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Research Article
Dynamics of Soil Porosity as Influenced by Some Soil Properties in a Tropical Humid Environment

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Abstract

Background and Objective: The dynamics of soil porosity is shaped and sometimes overwhelmed by other soil properties if proper soil management is not ensured. The effects of soil properties on soil porosity and the resultant implication were evaluated. **Materials and Methods:** Slope maps were generated from the digital elevation model obtained from United States Geological Survey Explorer SRTM 1 for three agrarian communities underlain by four geologic formations in Cross River State. Each slope range represented a mapping unit (8 mapping units were obtained) and 2 profile pits were sunk in each, resulting in 16 soil profile pits. Fifty-three soil samples were obtained from pedogenic horizons and used for analysis in the Soil Science Laboratory, University of Nigeria, Nsukka in 2019. **Results:** Bulk density (Bd) decreased with increasing total (St) and micro (Sμ) porosities. On the other hand, saturated hydraulic conductivity K_{sat}, the volume fraction of water at all tension levels (θvt) as well as exchangeable bases increased with increasing total and micro porosities. **Conclusion:** Exchangeable Na^+, Bd and volume fraction of water at 30 cm of tension as well as lithology are important factors that influence soil porosity. The values of R^2 for models between St and Sμ, against Bd and θvt, were >50 %. Macro porosity was as a result, least influenced by other soil properties. Factor analysis further affirms the contributions of Bd, Na^+ and volume fraction of water at 30 cm of tension to variation between lithologies for PC1 of St and Sμ.

Key words: Water desorption, soil porosity, physicochemical properties, regression functions

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Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

Soil pore spaces are channels through which water, nutrients solutions, gases and gas mixtures as well as organisms move through the soil, causing soil heterogeneity. The fraction of total soil volume that is occupied by pore space defines soil porosity[1]. It is an integral component of the soil matrix that impacts the habitat of plant roots and soil biota[2].

Soil pores have a non-uniform structure with a complicated geometry that affects soil hydraulic properties[3,4]. Its connectivity, arrangement and size influence the movement of dissolved solutes in soil. Consequently, continuous pores may facilitate such movements which are of great importance to plant nutrient adsorption and pollution of underground water sources. This is mainly because water and air movements, soil chemical reactions as well as general fluid flow, root growth and development depend on the size and shape of soil particles and the arrangement of pores as influenced by pore fluids[5].

Many methods have been developed for the quantitative determination of pore volume and pore size distribution of soils. This includes the direct (micromorphological analysis and computed tomography) and indirect methods (soil water retention curve, gas adsorption, mercury intrusion porosimetry and resin impregnation)[6-11]. Straight forward measurements of pore sizes are done with the geometric analysis of images of individual pores using thin sections or tomographs. These are sophisticated but reliable techniques that provide high-quality data for pore size distribution. However, the methods are expensive and unavailable in most Sub-Saharan parts of Africa.

Other soil properties have a pronounced influence on soil porosity. Weathering increases porosity and water holding capacity and reduces Bd. Soils with different Bds have different volumes of air and water at any given value of water-filled pore space, resulting in considerable variation in relationships based on water-filled pore space[12]. Furthermore, Bd and macro porosity Sm are responsible for changes in soil porosity and not size[10]. Consequently, Weerden *et al.*[12] identified clay amount as being responsible for variation in pore size distribution. Marchuk *et al.*[5] observed that the chemical composition (exchangeable cations) of pore fluids, causes changes in hydraulic conductivity and the architecture of pore systems. Its variation has been attributed to Na^+ accumulation, organic matter deposition and clay dispersion or expansion[13]. According to Marchuk and Rengasamy[14], Na^+ causes soil structural deterioration and by implication its pores, while Ca^{2+} preserves soil structural integrity. Furthermore, the effects of exchangeable K^+ and Mg^{2+} on soil structure have also been reported[15]. Active porosity influences hydraulic conductivity, with significant correlations between exchangeable bases, CEC and K_{sat}[5]. Organic matter also plays a key role in cementing the pore walls and keeping them away from collapse[16].

Soil porosity has amazing significance in soil genesis and fertility and relates with other soil properties in a complex but useful manner. The size distribution of pores may be described in detail by applying a series of tensions which is a function of soil water content[17]. This appears to be the most convenient and easy-to-apply method for pore determination, especially in the face of limited technology. However, attempts made to document the distribution of pore sizes in soils using the water desorption technique are scanty and sometimes unavailable, particularly in Nigeria. Previous studies on pore size distribution focused on the use of specialized techniques with difficult-to-source reagents. The present study seeks to determine soil porosity at various tensions and how it is affected by other soil properties and the resultant implication of such impact as well as its variation between lithologies.

MATERIALS AND METHODS

Location, geology and climate of the study area: The research was conducted in Cross River State (5°32' and 4°27'N, 7°50' and 9°28'), southeast Nigeria. The selected study sites were Ishibori in Ogoja (06°39'17"N, 08°47' 51"E), Agoi Ibami in Yakurr (05°43'27"N, 08°10'37.2"E) and Mfamosing in Akamkpa (05°04'41.8"N,08°27'49.8"E). Ogoja is characterized by southern guinea savanna, while Yakurr and Akamkpa are described as tropical rainforest areas. The geology of Cross River State is dominated by Basement Complex and Sedimentary Basin and grouped into Cretaceous and Tertiary geological ages. The study areas are characterized by Sedimentary limestone of Cretaceous and Tertiary ages which intercalates with shale, siltstone and fine-grained sandstone[18,19].

Tropical humid climate with clear wet and dry seasons vary from the moist humid to per humid Akamkpa and Yakurr areas to the moist sub-humid southern guinea savanna in the Ogoja area. The Ogoja area has a rainfall range of 1251.4-3347.8 mm/annum and a temperature of 22.96-33.75°C, while Yakurr and Akamkpa areas have ranges of 1760.3-3770.8 mm/annum and 22.56-31.95°C as annual rainfall and temperature, respectively[19].

Field and laboratory procedures: Guided by the elevation ranges of Ishibori, Agoi Ibami and Mfamosing as obtained by digital elevation model, two profile pits were randomly sited and dug in each of the 8 mapping units. Four geologic formations were identified in the locations using the geologic maps. IH1P1 and IH1P2 (mapping unit IH) were sited over shale, limestone and sandstone formation (SLS), while IH2P1, IH2P2 (IH2), AI3P1, AI3P2 (AI3), MF3P1 and MF3P2 (MF3P2) were sited over alluvium (AL). In the sandstone and limestone formation (SL), AI1P1, AI1P2 (AI1), AI2P1 and AI2P2 (AI2) were sited, while MF1P1, MF1P2 (MF1), MF2P1 and MF2P2 (MF2) were sited over Shale-Limestone with Sandstone Intercalation (SLSi). The field study was carried out between December, 2018 and February, 2019 in Cross River State, Nigeria. Analysis of 53 soil samples was done in Soil Science Laboratory, University of Nigeria, Nsukka in 2019.

Thereafter, core and soil samples were obtained from pedogenic horizons from bottom to top of soil profiles. Soil samples were processed for the determination of particle size distribution by Bouyoucos hydrometer and exchangeable cations by neutral NH_4OAc at pH (H_2O) 7.0 as outlined by Cools and De Vos[20]. Bulk density (Bd) was obtained by the undisturbed core method, while saturated hydraulic conductivity (K_{sat}) was determined by the constant head method of Cools and De Vos[20]. Total (St), macro (Sm) and micro (Sµ) porosities were obtained by dividing the volume of water in the soil at saturation, the volume of water drained at 60 cm of tension and volume of water retained at 60 cm of tension, respectively by the volume of cylinder and then expressing the results as a percentage.

The soil samples were saturated with water in standard core cylinders overnight (water desorption method) and drained with successively increasing tensions (t) (30, 60 and 90 cm) as outlined by Cools and De Vos[20]. The volume fraction of water (θvt) was obtained by multiplying the water content at 't' by bulk density. Where 't' is 30, 60 or 90 cm tensions.

Air-dry soils (<2 mm) were leached with 1 N NH_4OA_C (pH 7) in a 1:1 soil-solution ratio. Exchangeable K and Na in the extract were determined with the aid of a flame photometer, while Ca and Mg were determined by the versenate EDTA titration procedure[20].

Data analysis: Descriptive statistics of mean and range were used for interpretation. Correlation and regression analyses checked the effect of other properties on soil porosity parameters and the extent of the effect. Data were analyzed using Stat View version 5.0.1 and R studio software.

Principal components analysis (PCA): PCA enabled the grouping of soil variables based on lithologies (SLS, AL, SL, SLSi). The first three principal components were reported. PCA was performed with STATISTICA version 13.3.

RESULTS

The physical properties and exchangeable bases are presented in Table 1. The values of sand had ranges of 60-72, 58-86, 72-84 and 68-86% in the surface soils overlying SLS, AL, SL and SLSi, respectively (Table 1). In the surface soils of SLS, clay amount ranged from 14-26% with a mean of 21%, while in SL, its values had ranges of 10-16 and 14-228 % in the surface and subsurface soils of AL, respectively. Furthermore, 10-14% of clay was obtained in the surface soils of SLSi (Table 1). Sand amount in SLS was comparatively low with resultant high clay compared to soils over AL, SL and SLSi. Mean values of 1.5, 1.03, 1.15 and 1.21 g cm^{-3} in the surface soils corresponded with means of 1.6, 1.29, 1.5 and 1.45 g cm^{-3} for SLS, AL, SL and SLSi, respectively for Bd. Bulk density (Bd) values increased with soil depth and were generally less than 1.70 g cm^{-3} in the soils studied. The mean values of K_{sat} in the surface soils were 59.25, 91.36, 62.03 and 59.20 cm h^{-1} and 25.29, 21.56, 20.24 and 20.05 cm h^{-1} in the subsurface soils for the soils over SLS, AL, SL and SLSi, respectively. The decrease in the values of K_{sat} in the subsurface soils is similar to that of sand content.

Total porosity had means of 55.7 and 49.7% in the surface and subsurface soils, respectively for soils over SLS, while those over AL had 61.4 and 55.9% in the surface and subsurface soils, respectively. In the surface soils of SL and SLSi, means of 58.4 and 53.7% were obtained in the surface soils, while 48.1 and 45.5% were obtained in the subsurface soil, respectively (Table 1). In general, the values of St decreased with increasing soil depth. The highest values of St were obtained in soils formed over AL. The regression functions are presented in Table 2. The regression of St against Bd, $θv_{30}$ and $θv_{90}$ was significant, with R^2 values of 0.637, 0.753 and 0.557, respectively (Table 2). Total porosity significantly correlated with all soil properties except Mg^{2+} and particle sizes of sand, silt and clay (Table 3).

Macro porosity (Sm) had means of 11.7, 7.5, 3.9 and 2.7% in the surface soils and 7.9, 6.3, 7.3 and 4.1% in the subsurface soils of SLS, AL, SL and SLSi, respectively (Table 1). Higher values of Sm were obtained in the subsurface soils, except in soils over SLS and AL where higher values were obtained in the surface soils. The regression functions of Sm indicate no significant relationship with other soil properties (Table 2). Contrary to correlations of St and Su with other soil properties, Sm correlated positively with K_{sat} and St and negatively with Su and $θv_{60}$ ($p< 0.05$) but failed to correlate with other soil properties in Table 3.

In the surface soils of SLS, AL, SL and SLSi, means of 44, 54, 54.3 and 50.9% were obtained for Sµ, while 41.8, 49.6, 40.8 and 42.8% were obtained in the subsurface soils (Table 1),

Table 1: Physical properties and exchangeable basic cations of the soils

	Particle size distribution (%)			Bd	Ksat	Porosity (%)			θvt			Exchangeable basic cations (cmol$_c$ kg^{-1})			
Depth	Sand	Silt	Clay	g cm^{-3}	cm hr^{-1}	St	Sm	Sμ	30 cm	60 cm	90 cm	Na$^+$	K$^+$	Mg^{2+}	Ca^{2+}
Soils over SLS (IH1P1, IH1P2)															
ẍ surface	66	13.0	21.0	1.5	59.25	55.7	11.7	44	47.28	43.99	44.61	0.07	0.11	3.4	4.4
Range surface	60-72	12.0-14	14.0-26	1.45-1.54	40.31-78.18	46.4-65	2.3-21	43.9-44.1	44.97-49.59	43.94-44.04	44.4-44.81	0.04-0.10	0.07-0.14	-	3.4-5.4
ẍ subsur	63.6	12.8	23.6	1.6	25.29	49.7	7.9	41.8	44.31	41.8	41.87	0.024	0.06	2.5	5.6
Range subsur	58-68	19.0-20	20.0-28	1.48-1.66	0.61-106.28	44.4-54.5	3.1-14.5	35.0-47.8	36.23-51.36	34.94-47.89	32.84-48.83	0.02-0.03	0.05-0.07	1.4-4.0	3.8-7.2
Soils over AL (IH2P1, IH2P2, AI3P1, AI3P2, MF3P1, MF3P2)															
ẍ surface	74.7	12.0	13.3	1.03	91.36	61.4	7.5	54.0	55.52	53.75	52.75	0.10	0.14	2.2	5.8
Range surface	58-86	4.0-24	10.0-18	0.71-1.28	0.49-256.54	51.8-71.7	2.7-13.1	44.9-68.0	46.3-66.29	44.9-67.69	43.54-64.82	0.03-0.28	0.06-0.29	0.2-5.0	1.4-9.0
ẍ subsur	72.8	10.3	16.8	1.29	21.56	55.9	6.3	49.6	50.34	55.02	48.65	0.03	0.06	1.3	3.8
Range subsur	52-86	4.0-20	10.0-28	0.91-1.57	0.49-130.71	45.1-80.2	2.0-23.9	39.1-76.5	40.0-75.42	38.07-91.06	38.21-71.02	0.01-0.11	0.03-0.15	0.2-4.2	0.6-5.0
Soils over SL (AI1P1, AI1P2, AI2P1, AI2P2)															
ẍ surface	80	7.5	12.5	1.15	62.03	58.4	3.9	54.3	53.57	54.37	54.75	0.05	0.09	0.95	2.9
Range surface	72-84	6.0-12	10.0-16	0.99-1.35	8.28-106.89	52.2-63.4	2.7-6.6	47.8-54.0	38.0-62.67	47.93-60.49	48.47-60.59	0.04-0.06	0.07-0.09	0.6-1.4	1.6-3.8
ẍ subsurf	71	9.3	19.8	1.50	20.24	48.1	7.3	40.8	39.45	40.76	41.92	0.019	0.05	0.85	3.0
Range subsurf	62-80	6.0-14	14.0-28	1.26-1.66	1.22-63.52	42.7-60.0	2.6-23.5	35.5-46.2	28.7-47.54	35.50-46.11	36.29-46.91	0.01-0.02	0.04-0.06	0.2-2.2	0.8-5.6
Soils over SLSi (MF1P1, MF1P2, MF2P1, MF2P2)															
ẍ surface	79.5	8.0	12.5	1.21	59.20	53.7	2.7	50.9	47.52	50.86	42.34	0.077	0.13	1.3	4.2
Range surface	68-86	4.0-18	10.0-14	0.90-1.62	0.49-126.67	49.1-62.2	1.7-3.6	47.4-59.0	42.64-53.82	47.47-58.77	33.92-48.60	0.06-0.11	0.11-0.15	0.6-3.2	1.4-7.2
ẍ subsur	77.4	7.7	15.0	1.45	20.05	45.5	4.1	42.8	39.45	41.54	38.46	0.026	0.06	1.3	2.0
Range subsurf	71-86	4.0-13	10.0-26	1.31-1.62	2.68-65.77	37.1-48.6	0.9-7.7	31.6-57.1	29.21-51.85	31.57-52.82	26.59-55.24	0.0-0.04	0.0-0.09	0.4-4.8	0.4-5.6

ẍ : Mean, K$_{sat}$: saturated hydraulic conductivity, Bd: Bulk density, St: Total porosity, Sm: Macro porosity, Sμ: Microporosity, θvt: Volume fraction of H_2O (t: Tension levels of 30, 60, 90 cm), SLS: Shale, limestone and sandstone, SL: Sandstone and limestone, AL: Alluvium, SLSi: Shale-limestone with sandstone intercalation

Table 2: Regression models from the interaction between soil porosity and other soil properties

	St	Sµ	Sm
Sand	Y = 50.643+0.019*X, $R^2 = 3.387*10^{-4}$ (β)	Y = 38.865+0.101*X, R^2 = 0.009 (β)	Y = 7.923-0.026*X, R^2 = 0.002 (β)
Silt	Y = 50.025+0.209*X, R^2 = 0.013	Y = 44.022+0.235*X, R^2 = 0.016	Y = 6.997-0.102*X, R^2 = 0.009 (β)
Clay	Y = 55.609-0.21*X, R^2 = 0.017	Y = 53.529-0.427*X, R^2 = 0.068	Y = 3.585+0.143*X, R^2 = 0.023
Bd	Y = 89.136-27.387*X, R^2 = 0.637	Y = 83.718-27.634*X, R^2 = 0.629	Y = 5.554+0.333*X, $R^2 = 2.702*10^{-4}$ (β)
K_{sat}	Y = 49.931+0.057*X, R^2 = 0.132	Y = 44.974+0.036*X, R^2 = 0.05	Y = 5.094+0.025*X, R^2 = 0.07
θ_{V30}	Y = 12.274+0.85*X, R^2 = 0.753	Y = 4.963+0.883*X, R^2 = 0.79	Y = 9.375-0.072*X, R^2 = 0.015
θ_{V60}	Y = 29.176+0.487*X, R^2 = 0.357	Y = 17.365+0.617*X, R^2 = 0.555	Y = 12.686-0.142*X, R^2 = 0.087
θ_{V90}	Y = 19.9+0.719*X, R^2 = 0.557	Y = 12.565+0.754*X, R^2 = 0.595	Y = 10.337-0.097*X, R^2 = 0.029
Na	Y = 48.217+92.743*X, R^2 = 0.205	Y = 42.709+86.849*X, R^2 = 0.175	Y = 5.76+5.939*X, R^2 = 0.002 (β)
K	Y = 45.167+91.64*X, R^2 = 0.216	Y = 39.355+92.46*X, R^2 = 0.214	Y = 5.867+1.85*X, $R^2 = 2.526*10^{-4}$ (β)
Mg	Y = 50.109+1.286*X, R^2 = 0.037	Y = 44.994+0.864*X, R^2 = 0.016	Y = 5.681+0.215*X, R^2 = 0.003 (β)
Ca	Y = 47.022+1.383*X, R^2 = 0.143	Y = 40.774+1.52*X, R^2 = 0.167	Y = 6.951-0.26*X, R^2 = 0.014

Y: a+bX, Y: Dependent variable (St, Sµ, Sm), X: Independent variable (other soil properties) and β: No significant regression of Y on X, the larger the R^2 the better the model

respectively. At all depths and lithologies, micro-porosity (Sµ) exceeded its corresponding Sm values. The regression functions of Sµ indicate significant relationships with Bd, θv_{30}, θv_{60} and θv_{90} with R^2 values of 0.629, 0.790, 0.555 and 0.595, respectively (Table 2). Except for K_{sat}, Mg^{2+} and particle sizes of sand, silt and clay, all other soil properties correlated positively and significantly with Sµ. However, Sµ correlated negatively with Bd (Table 3).

The regression of all the soil porosity parameters (St, Sµ and Sm) on sand size was not significant and also weakly correlated (Table 2).

The volume fraction of water (θv) had ranges of 44.97-49.59, 46.3-66.29, 38.0-62.67 and 42.64-53.82 at 30 cm tension for the surface soils over SLS, AL, SL and SLSi, respectively. At 60 cm of tension, ranges of 43.94-44.04, 44.9-67.69, 47.93-60.49 and 47.47-58.77 were obtained in the surface soils of SLS, AL, SL and SLSi, respectively. Furthermore, the volume fraction of water at 90 cm of tension ranged from 44.4-44.81, 43.54-64.82, 48.47-60.59 and from 33.92-48.60 in the surface soils overlying SLS, AL, SL and SLSi, respectively (Table 1). Irrespective of the soil water tension, the soils experienced a drop in θvt at the subsurface. Consequently, in the soils over SLS, the trend $\theta v_{30} > \theta v_{90} > \theta v_{60}$ was obtained. In the soils over SL, $\theta v_{90} > \theta v_{60} > \theta v_{30}$ while in SLSi, $\theta v_{60} > \theta v_{30} > \theta v_{90}$ was obtained (Table 1). Soils over AL had an irregular trend in the surface and subsurface soils.

Exchangeable Na^+ values had means of 0.07 and 0.024, 0.10 and 0.03, 0.05 and 0.019 and 0.077 and 0.026 $cmol_c\ kg^{-1}$ in the surface and subsurface soils overlying SLS, AL, SL and SLSi, respectively (Table 1). Similarly, exchangeable K^+ decreased from surface to subsurface mean values of 0.11 and 0.06, 0.14 and 0.06, 0.09 and 0.05 and from 0.13 and 0.06 $cmol_c\ kg^{-1}$ in the soils overlying SLS, AL, SL and SLSi, respectively (Table 1). These ions were low in the studied soils and less than a benchmark of 0.3 $cmol_c\ kg^{-1}$ for soils in the tropics. Exchangeable Mg^{2+} had mean values of 3.4, 2.2, 0.95 and 1.3 $cmol_c\ kg^{-1}$, while exchangeable Ca had means of 4.4, 5.8, 2.9 and 4.2 $cmol_c\ kg^{-1}$ in the surface soils overlying SLS, AL, SL and SLSi, respectively.

The existing data was reduced to only three principal components (PC1, PC2, PC3) with the aid of factor analysis. The three components explained 76.6, 73.2 and 77.4% for St, Sm and Sµ, respectively of the existing variations between the soils using 13 variables in the analysis in Table 4. The percent total variance decreased from the first PC (PC1 = 41.5%) to the third PC (PC3 = 10.3%) for total porosity. However, the contributions of PC4 and PC5 to variation was low, hence the adoption of PC1 to PC3.

The first loading (PC1) for St explains 41.5% of the total variance and returns as the most important PC. It finds its loadings from θv_{30} (0.874), θv_{90} (0.746), Na^+ (0.835), K^+ (0.798) and Bd (-0.810). The high loadings of the above components are consistent with their significance in the models presented in Table 2, particularly for θv_{30}, Na^+ and Bd. PC2 and PC3 contributed 24.8 and 10.3%, respectively from other soil properties. Particle sizes {sand (-0.962), silt (0.775) and clay (0.826)} expressed their influence on total porosity in PC2. Loadings for PC3 were less than 0.50 for all other properties and contributed the least to soil variation between lithologies.

The first loading (PC1) for Sµ describes 41.6% of the variation resulting from θv_{30} (0.87), θv_{90} (0.74), Bd (-0.811) and Na^+ (0.830) (Table 4). The loadings and contributions of PCs to variations in Sµ is quite similar to St and describes the strong positive correlation that exists between them (r = 0.80 ‡). In Table 4, the 24.9 % contributed by PC2 to Sµ variation between the lithologies was dominated by sand (-0.966), clay (0.828) and silt (0.780).

The first loading for Sm defines only 36.8 % of the variability. This percent total variance was contributed by Bd, θv_{30}, Na^+ and K^+ (>0.75). The comparatively low contribution of the most influential PC (PC1) to the variation of Sm had been reported in its poor regression and correlation with Bd,

Table 3: Correlation matrix between soil porosity and other soil properties

	Sand	Silt	Clay	Bd	K_{sat}	St	Sm	Sμ	θv_{30}	θv_{60}	θv_{90}	Na	K	Mg
silt	-0.79‡													
clay	-0.84‡	0.34*												
Bd	-0.27*	0.01	0.44†											
K_{sat}	0.12	-0.02	0.03	-0.46‡										
St	0.01	0.12	-0.01	-0.8‡	0.36†									
Sm	0.03	0.08	0.15	0.01	0.26*	0.29*								
Sμ	0.08	0.12	-0.28	-0.79‡	0.22	0.80‡	-0.29*							
θv_{30}	0.14	0.22	0.09	-0.78‡	0.27*	0.87‡	-0.12	0.89‡						
θv_{60}	0.20	0.11	-0.16	-0.58‡	0.11	0.60‡	-0.30*	0.74‡	0.74‡					
θv_{90}	-0.12	0.22	0.06	-0.65‡	0.18	0.75‡	-0.17	0.77‡	0.89‡	0.66‡				
Na	0.11	0.06	-0.1	-0.61‡	0.66‡	0.45‡	0.26	0.42†	0.45‡	0.28*	0.37†			
K	0.12	0.06	-0.25	-0.63‡	0.63‡	0.47‡	0.09	0.48‡	0.45‡	0.28*	0.38†	0.98‡		
Mg	-0.38†	0.35†	0.27*	-0.12	0.15	0.19	0.06	0.12	0.25*	0.06	0.18	0.41†	0.36†	
Ca	-0.53‡	0.59‡	0.29	-0.28*	0.02	0.38†	-0.12	0.41†	0.5‡	0.36†	0.47‡	0.38†	0.36†	0.53‡

Significant at *0.05, †0.01, ‡0.001, θvt: Volume fraction of H_2O at 30 cm tension, t: Tension level (30, 60 or 90 cm), $\ddot{x}$: Mean, Bd: Bulk density, Ksat: Saturated hydraulic conductivity, St: Total porosity, Sm: Macro porosity and Sμ: Microporosity

Table 4: Factor analysis showing relative loadings from variables

	St			Sm			Sμ		
Variables	PC1	PC2	PC3	PC1	PC2	PC3	PC1	PC2	PC3
Sand	-0.102	-0.962	0.042	-0.143	-0.956	-0.104	-0.072	-0.966	0.042
Silt	0.248	0.775	-0.129	0.293	0.760	0.045	0.236	0.780	-0.099
Clay	-0.055	0.826	0.046	-0.031	0.829	0.122	-0.091	0.828	0.021
Bd	-0.810	0.425	0.012	-0.783	0.461	-0.019	-0.811	0.405	0.052
K_{sat}	0.684	-0.309	-0.269	0.669	-0.344	0.360	0.663	-0.283	-0.337
St, Sm, Sμ	0.814	-0.098	0.220	-0.012	-0.038	0.708	0.825	-0.145	0.343
θv_{30}	0.874	0.060	0.393	0.851	0.029	-0.315	0.879	0.074	0.360
θv_{60}	0.572	-0.045	0.550	0.569	-0.066	-0.605	0.608	-0.045	0.557
θv_{90}	0.746	0.129	0.462	0.736	0.102	-0.389	0.749	0.142	0.419
Na^+	0.835	-0.173	-0.437	0.853	-0.220	0.303	0.830	-0.147	-0.461
K^+	0.798	-0.217	-0.473	0.815	-0.262	0.322	0.799	-0.192	-0.488
Mg^{2+}	0.496	0.453	-0.321	0.529	0.425	0.211	0.479	0.469	-0.310
Ca^{2+}	0.554	0.651	-0.084	0.597	0.622	-0.008	0.550	0.662	-0.066
Total variance (%)	41.500	24.800	10.300	36.800	24.700	11.700	41.600	24.900	10.900
Cumulative total variance (%)	41.500	66.300	76.600	36.800	61.500	73.200	41.600	66.500	77.400
Eigen values	5.400	3.220	1.340	4.790	3.210	1.520	5.410	3.240	1.410

θv_{30}: Volume fraction of H_2O at 30 cm tension, t: Tension level (30, 60 or 90 cm), Bd: Bulk density, K_{sat}: Saturated hydraulic conductivity, St: Total porosity, Sm: Macro porosity and Sμ: Microporosity, PC1, PC2, PC3: Principal components 1, 2, 3

θv_{30} and θv_{90} which were well related to St and Sμ. The percent total variance obtained for PC2 (24.7%) and PC3 (11.7%) are quite similar to values obtained in PC2 and PC3 for total and micro porosities, respectively.

The first two factor loadings (PC1 and PC2) may be retained since their Eigenvalues were >2.0 (Table 4), while PC3 may be discarded. Furthermore, PC1 maximized variation especially for total and micro porosities in the data set with resultant highest Eigenvalues.

DISCUSSION

Total sand content dominated the soils but presented little influence on the porosity of the studied soils. The dominance of sand-size particles over silt and clay in the soils is traced to the intercalation of limestone with sandstone. In Table 3, it is implied that an increase in silt and clay will cause a significant rise in the concentrations of the divalent cations. Divalent cations have been found to concentrate in tropical soils[19,21]. High sand content enhances water conductivity particularly in the surface soils, resulting in the leaching of divalent cations and indicates that silt and clay have relative advantages in holding divalent cations in the soil exchange complex.

Bulk density values were within the recommended range for root proliferation as well as water and air movements. Total and micro porosities are responsible for changes in Bd and facilitate K_{sat}. Decrease in the values of Bd led to a rise in St and Sμ and negates findings by Schon *et al.*[10], that Bd and Sm are responsible for changes in soil porosity. Furthermore, Onweremadu and Akamigbo[21] opined that increased Sm results in high water conductivity. Bulk density values in the studied soils indicate high porosity and the absence of root limiting layers. The proliferation of adventitious roots is sensitive to an increase in soil Bd and soil water tension[17].

Values of K_{sat} in the surface soils were rated very high and high to moderate in the subsurface soils and significantly positively correlated with St and Sm ($p = 0.01, 0.05$). Similar high values of K_{sat} in the surface soils were reported by Igwe and Stahr[22] and Ezeaku and Anikwe[23]. They attributed such values to greater aggregation caused by higher organic matter, increased biological channels or bioturbation by plant roots and burrowing animals. As a result, basic cations will be leached from the surface soils[21]. Also, higher values of K_{sat} in the surface soils may be traced to higher sand content and total porosity in the soils. This may encourage plant nutrient loss[19]. However, K_{sat} correlated positively with exchangeable Na^+ and K^+. Soil chemical reactions, fluid flow and nutrients are influenced by soil porosity[5]. High K_{sat} in the surface soils was responsible for the relatively low basic cations.

The trend in the volume fraction of water (θvt) at the various tension levels, lithologies and agricultural zones indicate that tension is affected by soil type and therefore not proper to generalize on any particular tension level without referring to the type of soil. Crop yield and quality as well as nutrient and water stress, are closely related to soil water tension[24]. The yield and quality of crops are reduced by erratic irrigation schedules. Macro-pores conduct more water compared to micro-pores and are most likely to be drained at the slightest of tensions. Nunes *et al.*[17] affirm that soil water content depends on tension. At less water tension, soils have more moisture which needs less energy for plant uptake. Soil water tension is essential for irrigation schedules[25] and it is often affected by crop type, soil texture, climate and method of irrigation[25,26]. This way, different crops are adapted to different climates. Differences in air and water volume result in variations in water-filled pore space[12], while pore size geometry controls water conductivity in sandy soils[23]. In the northern agricultural zone (found in the northern guinea savannah) and central agricultural zone, large soil pores sizes conduct more water than they will do to air. In the southern agricultural zone (tropical rainforest), the reverse is the case mainly due to variation in vegetation. Soil aeration is therefore high at 30 cm tension and low at 90 cm tension, hence the correlation of Sm with θv_{60} ($r = -0.30^*$). Similarly, St and Sμ were positively regressed and correlated with θv_{30} ($p = 0.001$) resulting in a high degree of certainty (R^2>50 %) of θv_{30} being high at high St and Sμ. The influence of micro-porosity on total porosity was more than macro-porosity, hence their positive and significant correlation ($R^2 = 0.80$, $p<0.001$). Climates as well as soil and crop type, are important factors that affect soil water tension and should be exhaustively considered in subsequent studies. Soil water tension is important in the management of soil moisture[27] and regarded as a necessity in irrigation schedules[25].

Soil texture is an important soil property in agronomic studies, particularly as correlations indicate that a rise in divalent cations is imminent when silt increases and sand decreases (Table 3). Weerden *et al.*[12] opined that clay amount is responsible for pore size distribution, however, significant regression models were not obtained between porosity parameters and particle sizes.

St and Sμ indicated significant positive relationships with exchangeable K and Na ($p<0.001$) (Table 2 and 3). Therefore, dispersed particles in the solution will migrate easily through micro-pores. This corroborates the findings of Farahani *et al.*[28]. Variations in pore space and soil structural deterioration have been attributed to Na^+ accumulation[13,14], while Marchuk *et al.*[5] observed that the architecture of pore systems is influenced by the chemical composition of soil fluids. According to

Farahani *et al*.[28] monovalent cations can jeopardize soil pores and soil structural stability and encourage soil erosion. Therefore, erosion in the study areas may have been partly due to these interrelationships.

Macro porosity was poorly related to soil physical and chemical properties. However, pores occupied by water at 30, 60 and 90 cm tensions are most likely to increase when there is a rise in St and Sμ. Consequently as soil compaction leads to an increase in Bd, the values of θvt and Sμ decrease. The need for water in the plant shoot results in the transmission of tension to the roots to extract more water from the soil[24]. Soil water tension is a necessity in irrigation schedules[25] and crop yield and quality may be lowered by erratic irrigation schedules. For crop productivity to be maintained, supplementary irrigation is needed[26]. Crop nutrients that are lost due to excess irrigation water have the potential to contaminate ground and surface water. Changes in soil porosity are linked to Bd and Sm[10]. Low soil macro-pores will result in mottling/gleying, low soil faunal community and activity, slow organic matter decay and reduced release of nutrients to crops.

An increase in the concentrations of Na^+ and K^+ enhanced water conductivity through the soil. This is rather surprising as monovalent cations cause soil particle dispersion and disorient the soil aggregates which are most likely to cause pore clogging. The dispersion of soil particles is related directly to electrostatic forces and Diffused Double Layer (DDL). Furthermore, Abbaslou *et al*.[29] found a decrease in cation exchange capacity to be responsible for clay dispersion when Na^+ concentration remained the same. Electrolyte concentration, clay mineralogy, soil pH and organic matter are important factors responsible for the dispersion of soil particles.

Interrelationships between the monovalent cations, Bd, St and Sμ indicate that compacted soils are less likely to leach Na^+ and K^+ (Table 3). Irrespective of tension levels, an increase in St and Sμ enhanced K_{sat} as well as the concentration of monovalent cations which are often more loosely held in soil exchange complexes. Also, the loss of exchangeable Mg^{2+} may be unconnected with soil porosity. Consequently, the underlying lithology, vegetation and land use were responsible for the changes in soil porosity. Furthermore, exchangeable Ca, K and Na are most influenced by soil physical properties than Mg. Exchangeable Na and K seem to be correlated with similar properties, just like exchangeable Mg and Ca. Ions of similar valency behave in a like manner in soils. The effects of Mg^{2+} and Na^+ on soil physical properties are similar and likely to create clay dispersion[30]. A recent study of the soils[19] reported high cation exchange capacity. Soils with such high CEC values may adsorb high Na^+ concentration, thereby leading to the dispersion of soil particles[29]. Dispersion reduces soil porosity, affect water and air transport in soils and increases soil erodibility. Dispersion of colloidal fraction of the soil is an undesirable condition and can be reduced by the careful use of organic soil amendments.

Unlike Sμ, Sm did not have a significant relationship with exchangeable basic cations. Macro porosity (Sm) may be unconnected with the loss of basic cations mainly because they are air-filled, unlike the micro-pores that are agents of transport for solutions. This may be amended by the use of additives high in either Ca^{2+} or Mg^{2+} (calcite or dolomite), after all, Mg reacts similarly to Ca in stabilizing the physical condition of soils. Exchangeable Mg^{2+} correlated with other soil properties in a similar way as Ca, except Bd, K_{sat}, porosity parameters and volume fraction of water. When the concentration of exchangeable Mg^{2+} exceeds that of Ca^{2+}, its effect on soil physical properties become obvious[31]. Elevated concentration of exchangeable Mg^{2+} deteriorates soil structure, causes surface sealing and then reduces infiltration. These phenomena result in surface runoff and then surficial erosion, especially in the high rainfall zone of Cross River State.

CONCLUSION

Exchangeable Na^+, Bd and volume fraction of water at 30 cm of tension as well as lithology are important factors that influence soil porosity. Reliable functions (R^2>50 %) were obtained between St and Sμ, against Bd and volume fraction of water at all tension levels and emphasizes the relevance of water tensions in soil porosity studies. Macro porosity is least influenced by other soil properties, while sand is a poor predictor of porosity. Total and micro porosities contribute to the control and release of cations to the soil environment.

SIGNIFICANCE STATEMENT

This study discovered the relevance of soil porosity at various tension levels and how it is affected by other soil properties as well as its resultant implication and variation between lithologies. This study can be beneficial for predicting soil porosity using basic and easily determining soil properties. This study will help researchers to uncover the critical areas of soil porosity that many researchers were not able to explore. Thus a new theory relating water tension and porosity to soil properties may be arrived at.

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