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Saturated Hydraulic Conductivity in a Tropical Alfisol in South-West Nigeria

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Abstract: This study presents the results of a comprehensive laboratory investigation program on the spatial variability of saturated hydraulic conductivity within a 44.3 ha twin-forested watershed at the International Institute for Tropical Agriculture (IITA) Ibadan in south-west Nigeria. The saturated conductivity was excessively rapid. In pre-clearing 2001, the mean saturated hydraulic conductivity ranged from 178 cm h^{-1} for 15-20 cm depth to 336 cm h^{-1} for 0-5 cm depth. The standard deviation was often equal to or even more than the average. In addition to high values, the variability in saturated conductivity was also very high amongst the 14 sub-watersheds. The high variability in hydraulic conductivity was due to the effects of pre-clearing vegetation, influence of roots and stumps, activity of soil fauna (earthworm and termites) and the size distribution and percent of gravel and coarse fraction present. Empirical relationships have been developed between the hydraulic parameters and the properties of fines particles.

Key words: Hydraulic conductivity, percentage aggregation, volumetric water content, intergranular void

INTRODUCTION

Efforts have been made to grain understanding of the movement of water in pavement structures (Cedergren, 1974; Moulton, 1980; Ridgeway, 1982; Barbour *et al.*, 1992; Alonso, 1998) and among the factors influencing it, the hydraulic conductivity and the Soil-Water Characteristics Curve (SWCC) of the construction materials are the most important (Alonso, 1998).

The hydraulic conductivity of a soil depends on many factors related to fabric; it also depends on the degree of saturation. The comparison of many hydraulic conductivity values must be done for a unique degree of saturation, which is usually set to 100%. The saturated values of hydraulic conductivity were extrapolated following from the experimental degree of saturation achieved for hydraulic conductivity measurements for each material tested.

Hydraulic conductivity of granular bases: Compacted granular material can be considered as either a two-phase media (saturated state) or a three-phase media (unsaturated state). The saturated state is composed of solid particles and water that fills the voids between the solid particles. The unsaturated state is composed of intergranular void space between the aggregate particles that is filled with water and air. The ability of such media to allow the flow of water between the solid particles can be expressed by the hydraulic conductivity. It is usually determined in the saturated and unsaturated states from direct measurement of from predictive methods. The hydraulic conductivity in the unsaturated state is dependent on the volumetric water content or the degree of saturation. The predictive methods are based on the SWCC, which is the relationship between volumetric water content and matric suction.

Hydraulic conductivity models for the saturated case: In general, hydraulic conductivity k is influenced by the size, shape, texture and configuration of the particles, by the degree of compaction, pore-size distribution, tortuosity of flow and by the dynamic viscosity and the density of the permeant (Murray, 1995). Based on the hypothesis that the finer particles have a disproportionate influence, empirical relationships have been developed between hydraulic conductivity and effective particle size d_{10} for loose sands (Hazen, 1892) and for mixtures of sands and gravels (Lambe and Whitman, 1979). Other empirical relationships were developed using d_5 (Kenney *et al.*, 1984) and d_{15} (Sherard *et al.*, 1984). Also, Moulton (1980) analyzed numerous data for filter and granular drainage materials and presented an empirical relationship involving hydraulic conductivity, effective size of particles (d_{10}), porosity (n) and fines content ($d< 80$ μm). The latter exerted a marked influence on hydraulic conductivity, as was also observed by Babic *et al.* (2000). Similarly, Elsayed and Lindly (1996) introduced an equation to predict the hydraulic conductivity as a

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Corresponding Author: O.A. Ehigiator, Department of Civil Engineering, Ambrose Alli University, Ekpoma, Nigeria function of the void ratio, percentage by mass passing 0.6 mm and fines content. However, Hoppe (1996) who studied granular base-course materials form 19 quarries in Virginia and North Carolina, found a very weak statistical correlation between hydraulic conductivity and fines content alone. This suggests that other parameters also may influence the hydraulic conductivity. Murray (1995) reviewed relationships between the hydraulic conductivity and combination of such parameters as porosity, effective porosity, hydraulic radius, effective pore radius and tortuosity. However, most of these relationships rely on matching parameters such as shape and angularity factors and tortuosity that can only be determined from laboratory permeability test on actual soils.

Measurement of hydraulic parameters in granular bases: The measurement of the hydraulic conductivity of granular base-course materials can be performed from in situ tests (Moulton and Seals, 1979; Floss and Berner, 1989; Wolf, 2000) and from laboratory tests (Barber and Sawyer, 1952; Moulton and Seals, 1979; Raimbault, 1986b; Jones and Jones, 1989; Jones, 1995). Repeatability of laboratory tests can be influenced by numerous factors, such as degree of compaction, fines production during dynamic compaction and degree of saturation, among others. For a given sample it is common to obtain differences in k values of an order of magnitude. While typical values of hydraulic conductivity of unbound base-course aggregates range from 10^{-8}-10^{-5}m s^{-1}, the accurate prediction of hydraulic conductivity resides in the understanding of the most important controlling factors.

Since base-course materials consist mainly of coarse particles, the residual volumetric water content, θ_1, can be assumed to be close to 0. Considering the fairly narrow range of matric suction in pavement base-course layers (0-75 kPa according to Raimbault, 1968a), the Brooks and Corey (1964) model, in which θ_1 is set to 0, is particularly suited to materials as a function of volumetric water content (Eq. 1, 0 or as a function of matric suction, Eq. 2)

$$k_\theta = k_s \left(\frac{\theta}{\theta_s} \right)^{\delta} \qquad (1)$$

$$k_\psi = k_s \qquad \Psi \le \Psi_a$$

$$k_\Psi = k_s \left(\frac{\Psi_a}{\Psi} \right)^{\eta} \qquad \Psi \le \Psi_a \qquad (2)$$

Where,

K_s : The saturated hydraulic conductivity (m s^{-1}).

K_θ : The unsaturated hydraulic conductivity function of θ (m s^{-1}).

K_Ψ : The unsaturated hydraulic conductivity function of Ψ (m s^{-1}).

θ : The volumetric water content.

θ_s : The saturated volumetric water content.

Ψ : The matric suction (kPa).

Ψ_a : The air entry value (kPa).

η, δ : Empirical constants.

The air entry value, which correspond to the matric suction to the matric suction at which air begins to enter into the soil, can be used as a measure of the maximum pore size in a soil. The empirical constants δ and η are determined from the SWCC

$$\theta = \theta_s \qquad \Psi < \Psi_a$$
$$(\theta_r = 0) \qquad (3)$$

$$\theta = \theta_s \left(\frac{\Psi_a}{\Psi} \right)^{\lambda} \qquad \Psi > \Psi_a$$

Where, λ is the logarithmical slope of the SWCC, which is referred to as the pore-size distribution index

$$\lambda = \frac{\Delta \log \theta}{\Delta \log \psi} \qquad (\theta_r = 0) \qquad (4)$$

The empirical constant from Eq. 1 and 2 are functions of λ

$$\delta = \frac{2 + 3\lambda}{\lambda} \qquad (5)$$

$$\eta = 2 + 3\lambda \qquad (6)$$

The hydraulic characteristics of granular bases can thus be idealized with parameters such as the hydraulic conductivity in the saturated state K_s, the air entry value Ψ_a and the pore-size distribution index λ taken from SWCC and the saturated volumetric water content θ_s, which is equal to the porosity of the soil n.

MATERIALS AND METHODS

An experimental procedure using tensiometers to measure matric suction from 100 kPa was adopted. The samples were compacted in five layers at the optimum

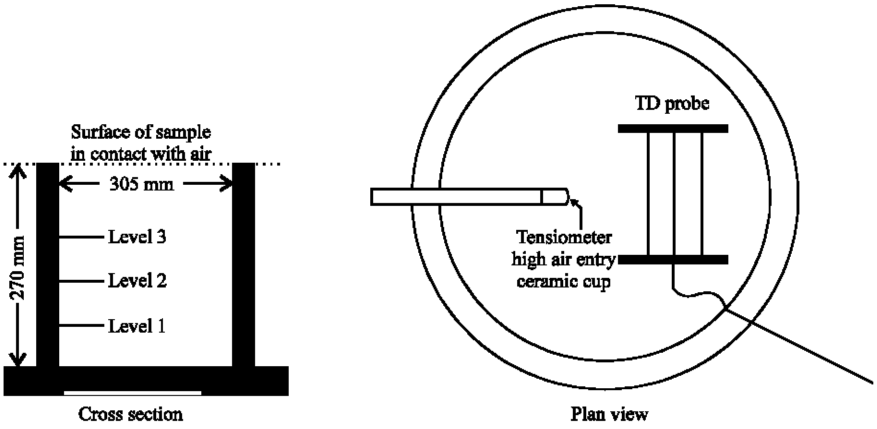

Fig. 1: Schematic of test apparels in a 305 mm mould

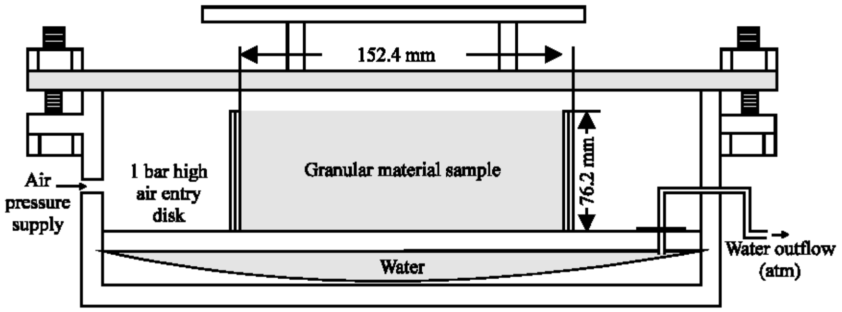

Fig. 2: Schematic of the pressure plate apparatus

modified Proctor conditions in a 305 mm diameter, 270 mm high mould. This mould was instrumented with tensiometers (matric suction) installed during compaction, at three different levels from the base of the mould (Fig. 1). This laboratory testing procedure gives the SWCC of a 20 000 cm^3 sample for matric suction ranging from 0 to almost 100 kPa within 4-10 days. A pressure plate apparatus test was carried out for a 1500 cm^3 (truncated modified Proctor mould) sample for which the determination of the SWCC required more than 30 days (Fig. 2). In the pressure plate apparatus, the matric suction at equilibrium (no more water loss, $u_w = 0$) corresponds to the air pressure applied to the sample ($\Psi = u_a$). When equilibrium was reached for each value of applied air pressure u_a, the change in water content was obtained by weighing both the sample and the pressure plate apparatus. The hydraulic conductivities for nearly saturated samples were obtained from constant head permeability tests, at a controlled temperature of 20°C. The samples were compacted using modified optimum proctor water content, in a mould 152.4 mm in diameter and 101.6 mm in height and subjected to a constant head flow of de-aired water in the vertical direction. Hydraulic conductivity was calculated from the measured flow rates.

$$k_s = \frac{Q}{iA} \qquad (7)$$

Where, k_s is the saturated hydraulic conductivity ($m\ s^{-1}$), Q is the flow of water ($m\ s^{-1}$), i is the hydraulic gradient and A is the area of the sample (m^2). Soil aggregation was determined by the wet sieving method and the results were expressed in terms of the Mean Weight Diameter (MWD). Penetration resistance was measured using the standard Dutch Cone Penetration Test (CPT) for each horizon of the sampling depths.

RESULTS AND DISCUSSION

Table 1 presents the saturated hydraulic conductivity for four depths; 0-5, 5-10, 10-15 and 15-20 cm under secondary forest cover at the watershed between 1986 and 2001. The same parameter values obtained during 2002 for 0-10 and 10-20 cm depths respectively are shown in Table 2. The saturated hydraulic conductivity was excessively rapid under the forest cover as measured in 2001 The mean saturated hydraulic conductivity ranged from 178 cm h^{-1} for 10-15 cm depth to 336 cm h^{-1} the highest value of 1029 cm h^{-1} was measured for 15-20 cm

Table 1: Saturated hydraulic conductivity (cmh^{-1}) for four depths under secondary forest

Sub-Watershed	Depths 0.5 cm	5-10 cm	10-15 cm	15-20 cm
1	218±134	350±343	119±184	174±167
2	205±93	128±81	216±144	81±88
3	271±187	48±44	180±337	309±413
4	271±362	625±816	308±442	337±343
5	250±195	245±147	84±19	235±393
6	841±439	113±112	349±532	1029±1588
7	687±769	66±55	58±65	55±59
8	154±103	157±100	118±167	133±133
9	141±63	199±284	368±313	253±339
10	61±36	75±46	73±39	87±81
11	310±207	283±25	166±18	117±28
12	283±385	81±88	45±46	89±88
13	580±856	202±52	121±29	623±988
14	432±141	386±182	289±220	205±156
Mean	336±215	211±154	178±106	266±255

Each value is a mean of 5 separate measurements

Table 2: Saturated hydraulic conductivity (cm h^{-1}) measured under forest cover during 2002

Sub-watershed	0-10 cm	10- 20 cm
1	35.1±23.0	49.1±40.9
2	45.2±34.8	31.4±35.4
3	39.2±29.3	43.3±35.7
4	32.6±30.2	86.0±27.6
5	53.9±40.5	35.0±37.1
6	31.2±32.2	52.7±57.3
7	56.4±37.9	46.9±37.1
8	39.2±41.3	45.0±58.9
9	50.2±45.9	47.0±42.3
10	49.3±66.6	83.2±50.2
11	66.4±43.2	109.7±41.2
12	53.0±54.7	35.9±34.7
13	63.7±47.5	93.7±46.7
14	77.3±53.2	97.9±62.9

Each value is a mean of 25 separate measurements

Table 3: Mean weight diameter (MMD) of soil aggregates under forest cover

Sub-watershed	MMD (mm) for different depths (cm) 0.5 cm	5-10 cm	10-15 cm	15-20 cm
1	4.03±0.43	3.45±0.29	3.97±0.41	3.01±0.25
2	4.42±0.50	4.09±0.07	3.61±0.72	3.19±0.77
3	4.74±0.50	4.26±2.07	4.46±0.53	3.78±0.60
4	3.77±0.98	3.04±0.81	2.98±1.05	2.70±0.64
5	3.07±0.57	2.83±0.54	2.93±0.27	2.37±0.40
6	3.29±0.54	3.00±0.43	2.59±0.64	2.41±0.60
7	3.69±0.71	3.67±0.25	3.59±0.22	2.71±0.84
8	3.94±0.54	3.87±0.67	3.35±0.61	2.90±0.77
9	3.10±1.18	3.33±0.83	3.03±0.80	2.97±1.27
10	3.53±0.53	2.95±1.50	2.35±0.47	2.30±0.61
11	2.58±1.37	1.79±0.32	2.31±0.85	1.76±0.58
12	4.19±0.79	2.60±1.81	1.97±1.09	2.21±1.90
13	ND	ND	ND	ND
14	ND	ND	ND	ND
Mean	3.72±0.55	3.24±0.66	3.10±0.70	2.69±0.51

Each value is a mean of 5 separate measurements

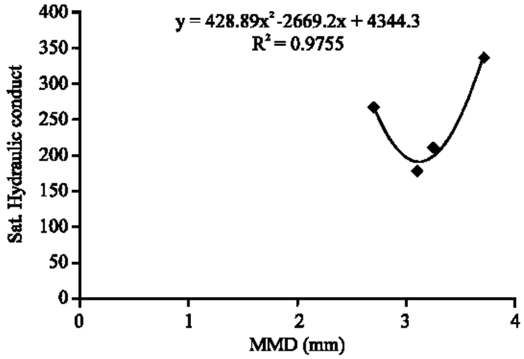

Fig. 3: Saturated hydraulic conductivity versus mean weight diameter (MMD) of aggregates

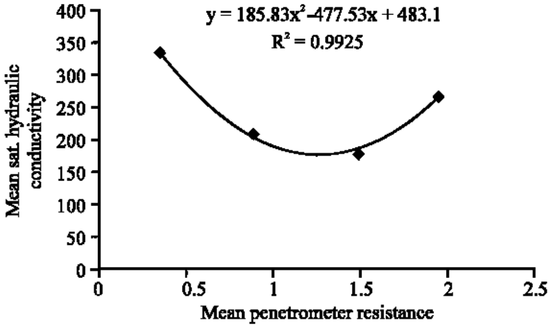

Fig. 4: Variation of mean saturated hydraulic conductivity with mean penetration resistance

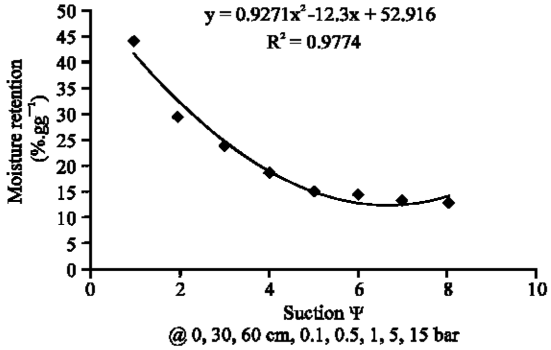

Fig. 5: Soil- water characteristics curve (SWCC) θ for matric suction Ψ

depth in sub-watershed No.6 and the least value of 55 cm h^{-1} for 15-20 cm depth in sub-watershed No.7. In addition to high values, the variability in saturated conductivity was also very high. The standard deviation was often equal to or even more than the average. The soils were rendered highly porous under the forest cover as a result of coarse texture and predominance of biopores (root and earthworm channels). In contrast, the hydraulic conductivity measured in 2002 on undisturbed cores using the same constant head permeameter, ranged from 31.2-66.4 cm h^{-1} for the 0-10 cm depth and from 31.4-109.7 cm h^{-1} for 10-20 cm depth.

Although percent aggregation was generally 30- 40%, probably due to low clay content, the Mean Weight Diameter (MWD) of aggregates was high. The averaged MWD ranged from 3.72 mm for 0-5 cm depth to 2.69 m for 15-20 cm depth. The MWD progressively decreased with increasing depth Table 3. The large value of MWD for these soils was partly due to high proportion of earthworm casts present in the layer.

In accordance with saturated hydraulic conductivity, infiltration rate was also very high. The equilibrium infiltration rate ranged from 26 cm h^{-1} for sub-watershed No.6 to 285 cm h^{-1} for sub-watershed No.11. The corresponding value of cumulative infiltration in 2 h for these sub-watersheds was 86 and 740 cm, respectively. The high infiltration rate was attributed to "open structure" with predominance of macrospores and also due to large horizontal components of saturated conductivity. Figure 3 depicts the plot of mean saturated hydraulic conductivity against Mean Weight Diameter (MWD) of soil aggregation under the secondary forest that existed at this watershed prior to this study. A reasonable coefficient of correlation of 0.9725 was obtained. The relationship between the mean values of saturated hydraulic conductivity K_s and penetration resistance f (Fig. 4) could be represented by the following equation with a correlation coefficient of 0.9925.

$$K_s = 186 f^2 - 478 f + 483$$

where, f is measured CPT friction sleeve stress (N cm^{-2}).

The Soil Water Characteristic Curve (SWCC) presented in Fig. 5 relies on pressure head units to define Ψ (given in cm of water). This model retains the same physical concepts from which the original Kovács (1981) MK model was constructed. From this curve, input values can be deduced for the unsaturated hydraulic conductivity function K_θ.

CONCLUSION

The major obstacles for the direct measurements of the SWCC of granular base-course materials are the need for precise calibration and large samples for the TDR-tensiometers method. These difficulties are probably the reasons why practically no data are found in the literature for these materials. The high variability in saturated hydraulic conductivity was due to the effects of pre-clearing vegetation, influence of roots and stumps, activity of soil fauna (earthworm and termites) and the size distribution and percent of gravel and coarse fraction present at the investigated watershed. As a result of coarse texture and predominance of biopores (root and earthworm channels), these soils were highly porous under the forest cover.

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