American Journal of Engineering Research (AJER)
e-ISSN: 2320-0847 p-ISSN : 2320-0936
Volume-5, Issue-7, pp-47-52
www.ajer.org
Research Paper Open Access

Saturated Hydraulic Conductivity (K_s) of Lower Coal Measure Geological Formation of Owukpa in the River Benue Trough, Nigeria

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ABSTRACT : *A study was conducted to determine saturated hydraulic conductivity (k_s) of lower coal measure geological formation of Owukpa region of Benue State Nigeria. The process involved the selection of points on the location (soil formation) and sample collection at a depth of 20cm (0.2m). The soil samples were analyzed in the laboratory to determine the saturated hydraulic conductivity using falling head method. Particle size distribution, bulk density and pH were also determined. The result indicates that highest and lowest hydraulic conductivity determined were 2.59 x 10^{-4} cm/sec and 2.38 x 10^{-4}cm/sec respectively. The characteristic of soil shows that the nature of the soil in the region is very compactable to use for engineering purposes as to the construction of conservative structures such as earth dam.*

Keywords*: Conductivity, Porosity, Infiltration, Compaction, Runoff, Erosion.*

I. Introduction

Soil generally, is a vital natural resource that is non-renewable on the human time scale and it is a living, dynamic, natural body that plays major key roles in terrestrial ecosystems. Soil is a rich mix of mineral particles, organic matter, gases and nutrients, and is home to billions of macro- and microscopic organisms. It is the essence of life and health for the well-being of humankind and animals and the major source of most of our food production. The maintenance of soil health is essential for sustained production of food, decomposition of wastes, storage of heat, sequestration of carbon and exchange of gases. Soils also provide the geologic, climatic, biological and human history [1].

Agricultural management strongly affects soil erosion and soil erosion induces a decline of field productivity through removal, transport and deposition of top soil, and thus agricultural sustainability [2], [3], [4].

Depending on the soil type and the rainfall characteristics, the soil tries to resist erosion. Erosion occurs when the erosive forces overcome the resistive forces. Soils exhibit different degrees of susceptibility (saturated hydraulic conductivity) to the forces generated by erosion agents; wind and water.

Saturated hydraulic conductivity is defined as the quantitative measure of a saturated soil's ability to transmit water when subjected to a hydraulic gradient. It is a function of both physical and chemical properties of the soil, land use and crop management [5]. According to Darcy's law, in a saturated condition, the flow velocity can be expressed as

$$V = K \frac{\delta h}{\delta x}, \quad (1)$$

where x is the distance in the direction of groundwater flow, h is the hydraulic head.

Saturated hydraulic conductivity (K_s) is affected by several factors. Some of these have direct influence while some indirectly affect soil K_s by their influence on the soil properties. These soil properties include texture, structure, infiltration rate, organic matter content, clay mineral, cation exchange capacity, shear stress, bulk density, crust, slope and the crop cover, temperature, pressure, properties of soil fluid [5], [6], [7] and [8]. If other factors including rainfall are kept constant, a soil with high K_s will suffer more erosion than that with low K_s.

[9] showed that soils with 40% to 60% silt content are the most saturated. On the other hand, soils with clay content between 9% and 30% are susceptible to erosion. Clay particles combine with organic matter to form soil aggregates or clods and it is the stability of these that determines the resistance of the soil.

Soil structures go a long way in affecting saturation by affecting such soil conditions as; water movement, bulk density and porosity. A well aggregated soil permits paste, and water movement thereby reducing runoff which will eventually cause erosion when compared with a poorly aggregated soil of the same texture.

Infiltration rate exerts a major control over the generation of runoff. The value tends to be high at the beginning of a rain storm and declines to a level representing the maximum sustained rate at which water can pass through the soil. A high infiltration rate generally implies a low runoff, while a low infiltration rate gives rise to a high runoff. Infiltration rate depends on the characteristics of the soil.

Generally, coarse-textured soils such as the sandy and sandy loam have higher infiltration rate and thus lower runoff making them less Saturated. This is as a result of the fact that these soil particles have large pore spaces between them. Clay soils on the other hand have low infiltration rate and thus high runoff thereby making them more saturated. This is because of the small pore spaces between their particles. Large cracks or macro pores found between soil pods and clods also exert an important influence over infiltration.

Soils with low proportion of pore spaces have lower bulk density as compared with those that are more compact and with less pore space. Soils like silty loamy, loamy and clayey are less saturated than sandy soils because of their lower bulk densities than sandy soils. This is attributable to the fact that these soils have fine textures which tend to be organized in porous grains or granules. This condition assures high total pore space which means low bulk density.

The system of crop and soil management employed on a given soil influences its bulk density, especially of the surface layer.

The cation exchange capacity of a soil depends on the type of clay and amount present in the soil. This is because it is clay that possesses the element with negative charges. Generally, as that amount of clay increases, the cation exchange capacity increases [10]. The higher the cation exchange capacity of a soil, the less saturated the soil is.

Increase in the shear stress of a soil help in breaking the internal arrangement and ultimately the soil loses its structure. When the soil looses its structure erosion then sets in. The amount of clay increases in a soil, the critical shear stress which will induce failure increases.

Crust reduces infiltration capacity thereby promoting greater surface runoff and invariably making the soil concerned to be easily saturated. Measurement on a sandy soil has indicated that crushing reduces the infiltration capacity from 100 mm/hr to 9 mm/hr and on a loose soil from 45mm/hr to 5mm/hr [11]. Crushability decreases with increasing clay content and organic matter since this provides greater strength to the soil. Thus loamy and sandy loam with a small amount of clay present are the most vulnerable to crust formation. This implies that these soils are easily saturated. [12] in a laboratory experiment proved that medium and coarse particles are most easily detached from the soil mass than clay particles. This may be because the rain drop energy has to overcome the adhesive or chemical bonding forces by which the clay minerals are linked. Vegetation and land use influence Saturation by influencing organic matter content, permeability, infiltration and water stable aggregates.

[5] confirmed saturated hydraulic conductivity classes as the standard for communicating water movement. The subject of hydraulic conductivity is essential to the understanding of flow through soils. It controls the drainage rate of soil. Also it has significant impact on geotechnical problems (retaining walls, slopes, embankment, foundations etc). The knowledge of saturated hydraulic conductivity is essential for irrigation and drainage management purposes and for hydrological modelling [13], [14], [15], [16]. Management and tillage practices have significant influence on different hydraulic properties under agricultural land use [17].

[7] pointed out that K value is the best and the most plausible basis upon which to design, optimize and control the rice fields water management. Also that such data are necessary for design of basic parameters of paddy fields irrigation and drainage systems, and can also be used for the verification of the correctness and hydraulic efficiency of the designed systems. [18] and [19] also reported that K is one of the principal soil hydrologic characteristics especially in case of paddy fields. Surface layers of soils of fluvial deposits above a low permeable layer ($< 1.10^{-6}$ m/s) will be much more permeable.

Researchers have reported spatial and temporal variation of K frequently found in the field. There is seasonal variation in K_{sat} values due to change in vegetation cover and rainfall intensity [20], [21], [22], [23]. Soil compaction affects hydraulic properties and thus can lead to soil degradation and other adverse effects on environmental quality. It changes the ability of soil to hold water, decreases infiltration rate and saturated hydraulic conductivity, and increases penetration resistance [8].

According to [7] saturated hydraulic conductivity can be determined either by laboratory methods (constant head or falling head) or Field Methods (Test basins). Constant head method is used for soil with high K_s (> 0.0011 m/s). The falling head is used for soils with lower K_s ($10^{-3} – 10^{-6}$ cm/s). The constant-head method is the simplest method of determining hydraulic conductivity of saturated soil samples. The inflow of fluid is maintained at a constant head (h) above a datum and outflow (Q) is measured as a function of time (t). Using Darcy's law, the saturated
hydraulic conductivity can be determined using the following equation after the outflow rate
has become constant:

$$K = QL/hA, \quad (2)$$

where:

K = hydraulic conductivity, LT-1; L = length of sample, L; A = cross-sectional area of sample, L2; Q = outflow rate, L3T-1; and h = fluid head difference across the sample, L.

Constant-head methods should be restricted to tests on media having high fluid conductivity.
In the falling head method, the head of inflow fluid decreases from h_1 to h_2 as a function of time (t) in a standpipe directly connected to the specimen. The fluid head at the outflow is maintained constant. The quantity of outflow can be measured as well as the quantity of inflow. The hydraulic conductivity can be determined using the following equation:

$$K = \frac{aL_s}{A\,t_2 - t_1} In \frac{h_1}{h_2} \quad (3)$$

where a is the cross-sectional area of the burette, L^2; A is the cross-sectional area of the soil column, L^2 ; and $t_2 – t_1$ is the time, T required for the head to drop from h_1 to h_2 , L.

The objectives of the study include: To determine the hydraulic conductivity of the soil of lower coal measure geological formation of Owukpa.

II. Materials and Methods

2.1 Study Area

Owukpa in Benue State of Nigeria is geographically located within latitude 06°57' and 07°00'N, and longitude 07°38' and 07°42'E. It has an estimated land mass of about 350 square km and an estimated population of about 100,000 people. The area is a very rich natural resource, fertile land suitable for all kinds of agricultural activities. The climate is a tropical type with distinct wet and dry seasons. Rainfall usually starts around April when the inter-tropical convergence zone (ITCZ) shifts towards the Anambra Basin and stops in October with an average monthly precipitation of 4 – 1100 mm (0.2inches to 0.4 inches). The mean monthly temperature ranges from 16°C to 36°C. The coldest months are December and January during the harmattan period while the hottest months are February and March though slight variations may occur in their general pattern.

The geology of the study area is the lower coal measures (Mamu formation) and the Asata- Nkporo Shale Group (which includes; Afikpo sandstone, Otobi sandstone, Nupe sandstone and Agwu sandstone). Both geologies are of sedimentary formation that falls within the cretaceous system of the upper senonian age. The coal deposit within the lower coal measures geological formation in Owukpa is over 60 million tonnes [24].
Owukpa is a place blessed with very fertile soil, largely loamy (sandy loam) suitable for all kinds of crops cultivation. Forest resources (economic trees) such as oil palm, mahogany, dick nut (ogbono), locust bee, cashew, mango, iroko and orange are all present. Crops like groundnut, plantain, yam, sorghum and cassava are prominent produce in Owukpa. Others include pepper, rice, beans, maize, and Bambara nut.

2.2 Collection of Samples and Analyses

Soil auger was used to collect soil samples at a depth of 20 cm (0.20 m). The samples were collected 100 m apart from each other. The sampling points were at Ipole, Ibagba, Eyiupi, and Igbochi. On collection each sample was labelled and taken to the laboratory for analyses. The falling head method was used to determine the hydraulic conductivity of the soil samples.

III. Results and Discussion

Table 1 shows the field morphological description of the soil of the study area while Table 2 shows summary of results from analyses.

Table 1: Field Morphological Description of Soil of the Study Area

Locations	Unit	Soil Description
Ibagba	A	Loam soil with grits, darkish grey in colour, has crumb structure and compacted.
Ibagba	B	Loam soil with grits, darkish grey in colour, highly compacted and form heavy clods when dry
Eyi-upi	C	Clay loam soil with grits, darkish gray in colour, highly compacted in nature and forms heavy clods when dry.
Eyi-upi	D	Clay loam soil with grits, darkish gray in colour, highly compacted and form heavy clods when dry.
Ipole	E	Clay loam soil with grits, greyish in colour, highly compacted in nature and forms heavy clods when dry.
Ipole	F	Clay loam soil with grits, greyish in colour, highly compacted in nature and forms heavy clods when dry.
Igbochi	G	Loam soil with grits, darkish gray in colour, has a crumb structure and compacted.
Igbochi	H	Loam soil with grits, darkish gray in colour, highly compacted and heavy clods when dry.

Table 2: Summary of the Laboratory Analysis.

Location	Soil Parameters									
	Soil Depth (m)	Particle Size Distribution				Bulk Density (g/cm^3)	Porosity	Hydraulic Conductivity (cm^3/Sec)	Infiltration Rate (cm/Hr)	pH
		% Sand	% Silt	% Clay	Soil Type					
Eyi-upi	0.20^{ns}	49.55^d	13.25^a	37.25^b	Clay Loam	1.66^a	37.50^d	2.47x10^{-4}	14.20^d	6.62^c
Ibagba	0.20^{ns}	45.55^b	25.25^d	29.25^a	Loam	1.75^b	33.50^b	2.58 x10^{-4}	12.00^c	6.58^b
Ikpochi	0.20^{ns}	47.55^c	23.25^c	29.25^a	Loam	1.73^b	35.00^c	2.46 x10^{-4}	9.20^a	6.47^a
Ipole	0.20^{ns}	43.55^a	17.25^b	39.25^c	Clay Loam	1.85^c	31.00^a	2.40 x10^{-4}	10.85^b	6.64^c
LSD	0.310	0.196	0.196	0.196	-	0.031	1.388	0.128	1.405	0.105

Means on the same column with the same superscript are not statistically different ($p>0.05$),ns = not significant

From Table 1 the soils of the area are loam and clay loam. This makes the soils resistant to erosive forces. Sandy soil is easily detached but hard to transport while clayey soil is hard to detach but easily taken far distance if finally detached. This thus reveals that, the actual percentage of sand in any soil sample determines to a great extent the saturated hydraulic conductivity of that particular soil [25].

Table 2 shows that their respective bulk density depends greatly on the mineral make-up of the soil and the degree of compaction. But in some cases, soils of the same structural class may have varying bulk densities. The variation in bulk densities or degree of compaction is as a result of intensity of cultivation. The pH values (Table 2) ranged between 6.64 and 6.47. This shows that the soil formation is acidic.

Soil saturated hydraulic conductivity which is a quantitative measure of soil to erosion, has values ranging from 2.58 x10^{-4}cm/sec to 2.40 x10^{-4}cm/sec (Table 2). It was observed that the soils generally have low saturated hydraulic conductivity. The samples with high clay content have low saturated hydraulic conductivities because of higher binding and inter-binding forces that help in resisting detachment of soil particles by wind and water. This might be as a result of high compaction of the soil in nature forming heavy clods when dry. The soil sample at Ibagba location has the highest K_s of 2.58 x10^{-4}cm/s. while the least was at Ipole location with the value of 2.40 x10^{-4}cm/sec. The saturated hydraulic conductivity varied at different locations. This confirms spatial variation of hydraulic conductivity as reported by other researchers. This variation was also further confirmed by the statistical difference shown by other properties of soil determined which include porosity, infiltration rate and bulk density. It was also noted that locations with same soil textural class had different values of K_s. This is in line with report of [26] that soils of identical texture may have different K –values due to differences in structure.

The various K_s values of the soil samples when compared with the standard hydraulic conductivity show that the Ks values of the locations are permeable, well drained with stony substrata thereby having that inherent characteristic of being highly resistant to soil erosion.

IV. Conclusion

It was observed that the soils in the study area are mainly loam and clay loam. They are all highly compacted in nature forming heavy clods when dry which is due to the high clay content. The result showed that Ibagba sample has the highest saturated hydraulic conductivity of 2.58 $x10^{-4}$cm/s and the least saturated hydraulic conductivity was obtained from Ipole which is 2.40 $x10^{-4}$cm/sec. This has shown spatial variation of K_s values. It was concluded finally; that the lower coal measures geological formation in Owukpa, Benue State of Nigeria is highly resistant to soil erosion.

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