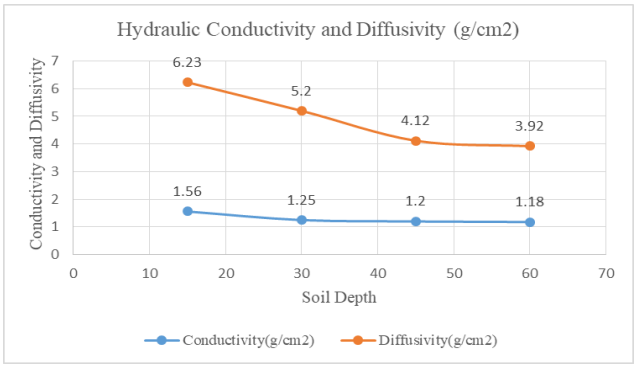

Fig 7. A Graph showing the Hydraulic Conductivity and Diffusivity (g/cm2).

2. Discussion:

From table 1.The Hydraulic conductivity as a function of suction and volumetric moisture content conformed to the empirically based equation by Mualem Van Gunatchen as; $k(\psi)=a\psi^n$ and $k(\Theta)=b\Theta^m$, where K is the hydraulic conductivity at any degree of saturation or instauration, ψ is the metric suction head which is the volumetric wetness, a, b, m, and n are empirical constants (different at each suction).

The exponential parameter m gives the characteristics of the volumetric moisture contents, where m value decreases with decrease in the magnitude R2 of the moisture contents. This agree with the research by Matsushi and Matsukura, 2006 which says that for an undisturbed soil, volumetric moisture contents decrease with decrease in hydraulic conductivity down the slope.

The exponential parameter n characterizes the steepness with R2 decreases with increasing suction ψ (n controls the steepness with which conductivity decreases with increase in suction or with decreasing water content).

The averages of the five profile pits from 0-60cm depth were calculated. The suctions were found to be negative for the unsaturated soils, and increasingly negative down the soil profile. This indicates that the drier the soil, the more positive the suction for the saturated soil. The suction in which water is retained in the soil structure is responsible for the pressure that exists at each levels of the soil profile (Bittelli et al., 2012). For a given degree of saturation, it is more negative in fine grained soil than in coarser grained soil (Nazil, 2018)

Table 2 observed that m and R2 value of the diffusivity as a function of volumetric moisture contents decreases down the profile pit, this may be because of the existence of materials in the soil and the characteristics of soil in various layers or horizon down the pit. Most of these particles that decreases or reduces the moisture contents of soil down the pits originate from the degradation of rocks; they are called mineral particles, some originate from residues of plants or animals (rotting leaves, pieces of bone, etc.)(Peter 2019).

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Table3 Indicate that the bulk density (B) affects the hydraulic conductivity (Ks) and diffusivity (Ds). As bulk density increases, Ks and Ds decreases, and when the bulk density decreases, Ks and Ds increase. Also, the total porosity (F) decreases down the profile pit, where Ks and Ds decrease also. Profiles of a soil and field capacity increase with aggregate stability. when total porosity reduces the bulk density of the soil increase and vice versa (Zeynep and Dognan, 2019) as seen in table3.Organic matter also improves soil porosity, the hydraulic properties of soils with identical texture depend on bulk density and structure (Dorota et al., 2008) The increasing bulk density not only induces changes in the pore-size distribution but also affects the ability of soil to shrink and to conduct water under unsaturated conditions. From the results, greater shrinkage was observed because of reduction of coarse pores. The water content differences increase with decreasing bulk density (Dorota et al., 2008).

IV. CONCLUSION AND RECOMMENDATION

From the results of the hydraulic conductivity and diffusivity using constant heads permeameter, it was observed that the values of hydraulic conductivity and diffusivity on the same site decreases down the horizon. The soil physical properties like the porosity, bulk density have great influence on the soil hydraulic conductivity and the soil-water diffusivity on the site.

This work should be adopted in the country especially in erosion and flood prone areas in determining the hydraulic conductivity and water diffusivity of soils in other to design and construct safe canals in controlling floods and erosion and also to determine aeration of various soil for the cultivation of crops in the country of various varieties for optimum and high productivity.

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