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Empirical Models for the Determination of the Compression Index from the Atterberg Limits: Case of the Soils of the Issaba Depression in Benin

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

The good realization of any infrastructure in civil engineering requires the implementation of geotechnical investigations. During these investigations, the physical properties of the soil, especially the mechanical ones, must be determined with care and precision because of their capital importance in the preliminary studies before the realization of the work. The soil compression index is one of these mechanical parameters, determined by laboratory tests. It allows the calculation of settlements and is therefore essential, especially for fine clay or silty soils which are often subject to swelling phenomena. However, the realization of the test to find the compression index in the laboratory takes time, and the test itself proves delicate. Several authors have therefore proposed the determination of this index from the limits of Atterberg, which can be obtained more quickly and easily. Through this study, empirical models have been proposed to

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easily calculate the compression index. Regression analyses in Matlab with 2D and 3D graph systems were performed for this purpose. The model was established for the soils of the Issaba depression in the Republic of Benin, where clayey and silty soils are very swelling. The models obtained show very good correlations with R^2 coefficients higher than 0.80 and the RMSE error minimized to less than 0.5.

Keywords: Empirical model; correlation regression; compression index; atterberg limits; Issaba depression.

1. INTRODUCTION

A sustainable realization of any infrastructure requires the implementation of geotechnical investigations. During these investigations, the physical properties of the soil, especially the mechanical properties, must be determined with care and precision because of their crucial importance in the preliminary studies for the realization of the work. The soil compression index is one of these mechanical parameters determined by laboratory tests. It allows the calculation of settlements and is therefore essential, especially for fine clay or silty soils which are often subject to instability phenomena. However, it takes time to carry out the laboratory test to find the compression index, and the test itself is delicate. Several authors have therefore proposed the determination of this index from the Atterberg limits, which can be obtained more quickly and easily.

Correlations and empirical relationships are used extensively in geotechnical engineering. The use of correlations and empirical relationships provides a fast, cost-effective means of predicting the value of a parameter based on the values of some other, possibly more easily determined, parameters provided that the appropriate correlations are employed. Generally, the more easily obtained parameters are correlated to the difficult to obtain parameters. The correlation between two or more soil properties is dependent in varying degrees on soil type, the testing method used to obtain the numerical value of the parameter itself, and the homogeneity of the soil [1]. Many correlations between soil properties have been published. In the last decade, much research were performed to correlate the physical properties with the mechanical properties [2].

Knowledge of the consolidation properties of soil is important in geotechnical design, particularly as they relate to the settlement of structures. These properties are usually determined by oedometer testing, and determined in terms of the compression index Cc and recompression index Cs. The compression index (Cc) is one of the salient parameters which the geotechnical engineer seeks to unravel to establish the safety of the proposed structure immediately after construction and during the lifetime of the structure [1].

A compression index value is required by the geotechnical to determine the soft clay soil settlement [3]. The compression index Cc is an important one-dimensional compressibility parameter with particular relevance to primary settlement calculations for normally consolidated or lightly overconsolidated natural soils [4].

However, the value of compression index testing in the laboratory requires much more time and the cost of laboratory testing is relatively expensive compared to other soil characteristics testing. For comparison, the calculation of unit weight and void ratio can be completed within 1-2 days, while the calculation of the compression index with a one-dimensional consolidation test in the laboratory is completed in more than 1 week [3]. The cost of consolidation testing is relatively high compared to other common engineering tests and may be considered cost prohibitive for very small projects. Hence it is cost effective to develop correlations between consolidation properties and other easily obtained properties, like the index properties. In view of the cost implications of the consolidation test, investigators have correlated the consolidation properties of soils and other easily and cheaply obtained properties, like the index properties [5]. Whereas planners and engineers usually needed that data quickly, so the use of the empirical formula is preferred [3].

Index properties of soil such as Atterberg limits, moisture content and initial void ratio are basic properties of soils. Therefore, it is possible to use these index properties to predict the compression index of the soil. Empirical models relating various index properties to the compression index have been presented by many researchers

[1]. The oldest correlation models were established by Skempton [6] for Remoulded clays, Nishida [7] and Yamagutshi) [8] for various clay, Peck and Reed [9] for Chicago clays, Hough [10] and Moran et al. [11] for organic soils, Cozzolino [12] for Brazilian clays, Terzaghi and Peck [13] for normally consolidated clays. We can also mention Sowers [14] for soils with low plasticity, Azzouz et al. [15] for various clay, Wroth and Wood [16], Bowles for organic silt and clays [17], Al-Khafaji and Andersland [18], Hong and Onitsuka [19] and many others.

Many researchers have used linear regression to establish empirical models between soil parameters. We can mention Yoon et al. [20] who proposed regression models for predicting compression index for marine clay, Abbasi et al. [21] used regression analysis to predict the compression behavior of normally consolidated fine grained soil, and Nihad [22] who adjusted the equations of Rashed et al [23]. In addition, Yildirim and Gunaydin [24] concluded that, the correlation equations obtained as a result of regression analyses are in satisfactory agreement with the test results and recommended that the proposed correlations will be useful for a preliminary design of a project where there is a financial limitation and limited time. It is evident in literature that prediction of compression index with regression analysis has proved to be successful and widely accepted [1].

Correlations are widely referenced by geotechnical designers, although strictly they should not be applied to soils elsewhere without considering the soil origin and sampling method [17]. In the south of Benin, a median depression called Lama depression, subdivides the bar land plateaus into two groups [25]. In this depression is found clay soils with high swelling potential, which generate various disorders in the infrastructure as mentioned by Gbaguidi et al., [26] and Tankpinou kiki [27]. In addition, Agbelele et al., [28] showed that east of this depression, the soils are composed of silt and clays of illite and montmorillonite. Their swelling potential and pathological risk were found to be high [28]. Therefore, this current study presents empirical models involving the compression index and Atterberg limits of soils in the Issaba depression, using linear regression analysis. The models established in this study can be used to predict the compressive index for preliminary design purposes and also to verify the accuracy of consolidation tests in this depression.

2. MATERIALS AND METHODS

2.1 Description of the Study Area

The Republic of Benin extends perpendicularly to the coastline of the Gulf of Benin between the meridians 1° and 4° and the parallels 6° and 12° north. Narrowly constricted south of the 9th parallel by Togo and Nigeria (average width 120 km), it extends further north to the borders of Burkina Faso and Niger. The Median Depression is the great depression crossing southern Benin from west to east in a southwest-northeast direction. This depression leaves Nigeria, crosses Benin and continues into Togo [25]. The median depression is oriented generally from west to east and forms a vast furrow 130 km long and varying in width from 5 km (Tchi) to 25 km (Issaba). It is called Issaba depression in the east, Ko depression in the center and Tchi depression in the west. It constitutes a low region with an altitude of less than 50m that is covered with clay soil [29].

2.2 Sampling and Quality Analysis

The data used for the study consist of laboratory results of soils sampled during geotechnical investigations in the localities of Massè, Onigbolo, Avissa, Ita-Itèlè, Issaba, Illèmon, Kounotcho, and Kpoulou of the depression depths varying from 0 to 3 m. The parameters such as the compression index, the liquidity limit, the plasticity index (PI), the plasticity limit (PL) have been determined to identify and characterize the nature of the soils of each site. In their 2016 study on the physico-mechanical characterization of clay soils and the Issaba depression in southeastern Benin, Agbelele et al showed that the soils of Adogon, Kpoulou, Onigbolo, Issaba and Illèmon are very plastic clays of class A-7-5 (according to AASHTO classification) ; and in the other localities, clays of class A-7-6. Silt is also found in the Kpoulou, Issaba and Illèmon areas.

The compression index (Cc), Liquidity limit (LL), and Plasticity index (PI) values in Table 1 below come from our previous studies on the Physico-mechanical characterization of clay soils of the Issaba Depression in southeastern Benin [28].

These data presented in Table 1 were used for the present study to determine the modulus of compression by an empirical model from the parameters of the Atterberg limit in the same area. These data presented in Table 1 were used

Table 1. Data test used for the determination of prediction model parameters

Sites	Deepht (m)	Compression index (Cc)	Liquidity limit (LL)	Plasticity index (PI)	Plasticity limit (PL)
Illemon	0,00-0,40	0,82	70	43	27
	0,40-1,00	0,35	86	57	29
	1,00-2,00	0,35	86	46	40
	2,00-3,00	0,35	91	48	43
Issaba	0,00-0,40	0,34	110	75	35
	0,40-1,00	0,35	92	37	55
	1,00-2,00	0,32	79	49	30
	2,00-3,00	0,34	89	31	58
Onigbolo	0,00-0,40	0,56	75	41	34
	0,40-1,00	0,49	68	39	29
	1,00-2,00	0,59	77	45	32
	2,00-3,00	0,48	70	40	30
Kpoulou	0,00-0,40	0,37	74	39	35
	0,40-1,00	0,35	107	40	67
	1,00-2,00	0,36	95	45	50
	2,00-3,00	0,41	55	31	24
Ita-Itèlè	0,00-0,40	0,28	80	61	19
	0,40-1,00	0,27	91	63,2	28
	1,00 -2,00	0,25	93	56	37
	2,00-3,00	0,27	84	55	29
Massè	0,00-0,40	0,29	88	62	26
	0,40-1,00	0,28	92	65	27
	1,00-2,00	0,26	86	62	24
	2,00-3,00	0,28	95	65	30
Adogon	0,00 -0,40	0,31	46,4	26,3	20
	0,40-1,00	0,29	50	27	23
	1,00-2,00	0,33	45	26,8	18
	2,00-3,00	0,35	50	25	25
Avissa	0,00-0,40	0,28	91	60	31
	0, 40-1, 00	0,28	92,7	62	31
	1,00 -2,00	0,3	89,78	63	27
	2,00-3,00	0,29	92	62	30
Kounotcho	0,00-0,40	0,27	69	46	23
	0,40-1,00	0,31	75	48	27
	1,00-2,00	0,32	79	50	29
	2,00-3,00	0,29	70	44	26

for the present study to determine the modulus of compression by an empirical model from the parameters of the Atterberg limit in the same area. The compression index values were taken from [28] and the liquid limit and plasticity limit values were taken from [28]. The plasticity limit is obtained through the difference between the liquid limit and the plasticity index.

2.3 Analytical Methods

Linear regression analysis was used to establish correlation models between the compression index and the parameters of the Atterberg limit such as: the compression index, the liquidity limit, the plasticity index.

Linear Regression is a statistical tool for the investigation of relationships between dependent variable and independent variables. The dependent variables are used to predict the independent variables; the aim of linear regression is to find the value of intercept and slope of the line that best predicts independent variables from dependent variables. The form of the regression equation is commonly written as [1]:

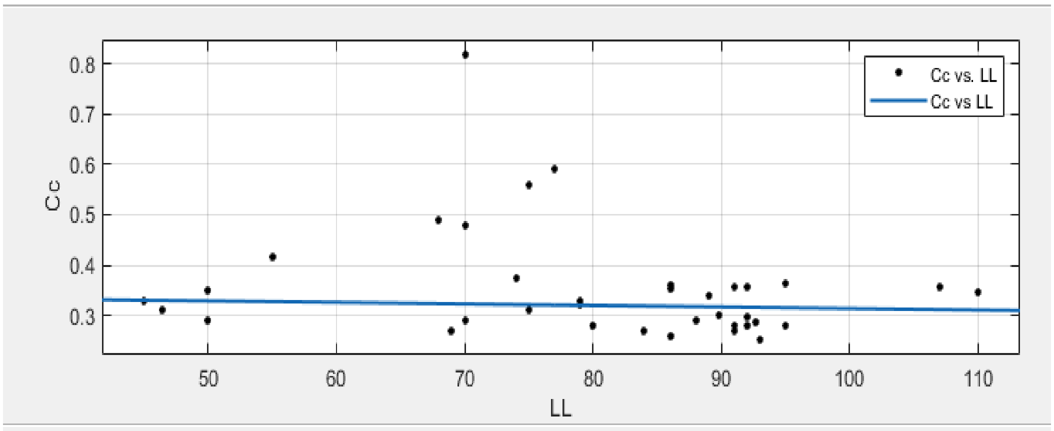
$$y = mx + c$$

where y is the independent variable, x is the dependent variable; m and c are the slope and intercept, respectively. The regression procedure finds estimates of c and m by a minimization process. This is done by minimizing the sum of squares of the vertical distances between the data points and the best-fit line in x-y space [30].

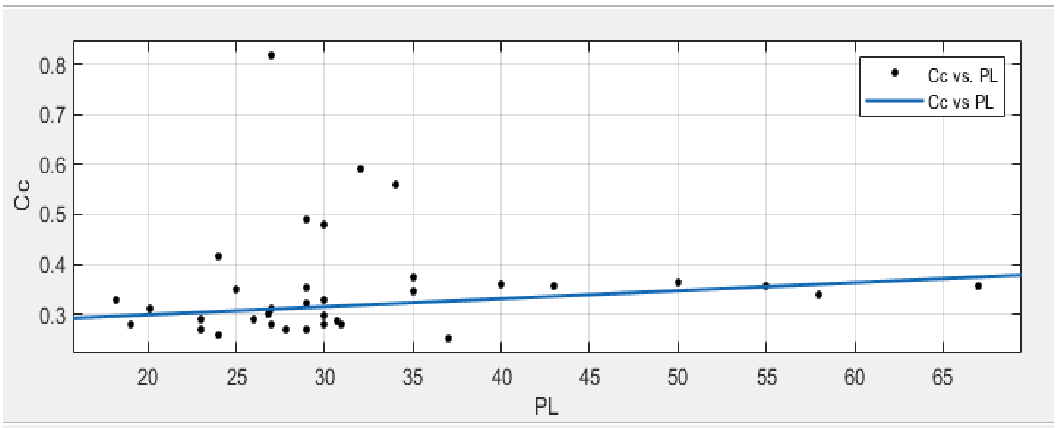
The predictive performance is judged by the coefficient of determination, R^2. For example an R^2 value of 0.5 means that 50 percent of the variation in y is being explained by x variable. R^2 values vary between 0.0 and 1.0. An R^2 value of 0.0 means that the x variable has no predictive advantage (i.e., there is no correlation between x and y). An R^2 value of 1.0 means that x is a perfect predictor of y [30]. The validity of correlations was also assessed on the basis of root mean square error (RMSE). RMSE is the square root of the average squared difference between the values calculated using a correlation and the corresponding observed values determined from laboratory tests. Errors in RMSE are squared before they are averaged; consequently, relatively high weight is given to large errors. This means the RMSE is most useful when large errors are particularly undesirable [5]. The RMSE has been used many researchers to evaluate the performance of empirical equations like Park and Lee [31], Ahadiyan et al. [32], Ozer et al. [33].

To conduct the regression analysis, Matlab R2020a software was used using 2D graph systems for the relationships between Cc and LL, PL, PI. A 3D graph system was then used to find the relationship between the three soil properties. The least squares method was used as well as the degree 1 polynomial model for each of the variables [34-45].

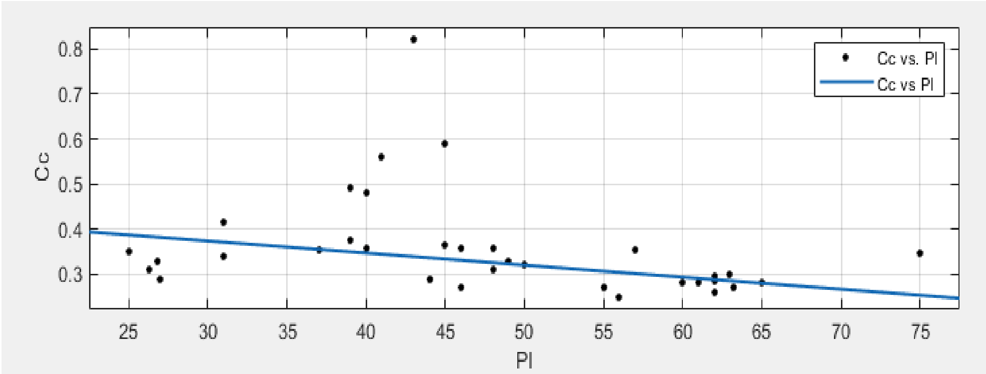
3. RESULTS AND DISCUSSION



(a)



(b)

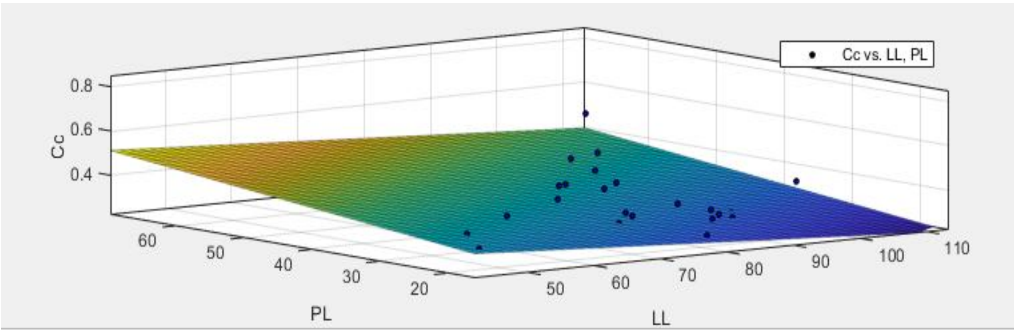


(c)

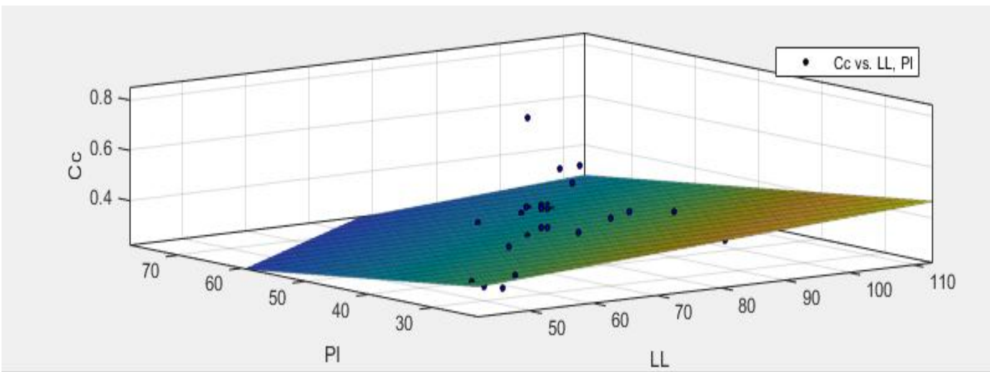
Fig. 1. Trend curves for the linear models of the the compression index versus (a) Liquidity limit, (b) Plasticity limit, (c) Plasticity index

Table 2. Summary of regression analyses

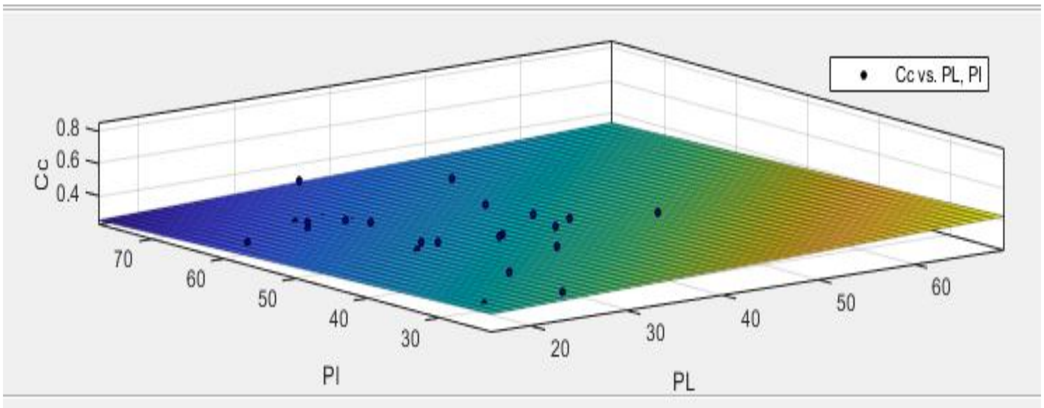
Independent Variable	Empirical Model	R^2	R^2 adjusted	RMSE
Plastic Limit – PL	Cc = -0.0016 PL + 0.2666	0.9006	0.8976	0.0361
Plasticity Index – PI	Cc = -0.0026 PI + 0.4541	0.9103	0.9076	0.0343
Liquid Limit - LL	Cc = -0.0002 LL+0.3432	0.9045	0.9017	0.0354
LL and PL	Cc = 0.3228 – 0.02674 LL – 0.0359 PL	0.8209	0.81	0.0492
PL and PI	Cc = 0.3228 + 0.0179 PL – 0.0219 PI	0.8209	0.81	0.0492
LL and PI	Cc = 0.3228 + 0.0267 LL – 0.0438 PI	0.8209	0.81	0.0492



(d)



(e)



(f)

Fig. 2. 3D trend curves for the polynomial models of degree 1: (d) determination of Cc via LL and PL, (e) determination of Cc via LL and PI, and (f) determination of Cc via PL and PI

In order to establish correlations between Cc, LL, Pl and PI, trend curves for the linear models represented by the graphs of Fig. 1 are drawn from the clouds of points. The graphs indicate that there is a significant level of correlation between the compression index and the other parameters. The points are well distributed around the regression line. Three equations are proposed to predict the compression index (Cc) with the independant variables.

In Fig. 1a, Cc = -0.0002 LL+0.3432. Very good correlation is observed with correlation coefficient of R^2 = 0.9045 and R^2 adjusted equal to 0.9017. The RMSE is minimized until 0.0354. The linear correlation presented in Fig. 1b shows that Cc = -0.0016 PL + 0.2666. It is characterized by a correlation coefficient of R^2 = 0.9006 and R^2 adjusted equal to 0.8976. The RMSE minimum is to 0.0361. Relationship between Cc and PI is illustrated in Fig. 1c. The equation found is Cc = -0.0026 PI + 0.4541 with R^2 equal to 0.9103 and R^2 adjusted is to 0.9076. RMSE is equal to 0.0343.

The graphs of Fig.2 shows 3D trend curves for the polynomial models of degree 1. The graphs also indicate that there is a significant level of correlation between the compression index and the other parameters because the points are well distributed around the regression plane. The empirical model found are notified in Table 2.

For correlation models found, the coefficient of determination R^2 is close to 1 (greater than 0.8) and confirms the existence of a high correlation between the variables. The coefficient equal to 0.8209 for the 3D analysis means that about 82.09% of the variables LL, PL, and PI can be predicted by Cc, and about 90% in 2D analysis. As for the RMSE error, it has been minimized to a value lower than 0.5. We also note that the values of R^2, adjusted R^2, and RMSE are identical for the 3D analyses, as well as the constant value of the relation which is equal to 0.3228.

4. CONCLUSION

The study carried out showed the possibility of reliably predicting the compressive index of clay soils, which can be difficult to determine. The Atterberg limit tests was performed and the relationships between compression index (Cc), Liquidity limit (LL), Plasticity limit (PL), and Plasticity index (PI) were found for plastics clays and silts collected in localities of the Issaba depression in Benin. Correlation equations are obtained by linear regression analysis performed with a 2D and 3D graphs systems in Matlab software. Appropriate equations were acquired to determine the value of Cc as a function of LL, PL and PI, based on the experimental tests performed. 2D graph system allows to obtained relationships between Cc and LL, Pl, and PI with a high value of R^2, respectively 0.9006, 0.9103, 0.9045. These values confirme the good correlation between the variables. With 3D graph systems, it was observed a coefficient of determination R^2 equal to 0.8209. It means that Cc can be predicted almost 82% from LL, PL, and PI. Also, the root mean square error (RMSE) has been minimized to less than 0.05. The high value of R^2 and adjusted R^2 (greater than 0.8), as well as RMSE minimum (less than 0.05) showed the applicability of the proposed model. So, the models developed in this study can therefore be used to accurately predict the compression index of clay and silt in the Issaba depression, from Atterberg limits test. Its can therefore be used to estimate this mechanical parameter during preliminary studies. The present study opens thereby the way for different parameter estimates that can be made based on the value of the compression index. The determination of the compression index from these models can contribute for example to the calculation of settlement of superficial foundations in the study area.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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