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Original Research Article

Study of Void Ratio Influence on Soil Permeability: Application to Clay and Silty Soils in Northern and Southern Togo

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ABSTRACT

Soil permeability depends on multiple factors, among which the compactness which is itself linked to the density and the void ratio. The purpose of this work is to determine the correlations that may exist between permeability coefficient and void ratio of clay and sandy soils present in the north and south of Togo. To do this, samples of these soils were compacted at different compaction energies and then subjected to permeability tests using a variable load permeameter. The test of different mathematical models of regression analysis made it possible to establish correlations between permeability coefficient, k_{20}, at 20°C of these materials and their void ratio, e. Thus, a correlation model in the form $k_{20} = 10^{-2} \times e^{15}$ has been proposed. Studies are continuing to see if this proposed model for the materials studied can be extended to other materials with different geotechnical characteristics.

Keywords: void ratio, correlations, permeability coefficient, variable load, clay and silty soils.

INTRODUCTION

Soil permeability corresponds to its ability to be let through by water. The compactness determined by density is one of the various factors on which soil permeability depends. High permeability implies a significant presence of voids in the soil. In civil engineering, depending on the nature of the work to be constructed, requirements are usually specified relating to the permeability and compactness of the soil involved in the construction, either as a foundation support or as a building material. As the permeability test is not easy to carry out, it is therefore important to be able to understand the relationships that may exist between soil permeability and void ratio. The purpose of this article is, on the one hand, to present the results of permeability tests with a variable load permeameter carried out on soils taken from North and South of Togo and compacted at different energies, and on the other hand, to establish correlations between the permeability coefficient of these soils and their void ratio.

MATERIALS & METHODS

The materials studied are of different natures and were collected from five (5) sites distributed in the Kara Region and the Maritime Region in Togo (Table 1 and Figure 1).

Table 1: Nature and origin of materials

Materials nature	Clay	Clay	Silty sand	Clay sand	Clay sand
Origin	Broukou	Kpassidè	Dalavé	Agbalépédogan	Massouhoin

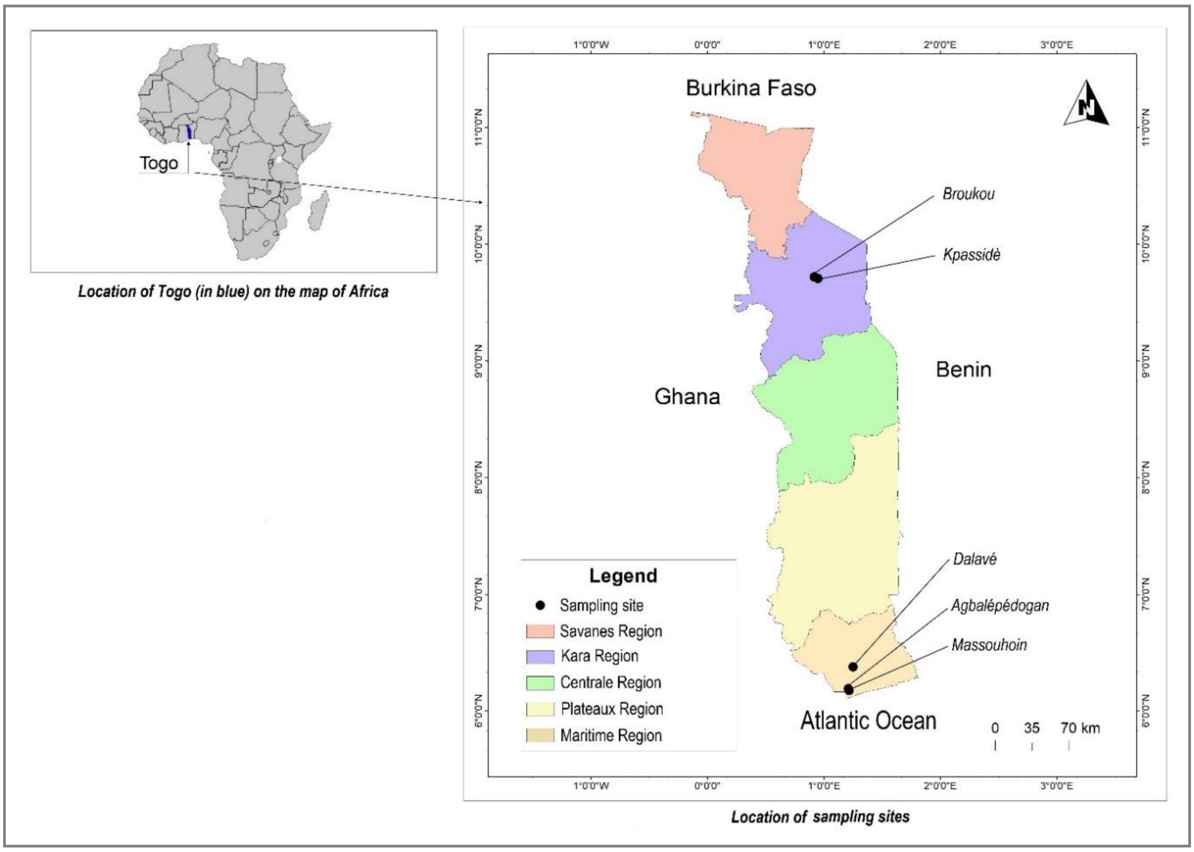


Figure 1: Location of sampling sites

After sampling, these materials were first subjected to identification tests (particle size analysis, [1] determination of Atterberg limits, [2] determination of water content, [3] determination of dry density, [4] Proctor test [5]) in order to know their geotechnical nature, then to the permeability test with the variable load permeameter. [6] Finally, the determination of a correlation between permeability coefficient and void ratio is studied.

Permeability Test with Variable Load Permeameter

The permeability test consists in subjecting a soil sample to a load difference, so as to establish a one-dimensional flow between its lower and upper ends. [7] For this study, the permeability test is done at variable load due to the low permeability of the soils studied. [8] The principle of the permeability test using a variable load permeameter is presented in Figure 2 and the device used in Figure 3. This device allows tests to be carried out at constant or variable load.

The objectives of the work being to study the evolution of the permeability according to the void ratio, the materials were compacted by varying the compaction energy.

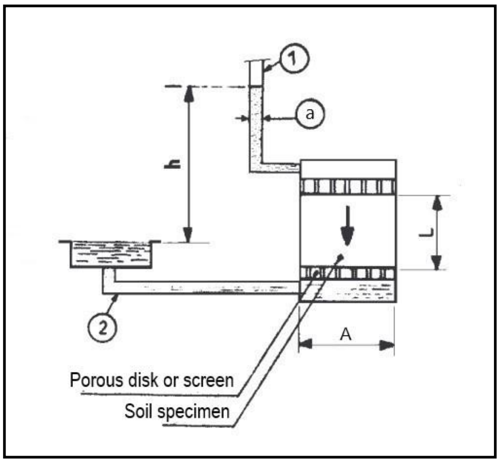


Figure 2: Principle scheme of variable load permeameter [9]

Figure 3: Constant or variable load permeameter

Each material sample is compacted into three (3) layers in the permeameter compacting mold. The layers are compacted using a normal Proctor rammer at N = 5, 10, 15 or 25 blows depending on the energy to be applied for the test. The compacted sample dry density (γ_d) and void ratio (e) are then determined.

Before the test starts, it is necessary that test samples are completely saturated with water. To do this, the entire compaction permeameter containing the compacted sample is placed in an immersion tank for 48 hours.

Following this saturation phase, the measurements are carried out as follows:

-The time t necessary for the water level in the pressure gauge tube to drop from a level h_1 to a level h_2 is measured; five (5) measurements are made for the same soil specimen;

-The temperature T of the water during the test is noted;

-The test piece is finally removed from the mold and a sample is taken there to determine the dry density and the void ratio of the material at the end of the test.

The permeability coefficient, k (in m/s), at variable load is [7]:

$$k = \frac{a \times L}{A \times t} ln\left(\frac{h_1}{h_2}\right) \qquad (1)$$

Where:

a is the section of the pressure tube (m^2);

L is the height of the test piece (m);

A is the section of the test piece (m^2);

t is the time necessary (s) for the water level in the pressure tube to change from a charge height h_1 to h_2.

The permeability coefficient, defined by equation (1), is evaluated at the temperature T of the test. The permeability of a soil depends on the viscosity μ of the water which varies according to the temperature.[10] The value of the permeability ($k = k_T$) measured at temperature T should therefore be reduced to a standard value k_{20} corresponding to a reference temperature taken equal to 20 ° C. The permeability coefficient k_{20} (in m/s) at 20 ° C is then obtained using equation (2).

$$k_{20} = k_T \times b = k_T \times \frac{\mu_T}{\mu_{20}} \qquad (2)$$

Where:

$b = \mu_T/\mu_{20}$ is a coefficient established by Jaynes [11] and defined as follows: $b = exp(2{,}44 \times 10^{-2}(20 - T) + 1{,}8 \times 10^{-4}(20 - T)^2 + 2{,}5 \times 10^{-6}(20 - T)^3)$

where T represent the test temperature (°C);

k_T is the permeability coefficient (m/s) measured at the temperature T (°C) of the test;

μ_T is the kinematic viscosity (m^2/s) of the water at the temperature T of the test;

μ_{20} is the kinematic viscosity of the water at 20°C (m^2/s).

Development of Correlations

Correlations are established between the permeability coefficient k_{20} determined with the variable load permeameter and the void ratio of the material. To do this, three (3) mathematical regression analysis models are tested for each material in order to select the best ones:

- the power model: $k_{20} = a.e^b$
- the exponential model: $k_{20} = a.\exp(b.e)$
- the second-degree polynomial model: $k_{20} = a.e^2 + b.e + c$

Where:

k_{20} is permeability coefficient;

e is void ratio;

a, *b* and *c* are real constants to be determined.

The existence of a correlation between the parameters will be assessed by the coefficient of determination R^2 which is an indicator giving the possibility of measuring the quality of the prediction of a linear regression: [12]

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(y_i - \tilde{y}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2} \qquad (1)$$

Where:
n is the number of measurements;
y_i is the value of the i-th measurement;
$\tilde{y}_i$ is the corresponding predicted value;
$\bar{y}$ is the average of the measurements.

In the context of this work, the models studied being not linear models, it is essential to linearize them by making variables changes. [13] The relationship between the parameters will be strong if the coefficient of determination is close to 1.

Following the obtaining of the models translating the strongest correlations between the variables studied according to materials, it is carried out a study of determination of a single model being able to translate the correlation between the permeability coefficient k_{20} and the void ratio e, and valid for all of the materials studied. This study will be done based on the models selected for each material.

RESULTS & DISCUSSION

Identification Test Results

The results of the identification tests of some nature and state parameters are presented in Table 2, Table 3 and in Figure 4.

Broukou soil is plastic and fine. According to the GTR classification of soils, these are marly clays or very plastic silts (class A3). Kpassidè soil is also plastic and fine but is of class A2 (fine clay sands, silts, clays and marls which are not very plastic). Massouhoin soil is also plastic, but with a few fine elements, and of class A3 (marly clays or very plastic silts). Agblépédogan soil is little plastic with few fine elements and of class B6 (sandy and gravelly clay to very clayey). Dalavé soil of is of nature B1 (silty sand) with very few fine elements. All the soils studied have the majority of grains with a diameter of less than 2mm.

Table 2: Results of tests to identify nature and state parameters

Material	**< 80 µm *(%)***	**< 2 mm *(%)***	**D_{max} (1) (mm)**	**Liquidity limit (%)**	**Plasticity index (%)**	**Absolute density (g/cm^3)**	**Water content (%)**	**GTR class (2)**
Broukou clay	70	94	2,5	44	26	2,53	7,28	A3
Kpassidè clay	81	99	0,315	45	24	2,43	3,32	A2
Massouhoin clay sand	42	100	1	47	25	2,50	(3)	A2
Dalavé silty sand	10	98	1,6	(4)	(4)	2,64	(3)	B1
Agbalépédogan clay sand	35	100	1	35	16	2,60	7,45	B6

Diameter for which 95% of grains are lower in size
GTR: Guide of Road Earthworks - Realization of embankments and form layers
Undetermined parameter
Non-determinable parameter on the material

Table 3: Proctor optimal values of materials

Provenance of material	**Optimal water content (%)**	**Optimal dry density**
Broukou (A3)	12.2	1.84
Kpassidè (A2)	13.2	1.82
Massouhoin (A2)	10.22	1.97
Dalavé (B1)	5.78	1.88
Agbalépédogan (B6)	11.9	1.94

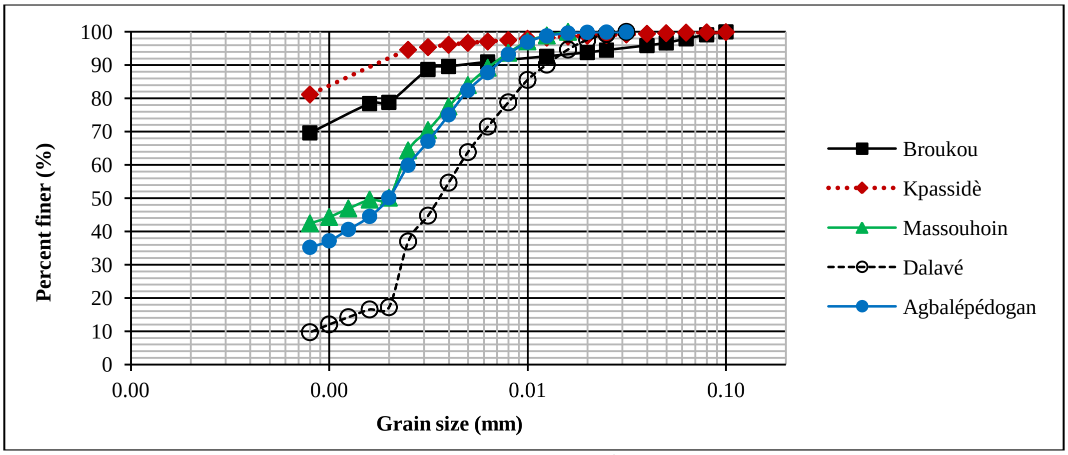


Figure 1: Granulometric curves of the soils studied

Results of Permeability Tests Using a Variable Load Permeameter

Table 4 presents the permeability coefficients at 20 ° C (k_{20}) of soils as a function of dry densities and void ratio. The results confirm that the permeability values increase with the void ratio. [14]

Table 4: Summary of permeability test results

Broukou clay (A3)					**Kpassidè clay (A2)**				
k_{20}(m/s)	Dry density		Void ratio		**k_{20}(m/s)**	Dry density		Void ratio	
	Initial	Final	Initial	Final		Initial	Final	Initial	Final
6.258×10^{-7}	1.57	1.58	0.611	0.601	3.902×10^{-8}	1.61	1,64	0,509	0,422
9.190×10^{-8}	1.64	1.66	0.543	0.524	1.297×10^{-8}	1.71	1,73	0,421	0,405
1.384×10^{-8}	1.72	1.74	0.471	0.454	1.822×10^{-9}	1.73	1.76	0,405	0,395
2.237×10^{-9}	1.77	1.79	0.429	0.413	1.238×10^{-9}	1.77	1,78	0,373	0,365
1.277×10^{-9}	1.78	1.81	0.421	0.398	4.587×10^{-10}	1.83	1,84	0,328	0,321
Massouhoin clay sand (A2)					**Dalavé silty sand (B1)**				
k_{20}(m/s)	Dry density		Void ratio		**k_{20}(m/s)**	Dry density		Void ratio	
	Initial	Final	Initial	Final		Initial	Final	Initial	Final
3.020×10^{-5}	-	1.57	-	0.590	7.460×10^{-5}	-	1,48	-	0,790
2.090×10^{-6}	-	1.67	-	0.490	4.760×10^{-6}	-	1,58	-	0,670
1.160×10^{-7}	-	1.86	-	0.340	2.990×10^{-7}	-	1,68	-	0,570
Agbalépédogan Clay sand (B6)									
k_{20}(m/s)	Dry density		Void ratio						
	Initial	Final	Initial	Final					
1.064×10^{-6}	1.85	1.86	0.406	0.401					
5.424×10^{-9}	1.90	1.91	0.370	0.362					
6.940×10^{-10}	1.94	1.95	0.338	0.330					
Note: The initial values correspond to those obtained by compacting the sample before immersion and the final values correspond to those obtained at the end of the test.									

Correlations Between Permeability Coefficient and Void Ratio of Materials

In order to establish these correlations, trend curves, represented by the graphs in Figure 5, are plotted from the point clouds whose coordinates correspond to the values of k_{20} and e_{final} contained in Table 4.

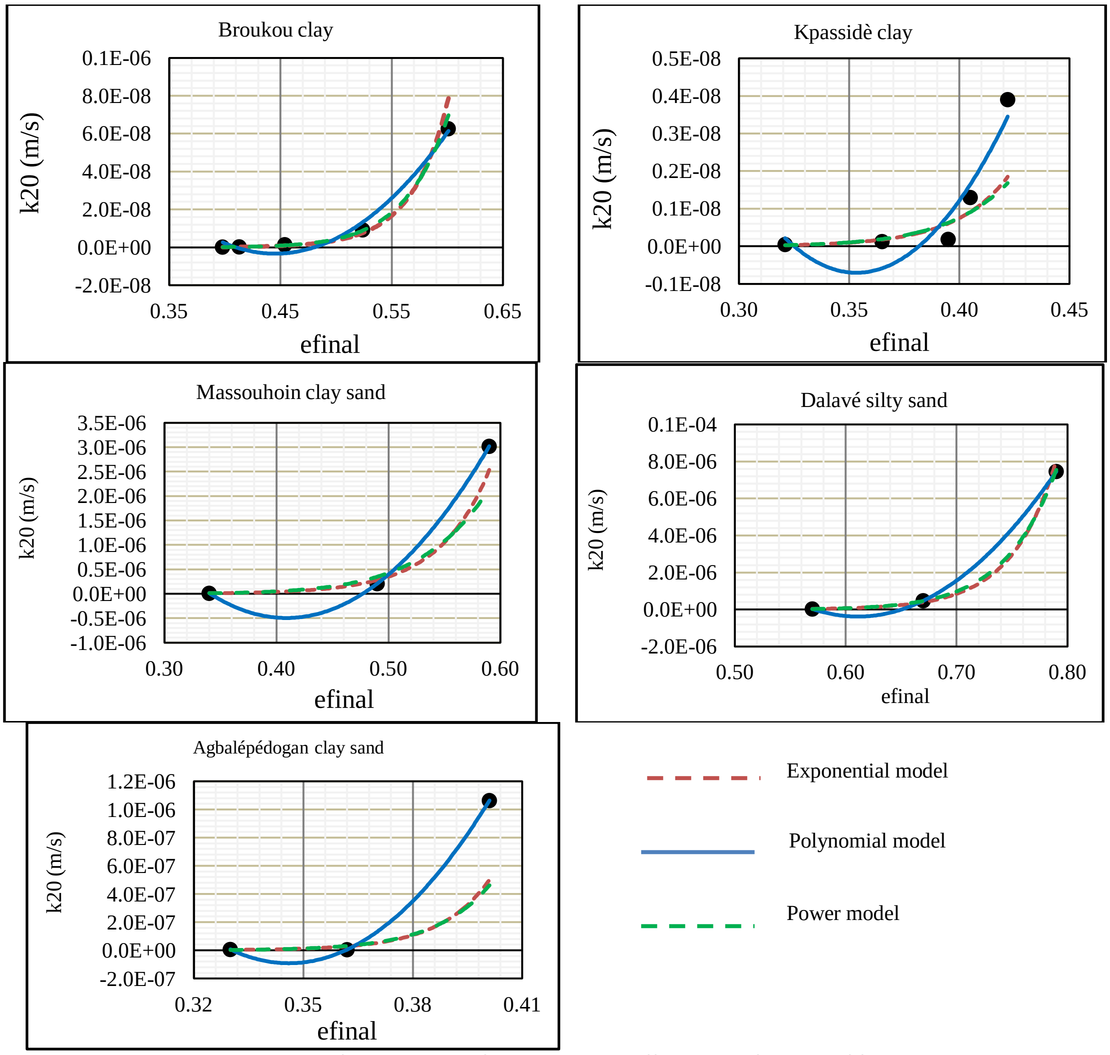


Figure 5: Trend curves for regression of permeability coefficient as a function of final void ratio

The equations and coefficients for determining *R²* of the trend curves obtained from the regression analyzes are presented in Table 5.

Table 5: Correlations between permeability coefficient k_{20} and final void ratio

Material	**Model**	**Correlation equation**	***R²***
Broukou clay	*Power*	$k_{20} = 0.0015 \times e^{15.015}$	*0.9954*
	Exponential	$k_{20} = 9 \times 10^{-15} \exp{(30.408e)}$	0.9865
	Polynomial	$k_{20} = 0.00003e^2 - 0.00005e + 0.000006$	0.9847
Kpassidè clay	*Power*	$k_{20} = 0.0065 \times e^{14.917}$	*0.7882*
	Exponential	$k_{20} = 5 \times 10^{-16} \exp{(41.178e)}$	0.8123
	Polynomial	$k_{20} = 0.000009e^2 - 0.000006e + 0.000006$	0.8822
Massouhoin clay sand	*Power*	$k_{20} = 0.0038 \times e^{9.7877}$	*0.9736*
	Exponential	$k_{20} = 6 \times 10^{-11} \exp{(22.013e)}$	0.9915
	Polynomial	$k_{20} = 0.0011e^2 - 0.0009e + 0.0002$	1
Dalavé silty sand	*Power*	$k_{20} = 0.0041 \times e^{16.91}$	*0.9999*
	Exponential	$k_{20} = 2 \times 10^{-13} \exp{(25.017e)}$	0.9971
	Polynomial	$k_{20} = 0.0024e^2 - 0.003e + 0.0009$	1
Agbalépédogan clay sand	*Power*	$k_{20} = 7 \times 10^{8} \times e^{37.886}$	*0.9526*
	Exponential	$k_{20} = 5 \times 10^{-25} \exp{(104.46e)}$	0.9637
	Polynomial	$k_{20} = 0.0004e^2 - 0.0003e + 0.00005$	1
Note: k_{20} is in m/s and "exp" represents exponential function.			

The results of Table 5 show at first sight that the three regression models are acceptable by referring to the coefficients of determination *R²* close to 1. However, each curve of the polynomial model observable in Figure 5 have a negative minimum permeability coefficient. Not being monotonous in nature, these polynomial curves do not reflect the fact that when the void ratio increases in a material, its permeability increases absolutely. [14]

Of the three adjustment models tested, these are the power and exponential adjustment models that can be used to determine the permeability coefficient as a function of the void ratio of the soils studied.

For each soil studied, the coefficients of determination of the power and exponential models are fairly close. The power model is better for Broukou and Dalavé soils with the parameter *b* very close (between 15 and 17). For other soils, the exponential model is better but with different parameter values. The power model for the Kpassidè soil also has a parameter *b* around 15.

To determine a single correlation model between the permeability coefficient and the void ratio, only the power adjustment models are used. In order to compare the evolution of permeability as a function of the void ratio of the different materials, the point clouds and trend curves in the power form of Figure 5 are represented on the same graph (Figure 6).

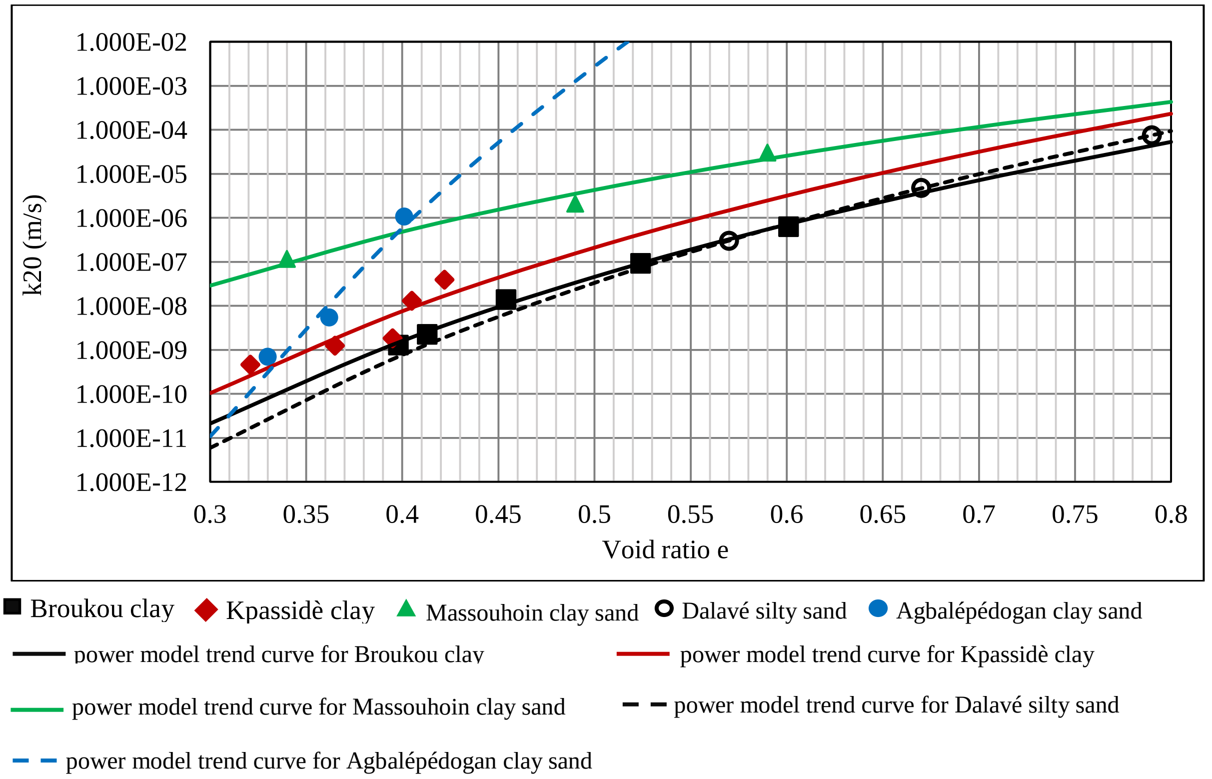


Figure 6: Power model trend curves showing the evolution of the permeability coefficient k_{20} as a function of the void ratio and according to the materials

The observation of Figure 6 shows a similarity in the shape of the trend curves of Broukou clay, Kpassidè clay and Dalavé silty sand, unlike those of Massouhoin and Agbalépédogan. clay sands.

The models are of the form $k_{20} = a \times e^b$ with, in particular:

$a = 0.0015$ and $b = 15.015 \approx 15$ for Broukou clay model;

$a = 0.0065$ and $b = 14.917 \approx 15$ for Kpassidè clay model;

$a = 0.0041$ and $b = 16.910 \approx 17$ for Dalavé silty sand model.

The coefficients *a* of these three models are of the order of 10^{-3} and *b* varies from 15 to 17. The aim of the work being to achieve a single correlation model valid for all the materials studied, the following approach is adopted.

The exponent *b* is first set to 15, the coefficient *a* then successively takes the values 10^{-3}, 10^{-2} and 10^{-1}. These combinations of *a* and *b* allow to obtain three (3) models $k_{20} = a \times e^{15}$ (with $a \in \{10^{-3}; 10^{-2}; 10^{-1}\}$) which can then be tested on the series of permeability coefficients measured on all materials. The quality of the models tested is assessed through the coefficients of determination R^2.

Table 1: Coefficients of determination R^2 obtained for the models $k_{20} = a \times e^b$

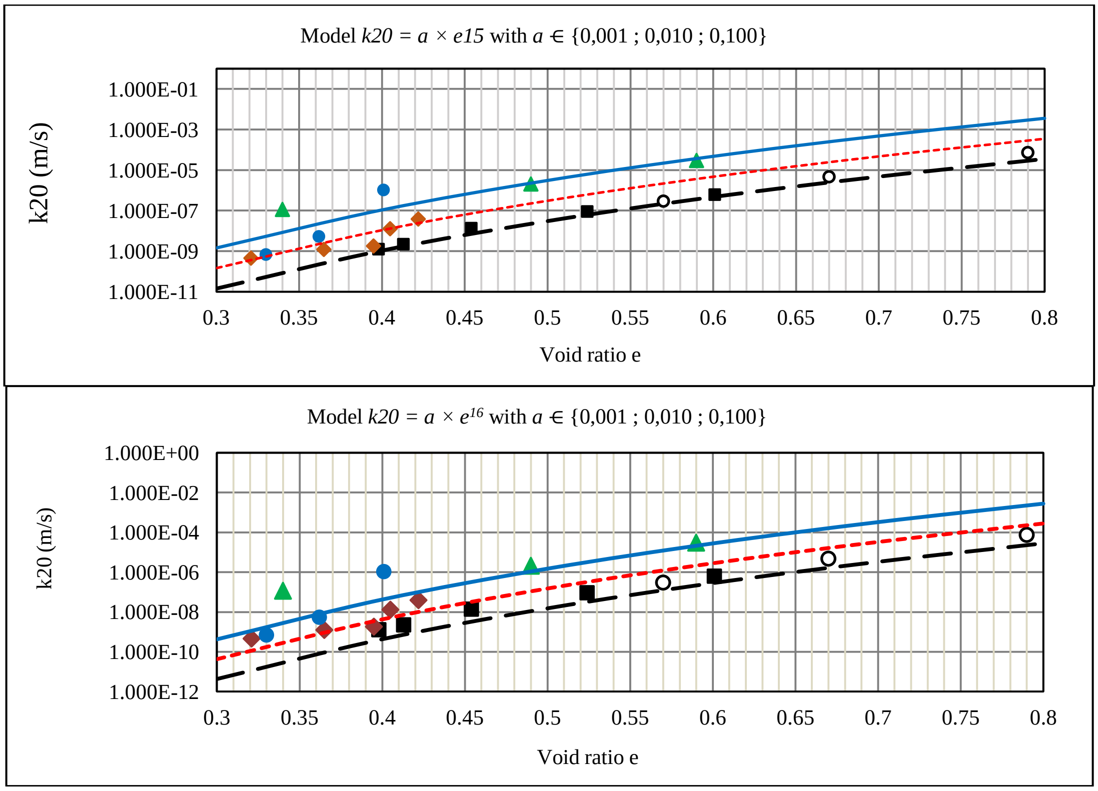
Parameter b	Parameter a	Correlation equation	R^2
15	10^{-3}	$k_{20} = 10^{-3} \times e^{15}$	0.28
	10^{-2}	$k_{20} = 10^{-2} \times e^{15}$	0.65
	10^{-1}	$k_{20} = 10^{-1} \times e^{15}$	0.21
16	10^{-3}	$k_{20} = 10^{-3} \times e^{16}$	-0.08
	10^{-2}	$k_{20} = 10^{-2} \times e^{16}$	0.58
	10^{-1}	$k_{20} = 10^{-1} \times e^{16}$	0.42
17	10^{-3}	$k_{20} = 10^{-3} \times e^{17}$	-0.54
	10^{-2}	$k_{20} = 10^{-2} \times e^{17}$	0.40
	10^{-1}	$k_{20} = 10^{-1} \times e^{17}$	0.53
Note: k_{20} is in m/s.			

This process is repeated by setting the exponent *b* to 16 then 17, coefficient *a* always taking the values 10^{-3}, 10^{-2} and 10^{-1}. The results obtained are presented in Table 6.

The models fitted to the series of permeability coefficients measured as a function of the void ratio in the soil are shown in the graphs in Figure 7.

The analysis of the coefficients of determination ^{R2} contained in Table 6 and the graphs of Figure 7 allows to retain the model $k_{20} = 10^{-2} \times e^{15}$ as being the most reliable because corresponding to the highest coefficient of determination. In addition, the curve of the latter is surrounded by the envelope curves of equation $k_{20} = a \times e^{15}$ with $a \in \{10^{-3}; 10^{-1}\}$ whose coefficients of determination are all positive.

Ultimately, the model $k_{20} = 10^{-2} \times e^{15}$ could therefore be used for the determination of the permeability coefficients according to the void ratio of the materials studied.



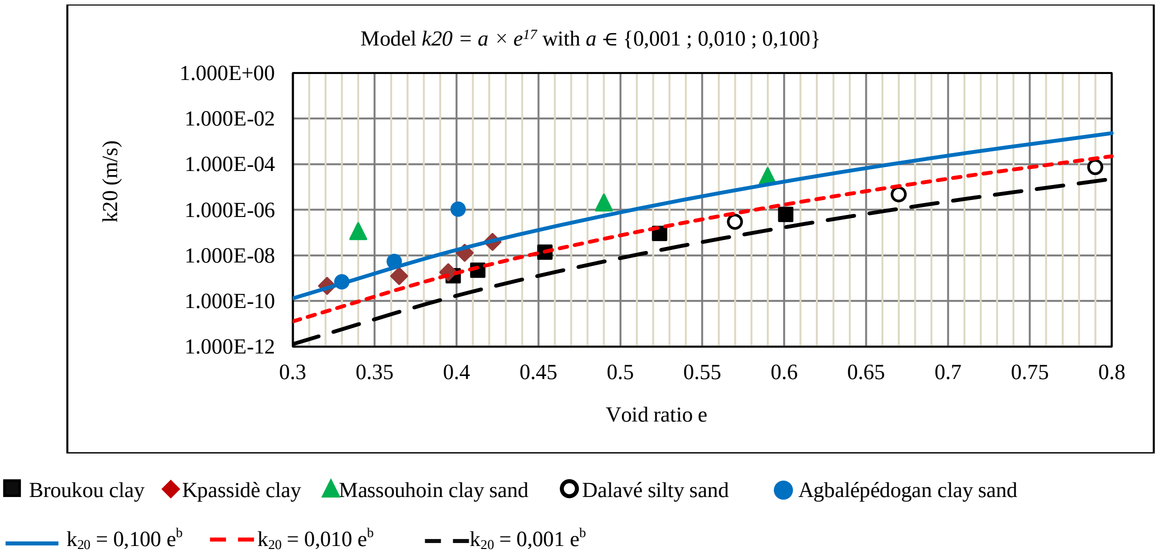


Figure 7: Adjusted models $k_{20} = a \times e^b$

CONCLUSION

The permeability of a soil is essentially linked to its particle size and other physical characteristics including the void ratio. The objective of this study was to determine the correlations that may exist between the coefficient of permeability k_{20} at 20 ° C and the index of voids and soil present in the North and South of Togo. To do this, samples of these soils were compacted at different energies and then subjected to permeability tests using a variable charge permeameter. Thus, among the regression analysis mathematical models tested for establishing correlations according to the soils, the exponential and power models appear to be the most reliable. Furthermore, following an in-depth analysis of the power models obtained, a simplified correlation model in the form $k_{20} = 10^{-2} \times e^{15}$ has been proposed.

Some points constituting the perspectives of this work remain to be deepened. This involves, among other things, continuing the studies in order to see if the last model proposed for the five (5) materials studied can be extended to other materials and then to better understand, thereby, the factors influencing the variability of the permeability coefficient.

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