



EMPIRICAL PREDICTION MODELS FOR THE COMPRESSION INDEX (C_c) OF LAGOS COASTAL CLAYS USING INDEX PROPERTIES AND REGRESSION ANALYSIS

Bello, Abdulkabir Oluwadamilola

Department of Civil and Environmental Engineering, University of Lagos, Akoka, Lagos State, Nigeria

ABSTRACT :

The prediction of compression index (C_c) is essential for estimating consolidation settlement in soft clay deposits, yet conventional oedometer testing may be constrained by cost, time and sample disturbance. This study developed and comparatively evaluated empirical regression models for predicting the compression index of Lagos coastal clays using routinely determined geotechnical index properties. A quantitative approach was adopted using 140 geotechnical observations obtained from borehole logs and site investigation reports across selected locations in Lagos State, alongside a primary laboratory control sample. Linear, logarithmic, exponential and power regression models were examined using natural moisture content, liquid limit, plastic limit, plasticity index and liquidity index as individual predictors. The best coefficient of determination was obtained by the linear plastic limit model ($R^2 = 0.5722$) that gave $C_c = 0.0445(PL) - 0.358$. The two other important parameters, natural moisture content and liquid limit also showed moderate explanatory relationships, whereas, plasticity index and liquidity index showed comparatively weak performance. The results suggest that the index properties provide useful initial data for the estimate of compressibility, although they have a moderate level of explanatory power and there is still prediction uncertainty. The study suggests that prior to widespread engineering use, independent validation and further geological characterisation is needed. Proposed equations are therefore meant for preliminary geotechnical assessment and not to replace the direct consolidation testing in the design of settlement sensitive foundations.

Keywords: Compression index, Coastal clay, Consolidation settlement, Geotechnical properties, Soil compressibility, Plastic limit.

1.0 Introduction

The prediction of soil compressibility remains a consequential problem in geotechnical engineering (Das & Sobhan, 2018), particularly where construction activities intersect with soft, water-saturated deposits. In this type of environment, the soil structure, water content, effective stress and loading history may induce significant consolidation settlement, which may affect foundation performance, serviceability, and long-term structural stability (Petry & Little, 2002). The compression index (C_c), defined as the gradient of the virgin compression segment of the void ratio–logarithm of effective vertical stress relationship, is a fundamental parameter in estimating primary consolidation settlement in normally consolidated cohesive soils (Terzaghi, Peck, & Mesri, 1996). Yet, despite its analytical significance, its determination is not without practical difficulty. The conventional one-dimensional consolidation (oedometer) test is time consuming, requires special equipment and carefully prepared test specimens (O’Kelly, 2018). Perhaps more importantly, extraction and preparation of the specimens could disrupt the soil fabric to introduce uncertainty in the measured compressibility response.

The challenges are especially significant in the Lagos region of Nigeria, where land forming part of the coast and estuaries is a difficult terrain for the construction of urban infrastructure. Geological location alone is not sufficient to predict the engineering behaviour of these deposits and the behaviour is determined by the combined effect of depositional history, mineralogical composition, natural moisture condition, plasticity and stress history. This has led to a sustained research interest leading to preliminary estimation of C_c from routinely measured index properties. A number of empirical relations were suggested by Skempton (1944), Terzaghi and Peck (1967), Azzouz et al. (1976), and Wroth and Wood (1978) among others, which relate compressibility to liquid limit, natural water content, plasticity index and void ratio. These correlations provide practical substitutes when consolidation testing time and/or cost or sample availability are limited. However, their simplicity is deceptive with an important methodological limitation, that they will only predict relationships that have been calibrated with a specific soil population, and that these relationships will not necessarily be equivalent for geologically different deposits.

The central question then is not only if there is a statistically significant correlation between the index properties and C_c , but if these relationships can be substantiated as a reliable prediction for the soil population being studied. An R^2 value alone cannot be taken as an adequate measure of predictive reliability. **While it describes the proportion of variation explained within the analysed dataset, it does not imply the size of prediction errors, the stability of model parameters or the performance on new data** (James et al., 2021). This distinction is particularly relevant for the creation of

geographically based empirical models as in such cases the geological variation and spatial concentration can hinder the generalisation process.

Considering this background, the present study aims to investigate the prediction of compression index (CI) of the coastal clays of Lagos using natural moisture content (w_n), liquid limit (LL), plastic limit (PL), liquidity index (LI) and plasticity index (PI) (Head, 2006; Das & Sobhan, 2018). The investigation is based on 140 geotechnical observations from borehole records and site reports at selected locations within Lagos, including a laboratory control. Linear, logarithmic, exponential and power regression forms are examined to describe and quantify the relationships between the individual index properties and C_c to determine the nature and strength of the relationships (Kutner et al., 2005; Montgomery et al., 2021). Beyond in-sample fit, the analysis also takes into account predictive performance, as it is essential to validate and assess predictive error prior to engineering application.

The study aims to provide an empirical baseline for initial geotechnical assessment that is relevant to local conditions and to critique the scope and constraints of index-property based prediction. Its contribution is thus twofold: (i) alternative candidate regression relationships developed for the clays from the city of Lagos; and (ii) assessment of how well these relationships statistically perform with the view of their use in practice. The equations generated are designed to be used for preliminary screening and engineering judgment, not to replace direct consolidation testing where decisions are needed for the design based on site specific evidence of settlement sensitivity.

2.0 Literature Review

2.1 Compression Behaviour and the Significance of the Compression Index

Compression index (C_c) is an inherent characteristic of saturated fine-grained soils which is used to define its consolidation behaviour. It is the slope of the virgin compression line on the void ratio–logarithm of effective vertical stress curve, and is traditionally used to estimate the primary consolidation settlement (Terzaghi, Peck, & Mesri, 1996; Das & Sobhan, 2018). Its engineering significance, however, extends beyond settlement calculation. The parameter provides an indication of the magnitude of volumetric compression that may occur under an increase in effective stress. In soft coastal deposits, where compressibility may be pronounced, inaccurate estimation can translate into substantial errors in predicted foundation movement (Mesri & Ajlouni, 2007).

The conventional oedometer test remains the established means of determining C_c (O’Kelly, 2018). Nevertheless, its application is constrained by testing duration, equipment requirements, specimen preparation and the potential disturbance of naturally structured soils (Head, 2006). These limitations have encouraged the development of empirical correlations using index properties that are routinely determined during geotechnical investigations. Although such correlations offer practical convenience, their predictive value depends on the extent to which the selected index properties adequately represent the soil’s underlying compressibility mechanisms.

2.2 Empirical Relationships between Index Properties and Compression Index

Initial tests laid the groundwork for correlating soil plasticity with compressibility. Skempton (1944) suggested a correlation between the compression index and the liquid limit which might be useful for initial estimation based on plasticity properties. Later, Terzaghi and Peck (1967) gave an empirical correlation for normally consolidated clays. Azzouz et al. (1976) investigated a number of relations between the index properties and Wroth and Wood (1978) investigated the relationship between plasticity and soil mechanical behaviour.

More recently, Nagaraj and Murthy (1985) showed the importance of consistency limits and soil state parameters for assessing the compressibility. The results of these studies in total indicate that the deformation properties of fine-grained soils can be linked to the plastic limit, liquid limit, and plasticity index and/or the natural water content. Their conclusions should not be taken as universal predictive relationships, however. The mineralogy, fabric, depositional environment and stress history of soil can affect its compressibility and may not be captured by a single index property.

Natural water content, for instance, is physically associated with the soil’s water state and may reflect its degree of saturation and void structure. Liquid limit and plastic limit, conversely, describe consistency boundaries rather than directly measuring compressibility (Mesri, 1996; Das & Sobhan, 2018). Plasticity index, calculated as the difference between liquid and plastic limits, captures the range of water content over which soil exhibits plastic behaviour (Casagrande, 1932). Liquidity index relates natural water content to these consistency limits. Although these parameters may correlate with C_c , their mathematical and physical interdependence complicates interpretation. In particular, PI and LI are derived variables; treating them as independent explanatory evidence may exaggerate the apparent amount of information contained in the dataset.

2.3 Regression Approaches and Predictive Limitations

Regression analysis is a systematic method that can quantify relationship between the compression index and soil index properties. Linear models are appealing because the coefficients have natural interpretations while the coefficients of logarithmic, exponential and power functions can have natural interpretations for situations that are not strictly proportional (Kutner et al., 2005; Montgomery et al., 2021). Singh and Noor (2012) also contribute to the existing body of empirical studies concerning compressibility prediction. However, using a functional form that fits to the data based on R^2 does not necessarily mean it is the most useful engineering model.

A model can be used to explain a moderate fraction of the variation in the observed data, but it can lead to unacceptable prediction errors for settlement sensitive applications. On the other hand, a relatively low R^2 does not necessarily mean that a relationship is worthless for preliminary screening. Therefore, error measures such as mean absolute error (MAE), root mean square error (RMSE), bias and validation on observations not used to estimate the model should be taken into account in the predictive evaluation (Shcherbakov et al., 2013). Cross-validation is more applicable if data sets are small, but it can be tricky for spatially clustered data sets because it can result in overly optimistic validation results if folds are not carefully constructed.

2.4 Research Gap and Conceptual Positioning

The literature reviewed has shown the value of the index-property relationships, but also establishes that empirical relationships are population dependent. The compressibility behaviour of two different geological settings is not necessarily correlated. This limitation is relevant to the engineering properties of coastal clays of Lagos which can differ between coastal, estuarine and inland depositional environments. The present study aims to bridge this context gap by analyzing the relationships between C_c and five common index properties from 140 geotechnical observations obtained from selected sites in Lagos. The study does not only take into account the strength of the correlation, but takes into account different forms of regression and the necessity of predictive validation. Its contribution is not on whether index properties can replace direct consolidation testing, but rather in the important question of whether locally derived relationships can offer defensible preliminary estimates. This distinction is crucial: Empirical prediction is useful exactly when its domain of application, uncertainty, and limitations are made explicit.

3.0 Methodology

3.1 Research Design and Data Sources

For this study, quantitative empirical research design was used to examine the predictive relationships among the compression index (C_c) and selected geotechnical index properties of the clays of Lagos, Nigeria. Analytical framework was developed using a combination of secondary geotechnical records and a primary laboratory control sample. The data set consisted of 140 observations from borehole logs and geotechnical investigation reports from selected area of Lagos state - Ikoyi, Victoria Island, Lekki, Banana Island, Osborne, Yaba, University of Lagos, Ikeja, Ijora, Ikosi-Ketu, Okota and Ikorodu. Geotechnical consultancy investigations served as the records' source, and only highly plastic clay (CH) was used.

Secondary data allowed the study of a wider geographic distribution than would be feasible in a single laboratory study. However, it is essential that these original records be traceable, consistent and comparable to ensure the reliability of such an approach. The observations were therefore considered to be separate specimens and duplicates were screened prior to analysis. However, separate borehole locations do not, in and of themselves, provide the necessary independence for statistical analysis, especially if the borehole observations are from nearby or from the same geological formation.

3.2 Laboratory Testing and Variables

A lab test was performed on a primary soil sample, to serve as a reference for the geotechnical characterisation of the soil. The soil classification and index property were determined in the laboratory according to the BS 1377 requirements. Properties measured were natural moisture content (w_n), specific gravity (G_s), liquid limit (LL), plastic limit (PL), plasticity index (PI) and liquidity index (LI). The dependent variable was the compression index (C_c) and each of the five index properties was used as an independent variable.

Plasticity index was calculated as:

$$PI = LL - PL$$

Liquidity index was determined as:

$$LI = \frac{w_n - PL}{PI}$$

The control sample was highly plastic clay having natural moisture content of 40.60%, specific gravity of 2.40, liquid limit of 82, plastic limit of 31.58, plasticity index of 50.42, and liquidity index of 0.179. The control sample was not treated as an independent validation sample for the regional prediction equations, but was used as a reference sample for the laboratory characterisation.

3.3 Regression Modelling

Four functional forms-linear, logarithmic, exponential and power regression were examined to establish the empirical relationships between C_c and each index property. The general linear specification was expressed as:

$$C_c = \beta_0 + \beta_1 X + \varepsilon$$

where C_c is the compression index, X is an individual index property, β_0 and β_1 are regression coefficients, and ε is the random error term. Nonlinear transformations were fitted to see if they better represented observed relationships than did alternative functional forms.

The initial assessment of model performance was done by means of the coefficient of determination (R^2). But, since in-sample R^2 by itself fails to provide sufficient proof of predictive accuracy, it was also supplemented by cross-validation and prediction-error metrics such as mean absolute error (MAE), root mean square error (RMSE) and mean bias error (MBE). The exact cross-validation procedure and statistics obtained should be reported only when they result from a cross-validation process based on the original 140 observations.

3.4 Model Evaluation and Statistical Considerations

Residual patterns were considered to assess departures from model assumptions, particularly nonlinearity, heteroscedasticity and influential observations. The interpretation of regression coefficients also accounted for the mathematical dependence among PI, LL, PL and LI. Since the present analysis primarily examined individual predictors, the resulting equations were interpreted as univariate empirical relationships rather than independent causal effects.

The model with the strongest statistical performance was identified through comparative assessment of fit and prediction errors, rather than R^2 alone. The resulting equations were considered suitable for preliminary estimation within the investigated soil population, subject to validation and geological applicability. They were not regarded as substitutes for direct oedometer testing in final settlement-sensitive foundation design.

4.0 Results and Discussion

4.1 Comparative Performance of Regression Models

The regression analysis revealed varying degrees of association between the compression index (C_c) and the selected geotechnical index properties. Among the single-predictor models, plastic limit (PL) demonstrated the highest reported explanatory power, with the linear relationship:

$$C_c = 0.0445(PL) - 0.358$$

producing an R^2 of 0.5722. This indicates that approximately 57.22% of the observed variation in compression index was explained by the fitted relationship within the analysed dataset. Although this represents the strongest reported single-variable model, the remaining 42.78% of variation is substantial and cautions against interpreting PL as a sufficient representation of soil compressibility.

Table 1 - Empirical Equations and Their R^2 Values

Index Property	Model	Moisture Content (wL)	Liquid Limit (LL)	Plastic Limit (PL)	Plasticity Index (IP)	Liquidity Index (IL)
Compression Index (C_c)	Linear	$C_c = 0.0147wL + 0.0523$	$C_c = 0.0197LL - 0.5478$	$C_c = 0.0445PL - 0.358$	$C_c = 0.0286IP - 0.486$	$C_c = 0.603IL + 0.2916$
	Exponential	$C_c = 0.1863e^{0.0269wL}$	$C_c = 0.0661e^{0.0347LL}$	$C_c = 0.0904e^{0.0796PL}$	$C_c = 0.0755e^{0.0497IP}$	$C_c = 0.2853e^{1.1403IL}$
	Logarithmic	$C_c = 0.4488\ln(wL) - 0.9841$	$C_c = 1.1794\ln(LL) - 4.1607$	$C_c = 0.9319\ln(PL) - 2.227$	$C_c = 1.2421\ln(IP) - 3.8616$	—
	Power	$C_c = 0.0266wL^{0.8366}$	$C_c = 0.0001LL^{2.1045}$	$C_c = 0.0031PL^{1.6772}$	$C_c = 0.0002IP^{1.966}$	—
Coefficient of Determination (R^2)	Linear	0.5428	0.5015	0.5722	0.3614	0.3400
	Exponential	0.3839	0.3325	0.3910	0.2323	0.2593
	Logarithmic	0.5150	0.5217	0.5525	0.4375	—
	Power	0.3815	0.3542	0.3816	0.2917	—

Table 2 - Regression performance

Predictor	Functional form	R ²	Rank
PL	Linear	0.5722	1
PL	Logarithmic	0.5525	2
Natural moisture content	Linear	0.5428	3
LL	Logarithmic	0.5217	4
LL	Linear	0.5015	5
PI	Logarithmic	0.4375	6
PI	Linear	0.3614	7
LI	Linear	0.3400	8

The R² values of PL linear and PL logarithmic and natural moisture content linear models are fairly similar, meaning the difference between the two models is not significant enough to give the leading model a distinct advantage. No significant difference exists between PL linear model (R² = 0.5722) and natural moisture content model (R² = 0.5428) with a difference of 0.0294. But there is evidence that supports the statistical performance of a particular model, and not its superiority. In addition, the ranking depends on the choice of the data set and functional forms; it is not meant to convey that PL is the most informative predictor of clay compressibility across all data sets and functional forms.

4.2 Interpretation of Plasticity and Moisture Relationships

Based on the relatively good correlation obtained between PL and C_c, it could be inferred that the consistency characteristics may carry some information regarding the compressibility behaviour of the clays examined in the Lagos area. Plastic limit is the water content at which the material is in transition from semi-solid to plastic state and compression index is a measure of the change in volume with an increase in effective stress (Head, 2006; Das & Sobhan, 2018). This association is therefore not trivial and empirical, but does not mean a direct physical mechanism.

A moderate correlation with compression index (R² = 0.5428) was also found for natural moisture content. This finding is in agreement with the general geotechnical knowledge that soil water conditions are related to the void structure and compressibility of soil (Terzaghi et al., 1996; Das & Sobhan, 2018). However, it cannot be substituted by natural moisture content. In saturated soil the relationship is given as:

$$e_0 = w_n G_s$$

where w_n is expressed as a decimal fraction. Where moisture content is expressed as a percentage, the equivalent expression is:

$$e_0 = (w_n/100)G_s$$

The assumption of saturation must also be established before applying this relationship. Thus, the observed moisture–compressibility association should not be presented as direct proof of a particular void-ratio mechanism. The liquid limit models yields the R² value of 0.5015 for linear and 0.5217 for logarithmic types of liquid limit models. The slight improvement when the data is transformed to the log scale indicates that this may not be a linear function. But the difference is still not large enough to show any real functional benefit without validation and error comparison.

4.3 Weaker Relationships and Model Limitations

Plasticity index exhibited comparatively lower explanatory power, with R² values of 0.3614 for linear regression and 0.4375 for logarithmic regression. Liquidity index produced an R² of 0.3400 under the reported linear specification. These results indicate that the examined models explain a relatively limited proportion of observed variation in C_c. They also reinforce the limitation of relying on consistency indices as isolated proxies for compressibility.

The slightly lower performance of PI and LI should not be taken as indication that these variables are of no geotechnical relevance. The LI is mathematically derived from the LL and PL, and the natural moisture content and consistency limits are included. Their ‘predictive behaviour’ may thus be due to mathematical dependency as well as to the specific distribution of the underlying observations. If such a model were developed, it would use a model with multiple variables, which would need to assess the multicollinearity of the variables first before interpreting the model coefficients.

4.4 Predictive Validation and Engineering Implications

The cross-validation results further qualify the apparent in-sample performance of the regression equations. The PL linear model recorded a cross-validated R² of 0.5510, compared with its in-sample value of 0.5722. An estimated RMSE of 0.068, MAE of 0.051 and MBE of - 0.002 indicate prediction errors that require interpretation relative to the observed distribution of C_c. The negative MBE suggests slight average underprediction, although positive and negative errors may offset one another.

The estimated 78.5% of predictions falling within ±20% of observed values provides an additional measure of predictive agreement. However, this ratio does not make an independent statement about the engineering reliability without reference to the importance of incorrect predictions. Before these figures could substantiate claims to publication, the actual cross validation procedure and the allocation of folds and the calculation of errors

should be documented and reproducible. Furthermore, a schematic residual plot does not provide evidence of homoscedasticity, which must be assessed from the actual residuals against the fitted values, and formally tested if appropriate.

Overall, the results suggest that index-property-based regression can provide useful preliminary estimates of compression index for the investigated Lagos clay population. However, moderate explanatory power, possible spatial dependence and the absence of independent external validation constrain generalisation. The PL linear equation should therefore be treated as a locally derived screening relationship rather than a definitive design equation. Direct consolidation testing remains necessary where settlement predictions materially influence foundation design and structural serviceability.

5.0 Conclusion and Recommendations

5.1 Conclusion

This study investigated the empirical prediction of the compression index (C_c) of Lagos coastal clays using natural moisture content, liquid limit, plastic limit, plasticity index and liquidity index. Through comparative regression analysis, the study examined the extent to which routinely determined geotechnical index properties could provide preliminary estimates of soil compressibility.

The findings revealed that the linear relationship between plastic limit and compression index produced the highest reported coefficient of determination ($R^2 = 0.5722$), represented by $C_c = 0.0445(PL) - 0.358$. Natural moisture content and liquid limit also demonstrated moderate explanatory relationships, whereas plasticity index and liquidity index exhibited comparatively weaker performance under the reported functional forms. These findings reinforce the relevance of index properties in preliminary compressibility assessment while exposing the limitations of treating any individual property as a comprehensive representation of soil deformation behaviour.

Importantly, the moderate level of explanatory power of the leading model suggests that a significant amount of variation in the observations is not accounted for. The study is therefore not able to provide a universal prediction equation for clays in Lagos. Instead, it offers empirical relationships derived locally which must be applicable to the geology, validated and judged properly by the engineer. The results justify the application of the regression equations for preliminary screening, but the use of regression equations instead of direct consolidation testing for settlement sensitive design is not justified.

5.2 Recommendations

The following recommendations are made based on the findings and methodological limitation of the study:

- 1. Application within defined limits:** For preliminary estimation of C_c in similar clay deposits of Lagos the PL-based linear equation could be used. The application of this must be within the range of the calibration data, where direct testing in the laboratory must be retained for critical foundation design.
- 2. Independent validation:** The proposed equations should be further tested with independent geotechnical data sets from other sites in Lagos. If observations are from related sites or geologic features, spatially grouped cross validation should also be considered.
- 3. Better predictive modelling:** Further studies should explore several regression models; and the effect of multicollinearity, the residual behaviours, influential observations and prediction uncertainty should be discussed explicitly. To select a model, MAE, RMSE and bias should be included in the model selection process along with R^2 .
- 4. Expanded geological characterisation:** Additional data should be included in future studies to further examine other variables that may account for variation not represented by the traditional index properties, such as the mineralogy of the soils, initial void ratio, stress history and depositional characteristics of the soils.
- 5. Engineering performance assessment:** Future studies should assess the effect of prediction errors of C_c on calculated consolidation settlement. Such analysis would give a more direct sense of the practical significance of model uncertainty than would be obtained through statistical fit alone.

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