Journal of Civil Engineering, Science and Technology

Volume 17, Issue 1, April 2026, 61-70

STATISTICAL EVALUATION OF SOILS INDEX PROPERTIES FROM SELECTED STATES OF SOUTHWESTERN NIGERIA

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Date received: 18/03/2025 Date accepted: 13/11/2025
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DOI: 10.33736/9309.2026

Abstract — Evaluation of index properties of soil samples is one of the essential assessments proposed for construction materials, as it sheds broad light on the class or group of soils. This study evaluates the natural moisture content (NMC), specific gravity (G_s), grain size analysis, and Atterberg limits tests of soils in Ekiti and Osun, southwestern states of Nigeria. Soil samples were collected randomly from sixty (60) and ninety (90) locations in disturbed states from Osun and Ekiti states, respectively. The laboratory tests conducted in accordance with the British Standard show that soil samples within the states have a mean NMC, G_s, gravel content, sand, fines content, liquid limit (LL), plastic limit (PL), plasticity index (PI), and linear shrinkage (LS) of 11.52%, 2.31, 22.38%, 36.76%, 40.85%, 41.67%, 24.97%, 16.70%, and 7.32%, respectively. Models were generated using multiple linear regression for the LL and PL, predicted using the specific gravity, fines, and gravel contents of the soils. The metric evaluation of the models gave coefficients of determination of 0.4338 and 0.3165, mean absolute errors of 5.5577 and 4.1587, and root mean square errors of 7.0800 and 5.1762 for LL and PL, respectively. The p-values of the F-test are 5.95E-18 and 4.77E-12 for LL and PL, respectively, which are far less than 0.05, showing that the models are statistically significant. An R^2 score below 0.5 diminishes the engineering relevance of the model.

***Keywords*:** statistical, index property, Southwestern Nigeria, multiple regression, standard deviation

1.0 INTRODUCTION

Any uncemented or weakly cemented accumulation of mineral grains and decayed organic matter (solid particles) with liquid and gas in the empty spaces between the solid particles formed by the actions of breaking of rocks into smaller pieces, which are widely used as construction and foundation materials, is termed 'soil' [1-4]. Jenny [5] defined soils as the unconsolidated layers of particles covering the earth's surface with different sizes and shapes forming a structure that undergoes deformation when subjected to stresses. It is also defined as a product of the environment whose formation depends on the climate organisms, parent rock, relief and time.

Soils are generally grouped as laterite, non-laterite, and lateritic according to the ratio of their silica (SiO_2) – sesquioxides (Fe_2O_3, Al_2O_3). Soil is said to be laterite, non-lateritic and lateritic when this ratio is found to be lesser than 1.33, greater than 2.0 and within 1.33 and 2.0, respectively [6]. Laterite is a weathered natural material developed as a result of the concentration of hydrated oxides of iron and aluminium, which, after further oxidization become an insoluble product of fine particles [7]. Understanding the inbuilt characteristics of soil is essential, as it plays a major role in its load-retaining capacity. Assessment of index properties of the foundation soil is, therefore, necessary, as it reveals some hidden information that plays a cogent part in designing any structures [8]. The index properties of soil include specific gravity, grain size analysis, and consistency limits. Specific gravity, which is defined as the ratio of the unit weight of a given substance to the unit weight of water, is an important index property of soils that is closely linked with their mineralogy or chemical composition, which also reflects the history of weathering. The specific gravity of soil, which is best determined in the laboratory, is useful in the determination of other properties of soil, such as consolidation, compaction characteristics, permeability, and void ratio. Grain size analysis is used to classify soil samples based on the arrangement of grains present in the soil. Some geotechnical properties, such as compaction characteristics, coefficient of permeability and degree of settlement of soils are hinged on the soil's particle distribution. Plasticity, on the other hand, is an important characteristic of fine-grained soils that describes the ability of a soil to undergo unrecoverable deformation without cracking or crumbling as a function of both the content of water present in the soil and its consistency. It is also one of the geotechnical parameters that determine the engineering properties of soil [2].

This research, therefore, focuses on the analysis of soil's index properties in Osun and Ekiti states and their statistical interrelationship.

2.0 MATERIALS AND METHODS

The soil samples used for this study were collected as disturbed soil from different locations within Osun and Ekiti states. Soil samples were collected randomly from sixty (60) and ninety (90) locations each at different towns and local government areas that made up Osun and Ekiti states, respectively. The soil samples from the areas, similar to those in six other states of southwestern Nigeria characterised by a basement complex, are underlain by crystalline rocks of igneous and metamorphic origin, including migmatite, quartzite, gneiss, schist and charnockite [9-10]. The position of each location on the earth was taken with the aid of GPS and found to be on latitude ranges from 7.055331°N to 8.055324°N and 7.429167°N to 8.006673°N with longitude ranges from 4.915410°E to 4.918875°E and 4.907849°E to 5.750278°E and a mean altitude of 317 m and 486 m for Osun and Ekiti, respectively. The distribution of the locations is shown in Figure 1, while the pictorial view of field and laboratory activities is shown in Figure 2. The soil samples collected were subjected to laboratory tests, such as natural moisture content, specific gravity, particle size distribution, and Atterberg limits. The tests were conducted in accordance with clauses 3, 4, 5, 6, 8, and 9 of the British Standards (BS 1377-2:1990) for soil testing [11].

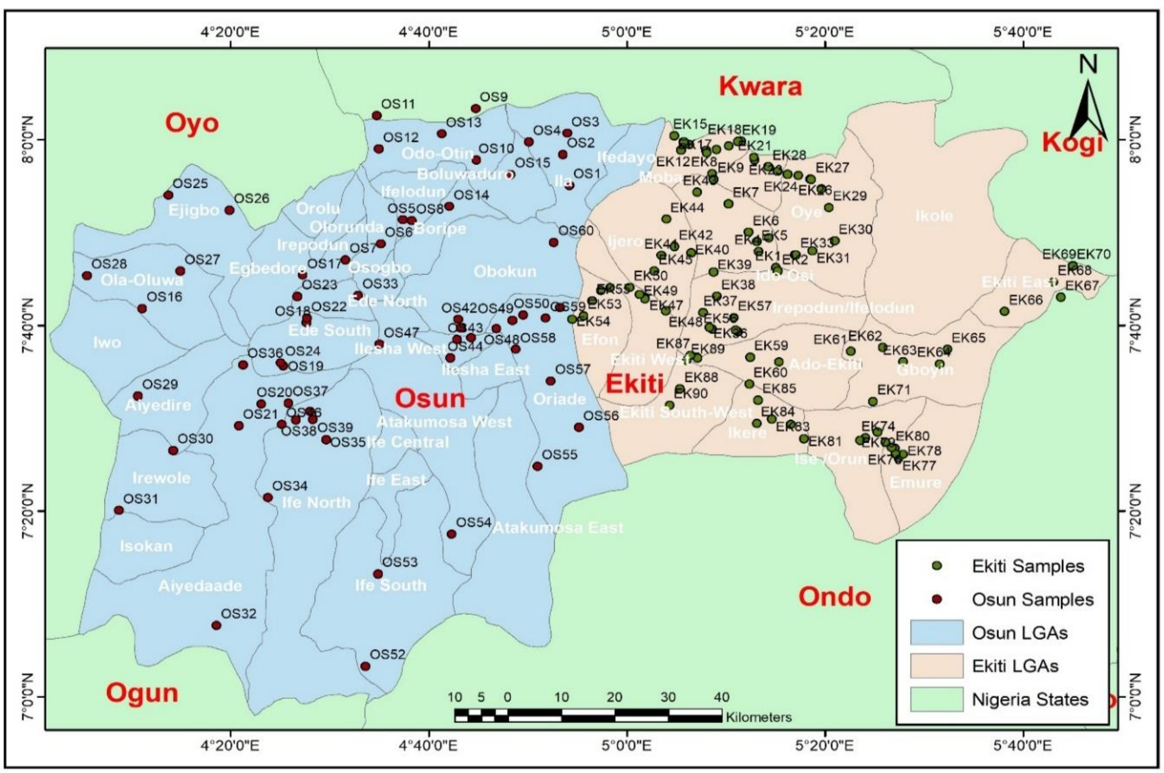

Figure 1 Map showing sampling locations

Figure 2 Pictorial chart of the field and the laboratory activities

2.1. Natural Moisture Content

Specimens of soil samples collected were subjected to laboratory tests for the determination of natural moisture content. The samples' weight in their wet state was determined and recorded before drying in an oven at the temperature of 105°C for 18 hours, after which the dry weight was measured and recorded. The moisture content, which is the ratio of the mass of water to the mass of dry soil in percentage, was determined from the laboratory test conducted using Equation 1.

$$\text{Moisture Content} = \frac{M_2 - M_3}{M_3 - M_1} \times 100\% \quad (1)$$

Where M_1 is the mass of the empty can, M_2 is the mass of the can and wet soil, and M_3 is the mass of the can and dry soil.

2.2. Specific Gravity

Specific gravity measures the ratio of the mass of a substance to the mass of an equal volume of water. The value was determined in the laboratory using density bottles of 50 cm³ filled with dry soil specimens to one-third of their volume. The mass of the soil specimen for this predetermined volume was determined and recorded, while the mass of an equal volume of potable water was also determined mathematically. The calculation used the mathematical formula shown in Equation 2 to determine the ratio of the mass of the soil specimen tested to the mass of an equal volume of water at the standard temperature.

$$\text{Specific gravity} = \frac{M_2 - M_1}{(M_4 - M_1) - (M_3 - M_2)} \quad (2)$$

Where M_1 is the mass of the empty bottle, M_2 is the mass of the bottle and dry soil specimen, M_3 is the mass of the bottle, specimen and water, and M_4 is the mass of the bottle and water.

2.3. Grain Size Analysis

A 500g dry soil sample was soaked for 24 hours for effortless removal of silt and clay glued to soil particles. The soaked samples, in accordance with AASHTO T 11-24 [12], were washed with a 0.075 mm sieve. The residue, tested in accordance with AASHTO T 27-24 [13], was dried and then poured into a set of sieves that were agitated on a mechanical sieve shaker for 10 minutes. The weight retained on each of the sieves was noted and used to determine the percentage weight retained, which was in turn used to determine the percentage passing each sieve. The curve of the percentage of soil passing through each sieve was plotted against the particle sizes on a semi-logarithmic graph.

2.4. Atterberg Limits

Atterberg limits, which involve the determination of plastic, liquid and shrinkage limits of soil, are very useful in judging the behaviour of fine-grained soil or the fine-grained component of coarse-grained soils. The tests were carried out on soil samples sieved through sieve no. 40 in accordance with BS 1377 [11] and American Standards (AASHTO T89-22 and AASHTO T90-22) [14-15]. The PL was achieved by determining the moisture content of a moist sample rolled on a glass plate to form a threadlike shape measuring about 3 mm in diameter without crumble. At varying moisture contents, the cone with an apex angle of 30° and length of 35 mm attached to the cone penetrometer was allowed to penetrate the soil sample at its weight for the liquid limit test. This procedure was carried out at four different trials with increasing moisture content. The graph of moisture content against cone penetration was plotted, and the liquid limit (LL) was determined as the moisture content in percentage corresponding to 20 mm cone penetration. The linear shrinkage of the soils was determined using Equation 3.

$$L_s = \frac{L_o - L_f}{L_o} \times 100\% \tag{3}$$

Where L_s is the linear shrinkage, L_o is the initial length of the specimen and L_f the length of the oven-dry specimen.

3.0 RESULTS AND DISCUSSION

3.1. Natural Moisture Content

The soil samples within the states show a moderate value of natural moisture contents with mean values of 12.9% and 10.6% and standard deviations of 3.94 and 6.01 for Osun and Ekiti states, respectively. As shown in Table 1, the standard error of 0.44 indicated that the mean NMC value for the states, which stands at 11.52% is a dependable estimate of the NMC of soils within the states. The positive skewness and kurtosis of 0.39 and 0.22, respectively, suggest that the distribution is slightly right-skewed, which implies a relatively symmetrical distribution with a few higher NMC.

Table 1 Summary statistics on soil properties

Soil Properties	Mean	Std. Error	Std. Deviation	Variance	Kurtosis	Skewness	Range	Min.	Max.
NMC	11.52	0.44	5.39	29.01	0.22	0.39	27.04	1.82	28.86
GS	2.31	0.01	0.13	0.02	-0.25	-0.37	0.71	1.91	2.62
Gravel	22.38	1.14	13.95	194.46	1.22	1.06	72.74	0.26	73.00
Sand	36.76	0.97	11.84	140.19	0.76	-0.11	69.71	6.99	76.70
Fines	40.85	1.21	14.80	218.93	-0.15	0.11	76.05	7.80	83.85
LL	41.67	0.77	9.47	89.63	-0.57	-0.07	42.20	20.90	63.10
PL	24.97	0.51	6.28	39.46	-0.05	0.19	32.49	11.16	43.65
PI	16.70	0.48	5.89	34.67	-0.11	0.30	31.63	2.56	34.19
LS	7.32	0.23	2.88	8.27	0.08	-0.18	15.29	0.71	16.00

3.2. Specifc Gravity

The specific gravity value of soils within the states ranges from 1.91 to 2.62, with an average mean value of 2.31. The range of soil's specific gravity within the states indicates the presence of minerals such as halloysite and kaolinite [3]. The lower values of standard error and standard deviation, as shown in Table 1, indicate a minimal variability in the specific gravity measures across the states; this conclusion is confirmed by the box plot for specific gravity with no outlier, as shown in Figure 3. Consistency was noted in the specific gravity values of soils in both states, with a mean value of 2.34 in Ekiti, which makes the G_s of soils in Ekiti slightly higher than that of Osun state, with a mean value of

2.27. The range of specific gravity of soils within the region agrees with the findings of some past research within the region [16-21].

3.3. Grain Size Analysis

The soil was grouped into gravel, sand, and fine contents, as classified by the American Association of State Highway Officials. The mean gravel, sand and fine contents within the states stand at 22.38%, 36.76% and 40.85%, respectively. The summary statistics of soil's grain sizes within the states indicate a notable difference in the grain sizes in Osun and Ekiti. These summary statistics reveal notable differences in the fines and gravel content between the soil samples from Ekiti and Osun. While Ekiti has a mean fine content of 39.94%, Osun's soils have a higher mean fine content of 42.22%. However, the variability in fines content is greater in Ekiti, as indicated by a higher standard deviation (17.61) compared to Osun (9.06). These values are consistent with the findings of Alo & Oni, Oyelami & Alimi and Adekeye *et al*. [10, 22-23]. In contrast, Ekiti's soils exhibit a higher mean gravel content (25.65%) than Osun's (17.48%), with a greater variability in gravel content in Ekiti (16.19) compared to Osun (7.42).

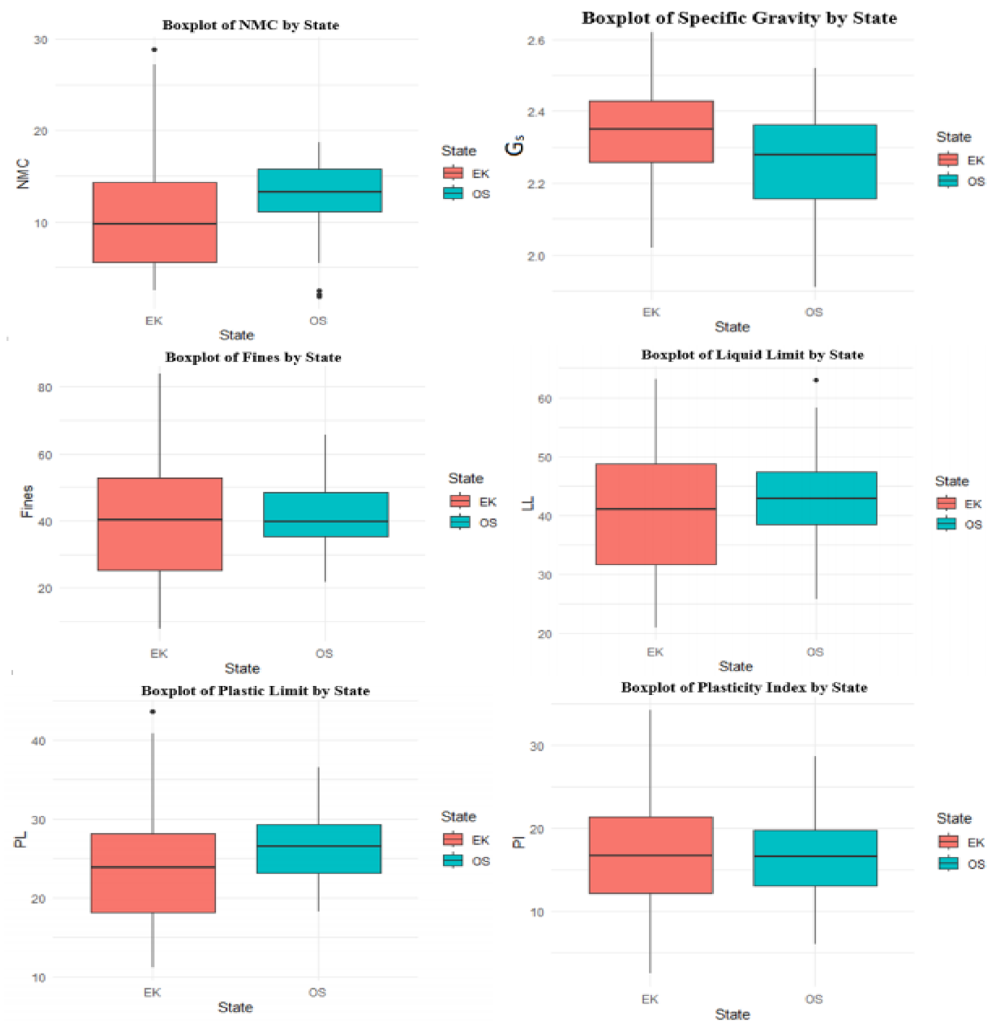

Figure 3 Boxplot showing the distribution of soils' index properties by state

3.4. Atterberg Limits

The liquid limit (LL), which measures the water content at which soil changes from a plastic to liquid state, is higher on average in Osun (43.10%) compared to Ekiti (40.72%). Osun's LL also shows less variability (standard deviation of 7.62) compared to Ekiti (10.45). The plasticity index (PI) is almost identical in both states, representing the range of moisture content where soil exhibits plastic properties, with a mean of 16.71% in Ekiti and 16.70% in Osun. However, the variability is slightly higher in Ekiti (standard deviation of 6.33) compared to Osun (5.21). The plastic limit (PL), which is the moisture content at which soil begins to exhibit plastic behaviour, is higher on average in Osun (26.40%) than in Ekiti (24.01%). The standard deviation for PL is lower in Osun (4.29) than in Ekiti (7.18), indicating more consistent PL values in Osun. Figure 3 presents the boxplots that show the distribution of the soil's index properties by state.

3.4. Model

Models were generated to predict the liquid and plastic limits of soil in the states using multiple linear regression. Values of the specific gravity, percentage fines and percentage gravel were used as independent variables, and the relationships are as shown in Equations 4 and 5 with 0.4338 and 0.3165 coefficients of determination for LL and PL, respectively, which shows that the model only explains 43% and 32% of the variability in LL and PL. The model with an R^2 value below 0.5 indicates that the combination of fines content, gravel and specific gravity of soil within the state does not provide an appropriate relationship for forecasting the liquid limit (LL) and plastic limit (PL) values of soils in the states. The summary of the soil parameters used and the regression statistics are as shown in Tables 2 and 3, respectively.

$$LL = 51.57675 + 0.45095\%Fines + 0.14053\%Gravel - 13.6044G_s \qquad R^2 = 0.4338 \tag{4}$$

$$PL = 33.12865 + 0.26257\%Fines + 0.11149\%Gravel - 9.24224G_s \qquad R^2 = 0.3165 \tag{5}$$

Table 2 Summary of soil parameters used for modelling

		Coefficients	**Standard Error**	**t Stat**	**P-value**	**Lower 95%**	**Upper 95%**
Liquid Limit (%)	Intercept	51.57674975	11.547419	4.4665175	1.582E-05	28.755058	74.398441
	GS	-13.60440028	4.8014247	-2.8334091	0.0052575	-23.093675	-4.1151255
	% Gravel	0.140527472	0.0574616	2.4455892	0.0156509	0.0269635	0.2540915
	% Fines	0.450953447	0.0534626	8.4349385	2.951E-14	0.3452929	0.556614
Plastic Limit (%)	Intercept	33.12864685	8.4185558	3.9351936	0.0001282	16.490671	49.766623
	GS	-9.242235131	3.5004412	-2.6403058	0.0091839	-16.160317	-2.3241534
	% Gravel	0.111484526	0.0418919	2.661241	0.0086571	0.0286916	0.1942775
	% Fines	0.26256778	0.0389765	6.7365723	3.48E-10	0.1855368	0.3395987

The residual plot for the predicted LL, as shown in Figure 4, shows that the predicted values are randomly scattered, with a few outliers observed. The residual plot of the predicted plastic limit shown in Figure 5 presents residuals that are randomly distributed around zero. The plot shows that there is no indication of heteroscedasticity in the data. The sequence plot comparing the actual liquid limits and plastic limits with their predicted values is shown in Figures 6 and 7. The plots show that the predicted values of LL and PL closely follow the pattern of their actual values, with few instances where the predicted values deviated from their actual values. The divergence is warranted due to the potential unsuitability of linear regression for the sample population and its heterogeneity, as seen by the low R^2 value.

Table 3 Regression statistics

	Liquid Limit	Plastic Limit
Multiple R	0.658649211	0.562594315
R Square	0.433818783	0.316512363
Adjusted R Square	0.422184922	0.302468097
Standard Error	7.196581708	5.246611718
Observations	150.00	150.00

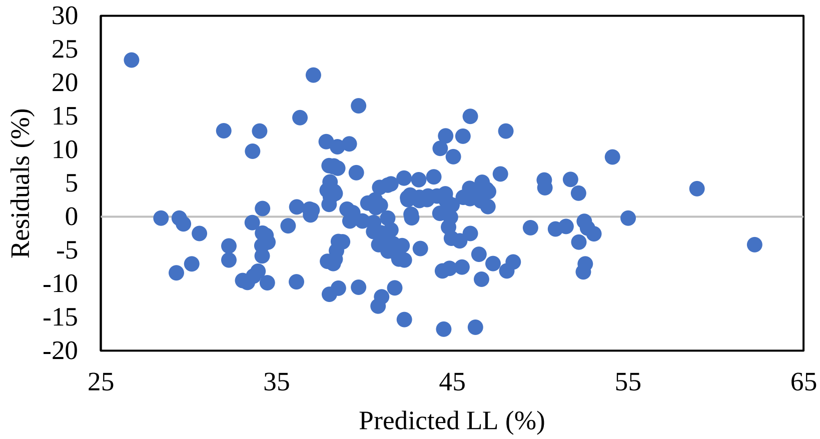

Figure 4 Residual plot for predicted values of liquid limit

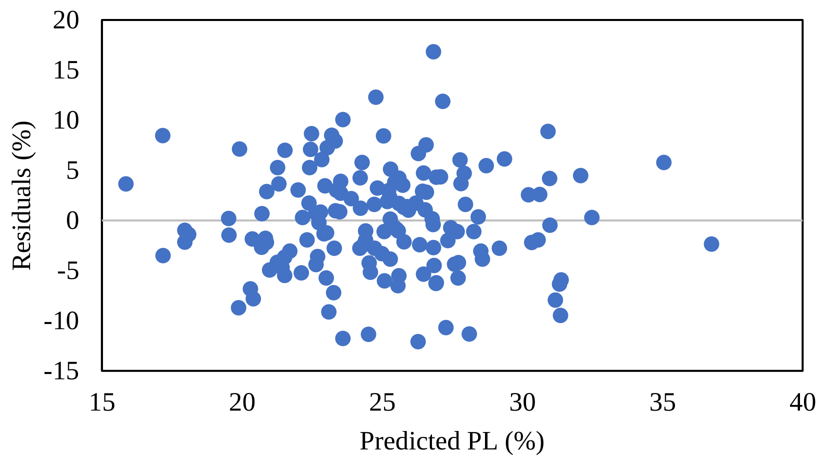

Figure 5 Residual plot for predicted values of plastic limit

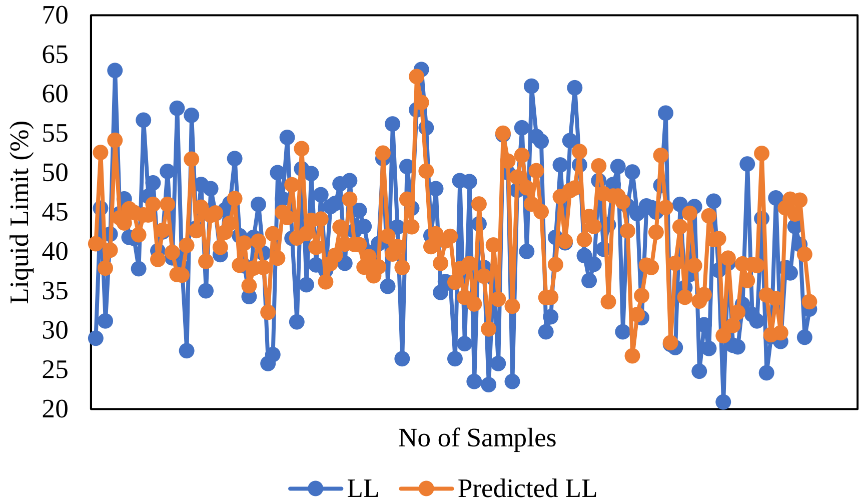

Figure 6 Sequence plot of actual and predicted liquid limit

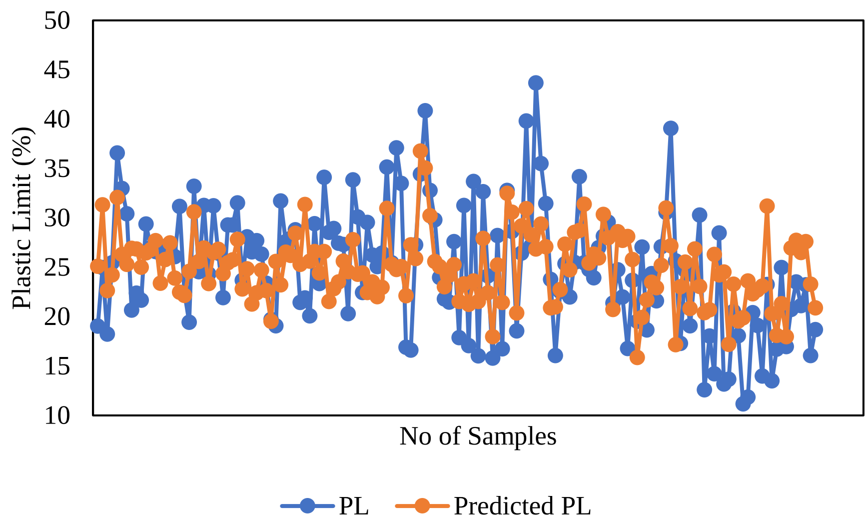

Figure 7 Sequence plot of actual and predicted plastic limit

4.0 CONCLUSIONS

Soil samples collected from one hundred and fifty (150) locations within the states of Osun and Ekiti were tested in the laboratory to ascertain their index properties. The samples were tested in accordance with the British Standards [11] and American Standards [12-15]. They were found in the class ranging from A-2- to A-7-6 soils as classified with the AASHTO M145 system [24]. Models were generated for the prediction of liquid limits and plastic limits of soils within the region from some other known indexes. The research shows that the soil samples within the region have a mean NMC, G_s, gravel content, sand, fines content, liquid limit (LL), plastic limit (PL), plasticity index (PI) and linear shrinkage (LS) of 11.52%, 2.31, 22.38%, 36.76%, 40.85%, 41.67%, 24.97%, 16.70% and 7.32%, respectively. The p-value of the models, determined to be below the threshold of 0.05, indicates that at least one of the variables (% (fines, % gravel, and specific gravity) has a statistically significant association in predicting the liquid limit (LL) and plastic limit (PL) of soil samples. Table 2 demonstrates that the low p-value of percentage fines in the model indicates a significant impact of fine content on the liquid and plastic limits of soils; however, the poor R^2 undermines the engineering significance of the model. It is thus proposed that alternative index property parameters of soils, utilising models distinct from linear regression, may yield a superior model.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgement

The authors wish to acknowledge the entire staff of the soil mechanics laboratory, the Federal Polytechnic, Ado Ekiti, for supporting this work.

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