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Comparative Consolidation Behaviour and Statistical Characterization of Settlement Variability of Soft Soils from Three Selected Sites in Lagos, Nigeria

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Abstract

Accurate prediction of consolidation settlement is fundamental to the serviceability design of foundations on soft cohesive soils. Although numerous studies have reported consolidation characteristics of soft soils, most investigations have focused on deterministic evaluation of individual consolidation parameters, with limited attention to statistical characterization of settlement variability from laboratory measurements. This study presents a comparative investigation of consolidation behaviour and settlement variability of soft cohesive soils obtained from Palm Grove Estate, GRA Ikeja, and Shonibare Estate in Lagos, Nigeria. One-dimensional consolidation tests were conducted in accordance with ASTM D2435/D2435M using undisturbed cohesive soil samples. The coefficient of consolidation (Cv), coefficient of volume compressibility (mv), void ratio (e), permeability (k), and primary consolidation settlement were determined under vertical loading from 50–100 to 400–800 kN/m². Settlement variability was characterized using the arithmetic mean, standard deviation, and coefficient of variation (COV) from repeated laboratory measurements. Results showed that mv decreased by approximately 60–63%, while Cv reduced by 32–41% with increasing effective stress. Permeability decreased by approximately 70–75%, with reductions in void ratio, confirming continuous densification of the soil skeleton during consolidation. Despite these reductions, primary consolidation settlement increased systematically with applied loading, attaining maximum average values of 84 mm, 74 mm, 136 mm, and 61 mm for Palm Grove Estate, GRA Ikeja (1.5 m), GRA Ikeja (3.0 m), and Shonibare Estate, respectively. The calculated COV ranged from 7.11% to 19.67%, indicating low to moderate variability and good repeatability of the laboratory measurements. The study demonstrates that settlement behaviour is governed by soil compressibility, effective stress increment, and the thickness adopted for settlement analysis rather than compressibility alone. Integrating deterministic consolidation analysis with statistical characterization of settlement variability provides clearer interpretation of laboratory settlement behaviour and offers a practical framework for improving confidence in serviceability-based foundation design for soft cohesive soils in urbanizing environments.

Keywords: *Consolidation behaviour, Soft cohesive soils, Primary consolidation settlement, Coefficient of consolidation, Coefficient of volume compressibility, Oedometer test.*

1.0 Introduction

Soft cohesive soils present one of the most persistent challenges in geotechnical engineering because of their low shear strength, high natural water content, high compressibility, and pronounced time-dependent deformation characteristics (Liu et al., 2024); (Amadi, A. A., & Eberemu, 2013); (Uzer, 2024). These soils are common in coastal and deltaic environments, where rapid urbanization and expanding infrastructure development have increased the demand for reliable geotechnical characterization of foundation soils worldwide (Bolarinwa et al., 2017); (Yunusa, G. H., Kida, S. A., Suleiman, A., & Idris, 2024). As suitable construction land becomes increasingly limited, engineers are frequently required to build on marginal ground conditions previously considered unsuitable for conventional shallow foundations (Adunoye, 2021); (Tsige, D., Korita, M., & Beyene, 2022). Although advances in foundation engineering have significantly improved structural safety, excessive consolidation settlement remains a critical serviceability issue that can adversely affect the long-term performance of engineering structures if not properly evaluated during design (Olek, 2022);(Phonchamni et al., 2025; Yin, J. H., Fang, Z., & Cheng, 2020).

Unlike bearing capacity failure, which occurs immediately after loading, consolidation settlement develops gradually as excess pore-water pressures generated by external loading dissipate, increasing effective stress and causing progressive compression of the soil skeleton (Liu et al., 2024); (Holtz, R. D., Kovacs, W. D., & Sheahan, 2011); (Tsige, D., Korita, M., & Beyene, 2022). The rate of consolidation depends primarily on soil permeability and compressibility, whereas the magnitude of settlement is controlled by the applied

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stress increment and the thickness of the compressible soil layer (Uzer, 2024); (Yin, J. H., Fang, Z., & Cheng, 2020). Accurate prediction of both the rate and magnitude of settlement is therefore fundamental to geotechnical site investigation and foundation design, and researchers continue to compare empirical and laboratory-based approaches to improve the reliability of such predictions (Fitri, S. N., Sutra, N., & Wahyuni, n.d.); (Olek, 2022); (Wang, Y., Zhao, T., & Cao, 2020).

The theoretical basis for consolidation analysis was established by Terzaghi's one-dimensional consolidation theory, which remains the foundation of modern settlement prediction. Despite its simplifying assumptions, the theory continues to underpin geotechnical engineering practice because of its applicability to saturated cohesive soils (Holtz, R. D., Kovacs, W. D., & Sheahan, 2011); (Olek, 2022), and subsequent contributions by Taylor, Casagrande, and other researchers have refined laboratory testing procedures and analytical methods for determining consolidation parameters while preserving Terzaghi's fundamental concepts (Ishola et al., 2022); (Olek, 2022). One-dimensional oedometer testing, conducted in accordance with ASTM D2435/D2435M, remains the standard laboratory method for evaluating consolidation characteristics (Uzer, 2024). The test determines key parameters — the coefficient of consolidation (Cv), coefficient of volume compressibility (m_v), void ratio (e), and permeability (k) — which collectively govern the consolidation response of saturated cohesive soils (Holtz, R. D., Kovacs, W. D., & Sheahan, 2011); (Olek, 2022), with accurate identification of the pre-consolidation pressure being a critical step in this interpretation [16]. The coefficient of volume compressibility controls the magnitude of settlement, the coefficient of consolidation governs its rate, permeability influences pore-water dissipation, and the void ratio reflects the soil's compressibility and state of densification (Bolarinwa et al., 2017); (Olek, 2022). Evaluating these parameters together, rather than independently, therefore provides a more comprehensive understanding of consolidation behaviour than considering them in isolation (Amadi, A. A., & Eberemu, 2013); (Olek, 2022).

Although consolidation theory and laboratory procedures are well established, interpretation of consolidation parameters remains challenging because soils exhibit inherent spatial and material variability (Löfman & Tanttu, 2025); (Phoon, K.-K., & Kulhawy, 1999; Phoon & Kulhawy, 2025). Variations in depositional history, mineralogical composition, moisture content, stress history, and sampling disturbance produce measurable differences in laboratory-derived consolidation properties, while laboratory testing itself introduces additional variability associated with specimen preparation, instrumentation, and measurement precision (Bolarinwa et al., 2017); (Jaksa, M. B., Kaggwa, W. S., & Brooker, 2021); (Yunusa, G. H., Kida, S. A., Suleiman, A., & Idris, 2024); (Olek, 2022); (Phoon, K.-K., & Kulhawy, 1999). Even specimens obtained from the same construction site and tested under identical procedures can display marked scatter in derived compressibility and secondary compression parameters, underscoring the influence of spatial variability at the microscale (Liu et al., 2024). Consequently, repeated oedometer tests on nominally similar specimens often yield different values of Cv, mv, permeability, and settlement, making it important to quantify the consistency of experimentally derived results rather than relying on deterministic estimates alone (Jaksa, M. B., Kaggwa, W. S., & Brooker, 2021); (Olek, 2022); (Löfman & Tanttu, 2025).

Conventional settlement assessment has traditionally relied on deterministic interpretation of laboratory-derived consolidation parameters, representing soil behaviour using single characteristic values (Phoon, K.-K., & Kulhawy, 1999); (Wang, Y., Zhao, T., & Cao, 2020); (Yunusa, G. H., Kida, S. A., Suleiman, A., & Idris, 2024). While this approach remains fundamental to engineering practice, it provides limited information on the variability associated with repeated laboratory measurements or the consistency of settlement predictions (Phoon, K.-K., & Kulhawy, 1999); (Olek, 2022). Statistical characterization using descriptors such as the arithmetic mean, standard deviation, and coefficient of variation complements deterministic analysis by quantifying the central tendency and dispersion of measured values, while remaining fully compatible with conventional consolidation theory (Phoon, K.-K., & Kulhawy, 1999); (Galkovski, 2023). Large-scale database studies of oedometer results have similarly shown that consolidation and creep parameters are characterized by significant inherent uncertainty, reinforcing the value of statistical treatment alongside deterministic design values (Löfman & Tanttu, 2025). Rather than replacing conventional consolidation theory, these statistical measures improve the interpretation of laboratory-derived settlement behaviour and provide greater confidence in engineering assessments (Galkovski, 2023); (Wang, Y., Zhao, T., & Cao, 2020).

This need is particularly relevant in Lagos, Nigeria — one of Africa's fastest-growing metropolitan regions, with continuous expansion of residential, commercial, transportation, and public infrastructure (Otuoze et al., 2021) — where rapid urban development continues across soft coastal and alluvial deposits susceptible to consolidation settlement (Adunoye, 2021); (Bolarinwa et al., 2017). Reliable characterization of these soils is essential for foundation systems intended to satisfy both safety and long-term serviceability requirements (Adunoye, 2021); (Ige, 2018). Previous investigations have reported the engineering properties and consolidation characteristics of tropical residual and coastal alluvial soils in Nigeria, and in Lagos specifically (Adebisi, N. O., Adeyemi, O. O., Kalumba, D., Chebet, F. C., & Osinowo, 2021); (Ishola, K. S., Amu, B. D., & Adeoti, 2023); (Oloruntola, M., Bayewu, O., Kehinde, K., Obasaju, D. O., & Mosuro, 2018); (William,

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T. E., Alege, T. S., Jimoh, A. O., & Musa, 2024), contributing valuable data for foundation design and ground improvement. However, important knowledge gaps remain. First, many of these studies report consolidation parameters such as C_v, m_v, k, and settlement independently rather than evaluating their combined response under progressive loading, despite these parameters being physically interrelated (Adebisi, N. O., Adeyemi, O. O., Kalumba, D., Chebet, F. C., & Osinowo, 2021); (Liu et al., 2024). Second, existing investigations are largely site-specific, with relatively few comparative studies involving representative urban locations across Lagos (Oloruntola, M., Bayewu, O., Kehinde, K., Obasaju, D. O., & Mosuro, 2018); given the spatial variability of the city's coastal and alluvial deposits (Ishola et al., 2022), comparative evaluation is essential for improving regional understanding of settlement characteristics. Third, laboratory consolidation data are generally interpreted deterministically using single representative values, and experimental variability is seldom quantified despite its potential value in strengthening the interpretation of laboratory-derived consolidation parameters (Ashioba, C., & Udom, 2023).

This study addresses these gaps by presenting a comparative experimental assessment of the consolidation behaviour of soft cohesive soils obtained from Palm Grove Estate, GRA Ikeja, and Shonibare Estate in Lagos, Nigeria. One-dimensional consolidation tests were conducted in accordance with ASTM D2435/D2435M to determine the coefficient of consolidation, coefficient of volume compressibility, permeability, void ratio, and primary consolidation settlement under progressive loading. In addition to conventional deterministic analysis, settlement variability was statistically characterized using the arithmetic mean, standard deviation, and coefficient of variation derived from repeated laboratory measurements (Phoon, K.-K., & Kulhawy, 1999; Phoon & Kulhawy, 2025). This approach does not replace deterministic settlement analysis; rather, it complements it by distinguishing representative settlement behaviour from experimental scatter consistent with observations from other Nigerian coastal soil investigations (Ashioba, C., & Udom, 2023) and provides greater confidence in the interpretation of oedometer test results.

The study makes three principal contributions. First, it provides a comparative experimental assessment of the consolidation behaviour of soft cohesive soils from three representative urban locations within Lagos, enabling direct evaluation of spatial variation in compressibility, permeability, consolidation rate, and settlement response under progressive loading. Second, unlike many studies that report consolidation parameters independently, this investigation evaluates the simultaneous response of C_v, m_v, permeability, void ratio, and settlement, providing a more integrated interpretation of the consolidation process. Finally, the study demonstrates that statistical characterization of repeated settlement measurements complements conventional deterministic analysis by quantifying experimental variability through the arithmetic mean, standard deviation, and coefficient of variation. By distinguishing representative settlement behaviour from experimental scatter, these statistical measures improve confidence in the interpretation of oedometer test results while remaining fully consistent with established consolidation theory and standard geotechnical laboratory practice (Amadi, A. A., & Eberemu, 2013); (Bolarinwa et al., 2017); (Ige, 2018); (Yunusa, G. H., Kida, S. A., Suleiman, A., & Idris, 2024).

2.0 Materials and Methods

2.1 Study Area and Site Selection

The study was conducted on soft cohesive soils obtained from three representative locations within Lagos Metropolis, Nigeria: Palm Grove Estate Lat: 6.54352°N, Long: 3.36628°, GRA Ikeja Lat: 6.5802°N, Long: 3.3587°E, and Shonibare Estate Lat: 6.5723°N, Long: 3.3621°E. These sites lie within the central urban corridor of Lagos, where rapid residential, commercial, institutional, and administrative development has increased the demand for reliable foundation systems. Their engineering significance arises from the concentration of major government facilities, business districts, transportation infrastructure, and high-density developments, making accurate settlement prediction essential for long-term structural performance.

Lagos, located in southwestern Nigeria within the eastern Dahomey Basin, is predominantly underlain by coastal plain sands, lagoonal deposits, soft clays, silty clays, and recent alluvial sediments (Ogunleye, R. O., Oluwakuse, M. M., Ajidahun, J., Ale, T. O., & Oluwakuse, 2024); (Oli, I. C., Okeke, O. C., Abiahu, C. M. G., Anifowose, F. A., & Fagorite, 2019). Owing to variations in depositional history and geological conditions, these soils exhibit considerable spatial variability in their engineering properties (Ogunleye, R. O., Oluwakuse, M. M., Ajidahun, J., Ale, T. O., & Oluwakuse, 2024). The occurrence of highly compressible fine-grained soils across many parts of the metropolis has contributed to recurring foundation problems associated with excessive and differential settlement, underscoring the need for reliable characterization of their consolidation behaviour.

The selected locations provide a representative basis for comparing the consolidation characteristics of soft soils developed under a common regional geological setting. They were also chosen to add to available geotechnical laboratory data base, enabling consistent comparative evaluation of consolidation behaviour and statistical characterization of settlement variability.

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Relatively undisturbed cohesive soil samples were collected using thin-walled Shelby tubes in accordance with (D1587/D1587M, 2015) standard geotechnical sampling practice. Samples were carefully sealed immediately after collection to minimize moisture loss prior to laboratory testing and were subsequently prepared following established laboratory procedures to minimize disturbance before testing. The sampling depths for all specimens are presented alongside the corresponding consolidation results in the relevant tables of this study.

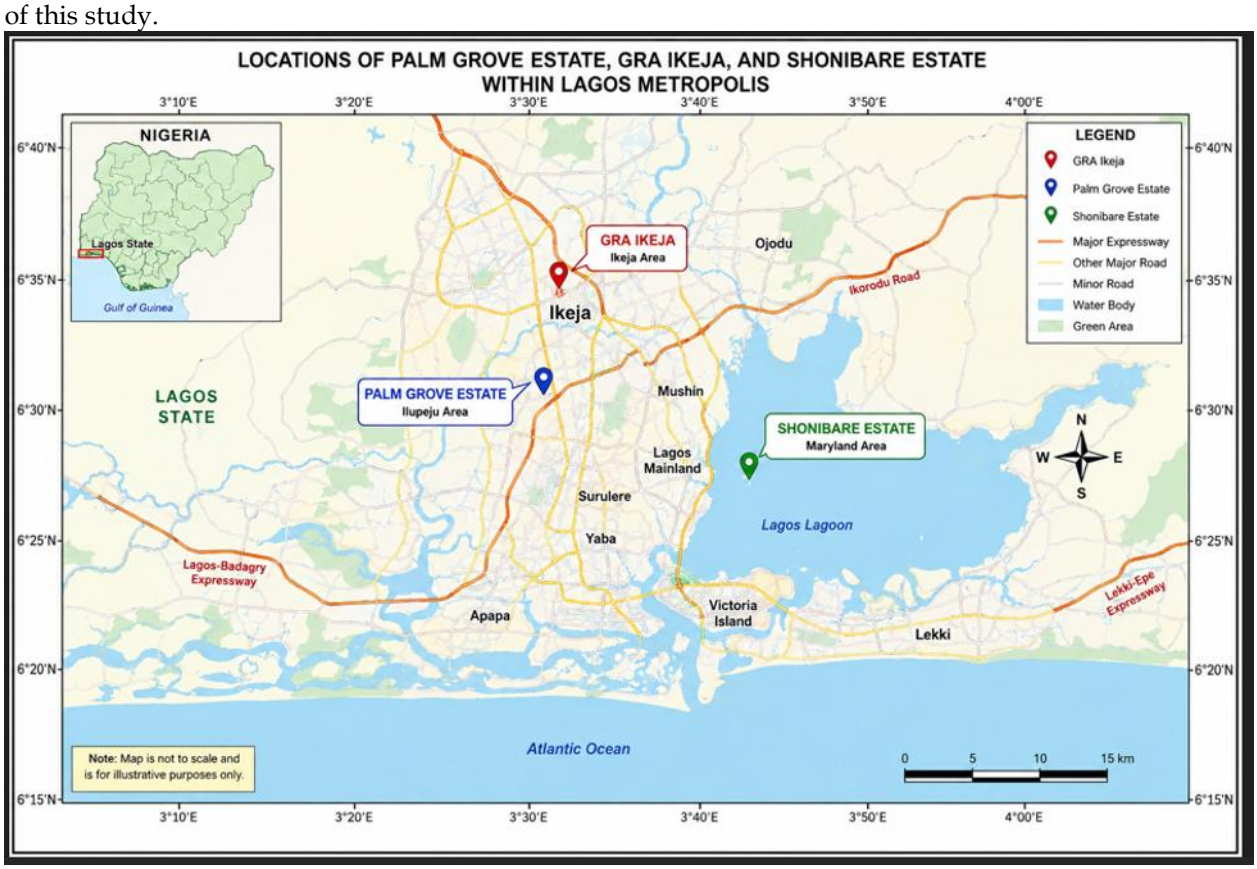


Figure 1: Locations of Palm Grove Estate, GRA Ikeja, and Shonibare Estate within Lagos Metropolis

2.2 Experimental Programme

The laboratory programme was designed to characterize the engineering and consolidation behaviour of soft cohesive soils obtained from Palm Grove Estate, GRA Ikeja, and Shonibare Estate, Lagos, Nigeria. Testing was undertaken to determine the consolidation parameters required for settlement analysis and subsequent statistical characterization of settlement variability. The programme comprised determination of the relevant index properties and one-dimensional consolidation characteristics using standardized laboratory procedures.

Prior to testing, soil specimens were carefully prepared following established geotechnical laboratory practice to preserve their representative engineering characteristics. Specimen preparation involved trimming and handling procedures appropriate for consolidation testing, with care taken to minimize disturbance and moisture variation before testing.

One-dimensional consolidation (oedometer) tests were conducted in accordance with (D2435/D2435M, 2025) Standard Test Methods for One-Dimensional Consolidation Properties of Soils Using Incremental Loading. The test provides the principal consolidation parameters required for settlement analysis, including the coefficient of consolidation (Cv), coefficient of volume compressibility (mv), void ratio (e), and the coefficient of permeability (k), which was subsequently computed from the consolidation parameters.

Test specimens were subjected to incremental vertical loading following the ASTM loading sequence, and vertical deformation was recorded with time for each load increment until primary consolidation was substantially complete. The resulting time–deformation data were interpreted using the Casagrande logarithm-of-time and Taylor square-root-of-time methods to determine the coefficient of consolidation, the two classical curve-fitting procedures that remain the standard basis for evaluating Cv in routine geotechnical practice (Shukla, S. K., Sivakugan, N., & Das, 2009). while the coefficient of volume compressibility was computed from the measured compressibility of each loading increment. These parameters were subsequently used to evaluate permeability and primary consolidation settlement.

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The laboratory programme produced a comprehensive dataset describing the consolidation behaviour of the investigated soils over the applied stress range. This dataset forms the basis for the comparative evaluation of consolidation characteristics and the statistical characterization of settlement variability presented in the subsequent sections.



Figure 1: Sample Preparation and Trimming of Specimen into Consolidation Rings



Figure 2: Specimen Seating in Consolidation Rings and Weighing



Figure 3: Assembly of the Oedometer Apparatus and Proper Seating of the Loading Cap



Figure 4: Recording initial dial gauge readings

2.3 Determination of Consolidation Parameters

The consolidation parameters required for settlement analysis were determined from the one-dimensional oedometer tests conducted on relatively undisturbed soil specimens in accordance with (D2435/D2435M, 2025). The experimentally measured deformation-time responses obtained under successive loading increments were analysed to determine the coefficient of volume compressibility (m_v), coefficient of consolidation (C_v), coefficient of permeability (k), and the corresponding primary consolidation settlement.
The oedometer tests were performed under incremental loading corresponding to effective vertical stress ranges of 50–100, 100–200, 200–400, and 400–800 kN/m², representing the anticipated stress conditions within the investigated soil deposits. Soil specimens were obtained from Palm Grove Estate, GRA Ikeja, and Shonibare Estate at investigation depths of 1.5 m and 3.0 m, depending on the site.

The experimental programme generated three independent measurements for each consolidation parameter at every loading increment, from which the average value and standard deviation were determined for subsequent Statistical assessment.

The experimentally determined consolidation parameters were subsequently used to estimate the permeability characteristics and primary consolidation settlement of the investigated soils.

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2.3.1 Coefficient of Volume Compressibility (m_v)

The coefficient of volume compressibility was determined for each loading increment from the measured one-dimensional vertical strain produced by the applied effective stress increment (Holtz, R. D., Kovacs, W. D., & Sheahan, 2011). The parameter was calculated as

$$m_v = \frac{\Delta\varepsilon_v}{\Delta\sigma_v'} \quad (1)$$

Where

$$\Delta\varepsilon_v = \frac{\Delta H}{H_0} \quad (2)$$

thus,

$$m_v = \frac{\Delta H}{H_0 \Delta\sigma_v'} \quad (3)$$

where

- m_v = coefficient of volume compressibility (m²/MN);
- ΔH = change in specimen height during a loading increment (m);
- H_0 = initial specimen height of the oedometer specimen (m);
- $\Delta\sigma_v'$ = applied effective vertical stress increment (MN/m²).

The calculated m_v values for the investigated soils are presented in Table 1. These values constitute the principal compressibility parameter adopted in the deterministic and Statistical settlement analyses.

Table 1: Coefficient of Volume Compressibility (m_v) Results

S/No.	Location	Stress Range (kN/m²)		Test Depth H (m)	Mv (m²/MN)		
	Lagos State	Initial	Final		1	2	3
1	Palm Grove Estate, Lagos	50	100	1.5	0.35	0.4	0.32
2		100	200		0.28	0.32	0.25
3		200	400		0.2	0.23	0.18
4		400	800		0.14	0.16	0.12
5	Ikeja, No. 6, Ajisafe Street	50	100	1.5	0.32	0.37	0.29
6		100	200		0.26	0.3	0.23
7		200	400		0.18	0.21	0.16
8		400	800		0.12	0.14	0.11
9		50	100	3	0.3	0.35	0.27
10		100	200		0.24	0.28	0.22
11		200	400		0.17	0.2	0.15
12		400	800		0.11	0.13	0.1
13	Shonibare Estate, Onigbonngbo, Shonibare Estate, Ikeja LGA, Lagos	50	100	1.5	0.38	0.44	0.35
14		100	200		0.3	0.35	0.27
15		200	400		0.22	0.25	0.2
16		400	800		0.15	0.17	0.13

2.3.2 Coefficient of Consolidation (C_v)

The coefficient of consolidation was determined from the deformation-time records obtained during each loading increment using both the Casagrande logarithm-of-time method and the Taylor square-root-of-time method, as recommended in (D2435/D2435M, 2025) (ASTM International, 2025) and described in detail in (Shukla, S. K., Sivakugan, N., & Das, 2009):

For the Casagrande method,

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$$C_v = \frac{0.197H_{dr}^2}{t_{50}} \quad (4)$$

where t_{50} is the time corresponding to 50% primary consolidation.
For the Taylor method,

$$C_v = \frac{0.848H_{dr}^2}{t_{90}} \quad (5)$$

where t_{90} represents the time corresponding to 90% primary consolidation.

The representative coefficient of consolidation adopted in this study was obtained as the arithmetic mean of the values determined from the Casagrande and Taylor methods for each loading increment. This approach minimizes the uncertainty associated with graphical interpretation and provides a more representative estimate of the consolidation rate. The average value was adopted to reduce interpretation bias associated with the graphical determination of characteristic consolidation times.

The experimentally determined C_v values are reported in the coefficient of consolidation results table in Chapter 2.

Table 2: Coefficient of Consolidation (C_v) Results

S/No.	**Location**	**Stress Range (kN/m²)**		**Test Depth H (m)**	**(C_v) (m²/s)**		
	Lagos State	Initial	Final		1	2	3
1	Palm Grove Estate, Lagos	50	100	1.5	9.89×10^{-8}	1.14×10^{-7}	1.06×10^{-7}
2		100	200		9.00×10^{-8}	1.04×10^{-7}	9.70×10^{-8}
3		200	400		7.80×10^{-8}	9.00×10^{-8}	8.40×10^{-8}
4		400	800		6.18×10^{-8}	7.13×10^{-8}	6.66×10^{-8}
5	Ikeja, No. 6, Ajisafe Street	50	100	1.5	9.67×10^{-8}	1.12×10^{-7}	1.04×10^{-7}
6		100	200		8.81×10^{-8}	1.02×10^{-7}	9.48×10^{-8}
7		200	400		7.54×10^{-8}	8.72×10^{-8}	8.12×10^{-8}
8		400	800		5.96×10^{-8}	6.88×10^{-8}	6.40×10^{-8}
9		50	100	3	9.22×10^{-8}	1.06×10^{-7}	9.92×10^{-8}
10		100	200		8.40×10^{-8}	9.70×10^{-8}	9.03×10^{-8}
11		200	400		7.04×10^{-8}	8.12×10^{-8}	7.58×10^{-8}
12		400	800		5.45×10^{-8}	6.31×10^{-8}	5.86×10^{-8}
13	Shonibare Estate, Onigbonngbo, Shonibare Estate, Ikeja LGA, Lagos	50	100	1.5	1.01×10^{-7}	1.16×10^{-7}	1.08×10^{-7}
14		100	200		9.16×10^{-8}	1.06×10^{-7}	9.86×10^{-8}
15		200	400		7.96×10^{-8}	9.19×10^{-8}	8.56×10^{-8}
16		400	800		6.31×10^{-8}	7.29×10^{-8}	6.78×10^{-8}

2.3.3 Coefficient of Permeability (k)

The coefficient of permeability was determined indirectly from the experimentally obtained consolidation parameters (Holtz, R. D., Kovacs, W. D., & Sheahan, 2011):

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$$k = C_v m_v \gamma_w \quad (6)$$

where

- k = coefficient of permeability (m/s);
- C_v = coefficient of consolidation (m²/s);
- m_v = coefficient of volume compressibility (m²/MN);
- γ_w = unit weight of water (9.81 kN/m³).

The calculated permeability values were subsequently used to evaluate the drainage characteristics of the investigated soft soils and to compare hydraulic conductivity among the three study locations.
The permeability results are presented in the permeability table in Chapter 3.

Table 3: Permeability ($\boldsymbol{k}$) Test Results,

S/No.	Location	Stress Range (kN/m²)		Test Depth H (m)	Permeability, k (m/s)		
	Lagos State	Initial	Final		1	2	3
1	Palm Grove Estate, Lagos	50	100	1.5	3.40×10^{-10}	4.47×10^{-10}	3.33×10^{-10}
2		100	200		2.47×10^{-10}	3.26×10^{-10}	2.38×10^{-10}
3		200	400		1.53×10^{-10}	2.03×10^{-10}	1.48×10^{-10}
4		400	800		8.49×10^{-11}	1.12×10^{-10}	7.84×10^{-11}
5	Ikeja, No. 6, Ajisafe Street	50	100	1.5	3.04×10^{-10}	4.07×10^{-10}	2.96×10^{-10}
6		100	200		2.25×10^{-10}	3.00×10^{-10}	2.14×10^{-10}
7		200	400		1.33×10^{-10}	1.80×10^{-10}	1.27×10^{-10}
8		400	800		7.02×10^{-11}	9.45×10^{-11}	6.91×10^{-11}
9		50	100	3	2.71×10^{-10}	3.64×10^{-10}	2.63×10^{-10}
10		100	200		1.98×10^{-10}	2.66×10^{-10}	1.95×10^{-10}
11		200	400		1.17×10^{-10}	1.59×10^{-10}	1.12×10^{-10}
12		400	800		5.88×10^{-11}	8.05×10^{-11}	5.75×10^{-11}
13	Shonibare Estate, Onigbonngbo, Shonibare Estate, Ikeja LGA, Lagos	50	100	1.5	3.77×10^{-10}	5.01×10^{-10}	3.71×10^{-10}
14		100	200		2.70×10^{-10}	3.64×10^{-10}	2.61×10^{-10}
15		200	400		1.72×10^{-10}	2.25×10^{-10}	1.68×10^{-10}
16		400	800		9.29×10^{-11}	1.22×10^{-10}	8.65×10^{-11}

Table 4: Void Ratio Test Results

S/No.	Location	Stress Range (kN/m²)		Test Depth H (m)	Void Ratio, e		
	Lagos State	Initial	Final		1	2	3
1	Palm Grove Estate, Lagos	50	100	1.5	0.72	0.76	0.69
2		100	200		0.65	0.69	0.62
3		200	400		0.56	0.6	0.53
4		400	800		0.48	0.51	0.45
5	Ikeja, No. 6, Ajisafe Street	50	100	1.5	0.69	0.73	0.66
6		100	200		0.62	0.66	0.59
7		200	400		0.54	0.57	0.51
8		400	800		0.45	0.48	0.42
9		50	100	3	0.67	0.71	0.64
10		100	200		0.6	0.64	0.57
11		200	400		0.52	0.55	0.49

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S/No.	Location	Stress Range (kN/m²)		Test Depth H (m)	Void Ratio, e		
12		400	800		0.43	0.46	0.4
13	Shonibare Estate, Onigbonngbo, Shonibare Estate, Ikeja LGA, Lagos	50	100	1.5	0.75	0.79	0.72
14		100	200		0.68	0.72	0.65
15		200	400		0.59	0.62	0.56
16		400	800		0.5	0.53	0.47

2.3.4 Determination of Primary Consolidation Settlement

Primary consolidation settlement was evaluated using the experimentally determined coefficient of volume compressibility (Holtz, R. D., Kovacs, W. D., & Sheahan, 2011):

$$S = m_v \Delta\sigma_v' H_c \quad (7)$$

where

- S = primary consolidation settlement (m);
- m_v = coefficient of volume compressibility (m²/MN);
- $\Delta\sigma_v'$ = increase in effective vertical stress resulting from the applied load (MN/m²);
- H_c = thickness of the compressible soil layer (m).

Settlement calculations were carried out for each stress increment and sampling depth. Three independent settlement estimates were obtained for each loading stage, from which the average settlement and corresponding standard deviation were computed.

Table 5: Settlement Results S.

S/No.	Location	Stress Range (kN/m²)		Test Depth H (m)	Settlement (mm)			Avg S (mm)	SD (mm)	Type
	Lagos State	Initial	Final		Trial 1	Trial 2	Trial 3			
1	Palm Grove Estate, Lagos	50	100	1.5	26.25	30	24	26.75	3.06	Loading
2		100	200		42	48	37.5	42.5	6.11	Loading
3		200	400		60	69	54	61	8.08	Loading
4		400	800		84	96	72	84	14.22	Loading
5	Ikeja, No. 6, Ajisafe Street	50	100	1.5	24	27.75	21.75	24.5	4.16	Loading
6		100	200		39	45	34.5	39.5	7.77	Loading
7		200	400		54	63	48	55	6	Loading
8		400	800		72	84	66	74	7.02	Loading
9		50	100	3	45	52.5	40.5	46	4.51	Loading
10		100	200		72	84	66	74	7.02	Loading
11		200	400		102	120	90	104	15.87	Loading
12		400	800		132	156	120	136	20.82	Loading
13	Shonibare Estate, Onigbonngbo, Shonibare	50	100	1.5	28.5	33	26.25	29.25	2.08	Loading
14		100	200		26.25	30	24	26.75	3.06	Loading
15		200	400		42	48	37.5	42.5	6.11	Loading

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S/No.	Location	Stress Range (kN/m²)		Test Depth H (m)	Settlement (mm)			Avg S (mm)	SD (mm)	Type
16	Estate, Ikeja LGA, Lagos	400	800		60	69	54	61	8.08	Loading

Table 6: Atterberg Limits of Investigated Soils

S/No.	Location	LL (%)	PL (%)	PI (%)	Soil Behavior
1	Palm Grove, Lagos	38	22	16	Low-medium plasticity clayey soil
2	Palm Grove, Lagos	42	24	18	Medium plasticity
3	Palm Grove, Lagos	45	26	19	Medium plasticity
4	Palm Grove, Lagos	35	20	15	Low plasticity
5	Ikeja, Lagos	40	23	17	Medium plasticity
6	Ikeja, Lagos	37	21	16	Low-medium
7	Ikeja, Lagos	44	25	19	Medium
8	Ikeja, Lagos	32	19	13	Low plasticity (more sandy)
9	Ikeja, Lagos	39	22	17	Medium
10	Ikeja, Lagos	41	23	18	Medium
11	Ikeja, Lagos	46	26	20	Medium plasticity
12	Ikeja, Lagos	33	18	15	Low-medium
13	Shonny High, Lagos	43	24	19	Medium plasticity
14	Shonny High, Lagos	36	21	15	Low-medium
15	Shonny High, Lagos	47	27	20	Medium-high
16	Shonny High, Lagos	34	20	14	Low plasticity

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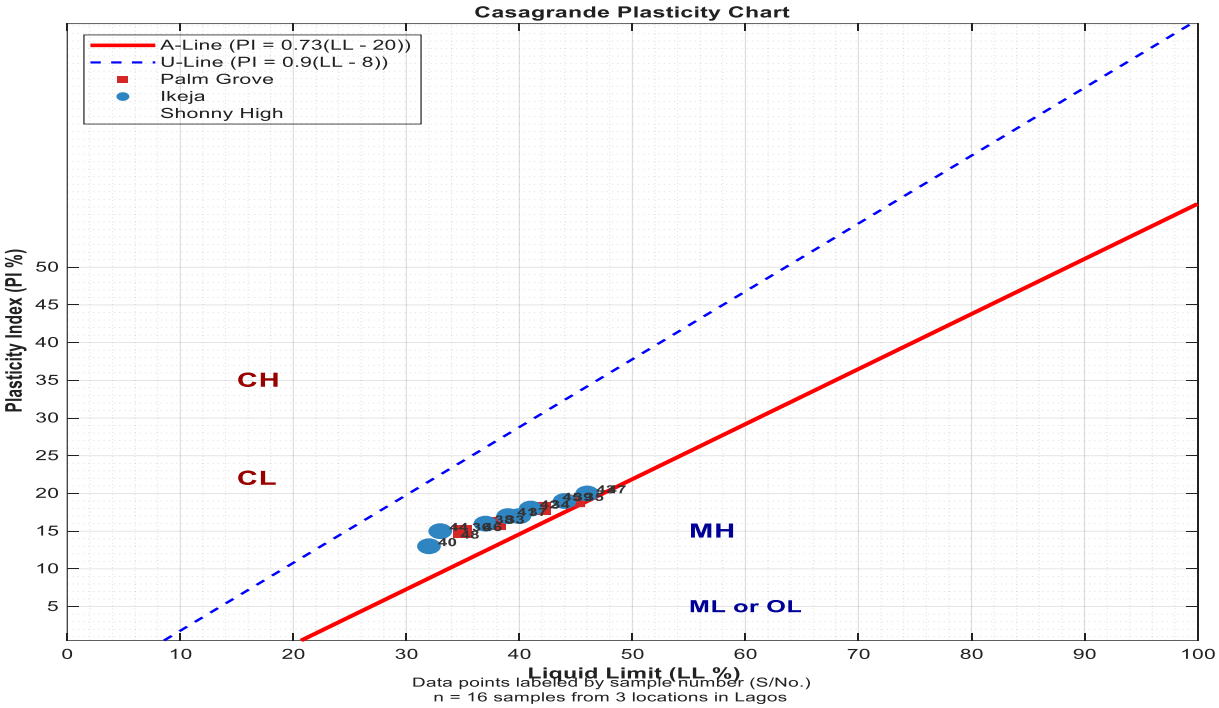


Figure 5: Casagrande Plasticity Chart for soil samples from Palm Grove Estate, Ikeja, and Shonibare Estate in Lagos

2.3.5 Soil Classification and Index Properties

The physical properties of the investigated soils were determined using standard laboratory procedures. The Atterberg limits are present in Table 6. As shown in Figure 5, the majority of the soil samples plot above the A-line, indicating inorganic clays of low to medium plasticity. The Liquid Limit (LL) ranges from 32% to 47%, while the Plasticity Index (PI) varies between 13% and 20%. These values are consistent with typical soft cohesive soils encountered in the coastal and lagoonal deposits of Lagos (Ogunleye, R. O., Oluwakuse, M. M., Ajidahun, J., Ale, T. O., & Oluwakuse, 2024).

One sample from Ikeja (S/No. 40) plots slightly below the A-line, reflecting a more sandy character, which correlates with its comparatively lower compressibility.

3. Results and Discussion

3.1 Experimental Results.

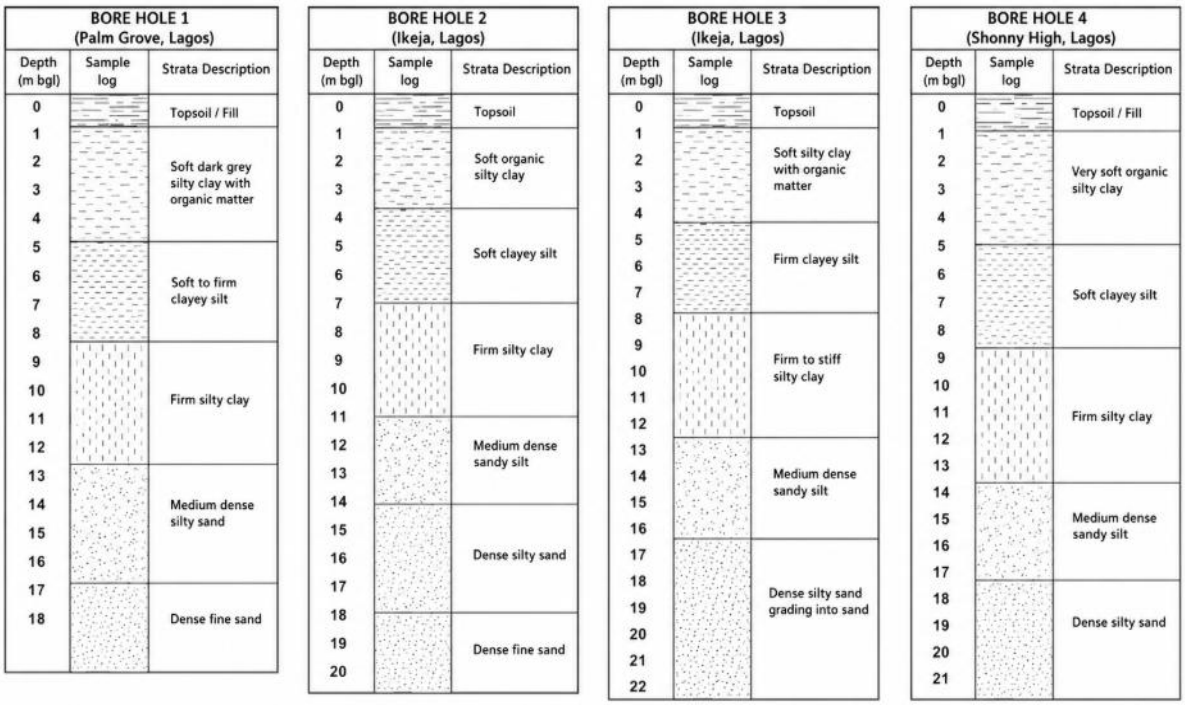


Figure. 6 Selected borehole logs from some of the study.

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Figure 6 presents the representative SPT borehole logs in some locations of investigation sites, showing the subsurface stratification and geological interpretation of the soil profiles. The boreholes generally indicate sequences of soft cohesive soils overlying silty sand and dense sand deposits, which are consistent with the laboratory classification and consolidation characteristics of the investigated soils.

One-dimensional consolidation tests conducted on relatively undisturbed soil specimens obtained from Palm Grove Estate, GRA Ikeja, and Shonibare Estate, Lagos, to evaluate the compressibility, consolidation rate, permeability, and settlement characteristics of representative soft soils. Laboratory testing was performed under four successive effective stress ranges of 50–100, 100–200, 200–400, and 400–800 kN/m^2, while the measured deformation responses were used to determine the coefficient of volume compressibility (m_v), coefficient of consolidation (C_v), coefficient of permeability (k), void ratio (e), and primary consolidation settlement.

The complete experimental dataset is presented in the following tables:

- Coefficient of Volume Compressibility (m_v) – in Table 1
- Coefficient of Consolidation (C_v) – in Table 2
- Permeability and Void Ratio – in Table 3 and 4
- Settlement Results – See Table 5.

The experimental results demonstrate consistent consolidation behaviour across the three investigated sites. Increasing effective stress resulted in a progressive reduction in void ratio, coefficient of volume compressibility, coefficient of consolidation, and hydraulic conductivity, while the corresponding primary consolidation settlement increased with applied loading. These observed trends are consistent with the fundamental principles of one-dimensional consolidation theory, where increasing effective stress causes particle rearrangement, reduction in pore volume, and progressive densification of the soil skeleton.

Although all three locations exhibited similar consolidation trends, differences in the magnitude of the measured parameters indicate variations in soil compressibility and drainage characteristics attributable to local geological conditions. Among the investigated sites, Shonibare Estate generally exhibited the highest compressibility during the initial loading stages, whereas the deeper clay layer encountered at GRA Ikeja (3.0 m) developed the largest settlement response under increasing stress. Palm Grove Estate consistently exhibited intermediate consolidation characteristics, indicating comparatively moderate compressibility and settlement potential.

The laboratory measurements further demonstrated strong internal consistency among the measured parameters. Reductions in void ratio were accompanied by corresponding decreases in the coefficient of volume compressibility and permeability, confirming the close relationship between soil structure, compressibility, and hydraulic conductivity during consolidation. The experimentally determined permeability values also exhibited systematic reductions with increasing stress, reflecting progressive closure of interconnected pore spaces as consolidation proceeded.

A statistical assessment of the settlement calculations showed relatively small standard deviations across repeated determinations, indicating good repeatability of the laboratory measurements and consistency of the adopted computational procedure. Consequently, the experimental dataset provides a reliable basis for subsequent deterministic and statistical settlement analyses.

The following sections examine each consolidation parameter in detail and discuss the engineering significance of the observed behaviour with respect to the performance of foundations constructed on soft Lagos soils.

3.2 Comparative Compressibility Behaviour of the Investigated Soils

The coefficient of volume compressibility (m_v) is one of the principal parameters governing one-dimensional consolidation and provides a measure of the volumetric strain developed per unit increase in effective vertical stress. The experimentally determined (m_v) values for the investigated soils are presented in Table 1. The results demonstrate a consistent reduction in compressibility with increasing effective stress across all three investigated locations.

At Palm Grove Estate, the average coefficient of volume compressibility decreased from 0.35 m²/MN within the 50–100 kN/m² loading interval to 0.14 m²/MN at 400–800 kN/m², representing an overall reduction of approximately 60.0%. A similar trend was observed at GRA Ikeja (1.5 m), where the coefficient decreased from 0.32 m²/MN to 0.12 m²/MN, corresponding to a reduction of approximately 62.5%. The deeper deposit at GRA Ikeja (3.0 m) exhibited a decrease from 0.30 m²/MN to 0.11 m²/MN, representing an overall reduction of approximately 63.3%. Likewise, Shonibare Estate recorded a reduction from 0.38 m²/MN to 0.15 m²/MN, corresponding to an overall reduction of approximately 60.5%. Despite differences in the absolute values of m_v, the magnitude of reduction observed at all locations remained remarkably similar, ranging between approximately 60% and 63% over the investigated stress interval.

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The observed reduction in the coefficient of volume compressibility with increasing effective stress is consistent with the expected response of cohesive soils subjected to one-dimensional consolidation as stated by (Liu et al., 2024); (Vivekananda & Nagaraj, 2025) . As vertical stress increases, soil particles undergo progressive rearrangement accompanied by a reduction in pore volume. This process results in a denser soil skeleton with increased resistance to further compression, thereby reducing the incremental volumetric strain produced by subsequent loading increments. Consequently, the coefficient of volume compressibility decreases progressively as consolidation advances.

Although all three sites exhibited similar compressibility trends, differences were observed in the magnitude of the measured m_v values. Shonibare Estate consistently recorded the highest coefficient of volume compressibility during the initial loading stage (0.38 m²/MN), indicating comparatively greater compressibility at lower stress levels. Conversely, the 3.0 m deposit at GRA Ikeja exhibited the lowest mvm_vmv values throughout most of the loading programme. Nevertheless, the settlement calculations presented later in this study indicate that the same deposit developed the largest settlement under the applied loading conditions.

This apparent difference between compressibility and settlement behaviour is consistent with the governing settlement relationship adopted in this study in equation (7)
where settlement is influenced not only by the coefficient of volume compressibility but also by the applied effective stress increment and the thickness of the compressible soil layer. Consequently, comparison of settlement behaviour should be based on the combined influence of these governing parameters rather than on m_v alone. The results obtained in this study therefore demonstrate that soils exhibiting comparatively lower compressibility may still develop larger settlements where the combined effects of stress increment and compressible layer thickness are greater.

The measured compressibility behaviour is further supported by the accompanying reductions in void ratio reported for the investigated soils. For example, the average void ratio at Palm Grove Estate decreased from 0.72 during the initial loading stage to 0.48 at the highest applied stress, while comparable reductions were observed at GRA Ikeja and Shonibare Estate. The concurrent decrease in void ratio and coefficient of volume compressibility indicates progressive densification of the soil structure during consolidation and demonstrates the strong interdependence between soil fabric and compressibility.

The experimental programme also demonstrated good repeatability of the measured compressibility values. Three independent determinations were obtained for each loading increment, producing consistent results with relatively small variability. This consistency provides confidence in the reliability of the laboratory measurements and supports the subsequent statistical settlement analysis based on the experimentally determined consolidation parameters.

Overall, the investigated soils exhibited moderate to high compressibility under the applied loading conditions which is also collaborated by (Bell, 2000), with all locations showing a systematic reduction in m_v as effective stress increased. While Shonibare Estate displayed comparatively greater compressibility during the early stages of loading, the deeper GRA Ikeja deposit ultimately produced the greatest calculated settlement, demonstrating that assessment of foundation performance requires consideration of all governing settlement parameters rather than the coefficient of volume compressibility in isolation.

3.3 Consolidation Rate Characteristics (C_v)

The coefficient of consolidation (C_v) governs the rate at which excess pore water pressure dissipates during one-dimensional consolidation and therefore provides an indication of the time required for settlement to occur under an applied load. The experimentally determined values of (C_v), obtained using the combined Casagrande logarithm-of-time and Taylor square-root-of-time methods, are presented in the coefficient of consolidation results Table 2.

Across the investigated locations, the coefficient of consolidation exhibited a gradual reduction with increasing effective stress. At Palm Grove Estate, the average (C_v) decreased from approximately 1.06×10^{-7} m²/s within the 50–100 kN/m² loading interval to 6.66×10^{-8} m²/s at the 400–800 kN/m² loading stage, representing an overall reduction of approximately 37%. Similarly, the shallow deposit at GRA Ikeja (1.5 m) exhibited a decrease from 1.04×10^{-7} m²/s to 6.40×10^{-8} m²/s, while the deeper 3.0 m layer reduced from 9.92×10^{-8} m²/s to 5.86×10^{-8} m²/s. At Shonibare Estate, the coefficient of consolidation decreased from 1.08×10^{-7} m²/s during the initial loading stage to 6.78×10^{-8} m²/s at the maximum applied stress. The reductions observed across the four datasets ranged from approximately 32% to 41%, indicating a consistent consolidation response despite differences in site conditions.

The progressive reduction in (C_v) indicates that the rate of primary consolidation became slower as the applied effective stress increased. This behaviour is consistent with the simultaneous reduction in hydraulic conductivity observed during the oedometer tests. As consolidation progressed, the reduction in interconnected pore spaces restricted the movement of pore water through the soil matrix, thereby reducing

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the rate of pore-pressure dissipation. Although the coefficient of volume compressibility also decreased with increasing stress, The experimentally determined coefficient of consolidation exhibited a progressive reduction with increasing stress. This trend is consistent with the concurrent reductions observed in permeability and compressibility, reflecting the overall consolidation behaviour of the investigated soils.

The measured behaviour is further supported by the experimentally determined permeability values. For example, at Palm Grove Estate, the average coefficient of permeability decreased from 3.40×10^{-10} m/s during the initial loading stage to 8.49×10^{-11} m/s at the highest stress increment, representing a reduction of approximately 75%. Similar reductions were observed at GRA Ikeja and Shonibare Estate. Since the coefficient of consolidation is directly related to both permeability and compressibility through equation (6)
the simultaneous decrease in both k and m_v explains the observed reduction in C_v. The close agreement among these independently derived parameters demonstrates the internal consistency of the experimental results and confirms that the consolidation characteristics obtained from the laboratory testing satisfy the expected relationships of one-dimensional consolidation theory.

Comparison of the three study locations indicates relatively small differences in the magnitude of the coefficient of consolidation. Although Shonibare Estate recorded the highest average C_v during the initial loading stage, the differences between the three locations became progressively smaller with increasing stress. This convergence suggests that the investigated soils responded similarly under higher stress levels despite exhibiting different initial compressibility characteristics.
From an engineering perspective, the measured C_v values indicate that the investigated soft soils possess relatively slow drainage characteristics (Adebisi, N. O., Adeyemi, O. O., Kalumba, D., Chebet, F. C., & Osinowo, 2021). Consequently, a significant proportion of settlement is expected to occur over an extended period following construction rather than immediately after loading. This behaviour has important implications for foundation design and construction scheduling in soft soil environments, where the rate of settlement may be as critical as the ultimate settlement magnitude.

The consistency observed among the measured coefficients of consolidation, permeability, void ratio and compressibility further demonstrates the reliability of the experimental programme. Collectively, these parameters describe a coherent consolidation process in which progressive loading produced simultaneous reductions in pore volume, hydraulic conductivity, compressibility and consolidation rate.

3.4 Evolution of Void Ratio and Permeability During Consolidation

The reduction in void ratio and permeability during one-dimensional consolidation provides direct evidence of the progressive densification of the soil structure under increasing effective stress. The experimentally determined values of void ratio and coefficient of permeability are presented in the void ratio and permeability results table 3 and 4. Both parameters exhibited systematic reductions throughout the loading programme, indicating continuous compression of the soil skeleton and progressive restriction of pore-water flow.

At Palm Grove Estate, the average void ratio decreased from 0.72 during the 50–100 kN/m² loading stage to 0.48 at the maximum applied stress of 400–800 kN/m², representing an overall reduction of approximately 33%. Similar reductions were observed at GRA Ikeja (1.5 m), where the void ratio reduced from 0.69 to 0.45, and at GRA Ikeja (3.0 m), where it decreased from 0.67 to 0.43. The greatest initial void ratio was recorded at Shonibare Estate (0.75), decreasing progressively to 0.50 at the final loading stage. Despite differences in the initial values, all four datasets exhibited remarkably similar reductions in void ratio, confirming a consistent consolidation response under increasing effective stress.

The coefficient of permeability exhibited an even more pronounced reduction throughout the loading programme. At Palm Grove Estate, permeability decreased from 3.40×10^{-10} m/s to 8.49×10^{-11} m/s, representing a reduction of approximately 75%. Comparable reductions were observed at GRA Ikeja and Shonibare Estate, where the permeability consistently declined as the applied stress increased. Across all investigated locations, the measured permeability values remained within the order stated by (Ishola et al., 2022) of 10^{-10} to 10^{-11} m/s, indicating soils of very low hydraulic conductivity and correspondingly slow drainage characteristics .

The simultaneous reductions in void ratio and permeability demonstrate the close interaction between soil fabric and hydraulic conductivity during consolidation. As vertical loading increased, the progressive rearrangement of soil particles reduced the volume and connectivity of pore spaces available for water flow. Consequently, the resistance to seepage increased, resulting in lower permeability values. The observed relationship between void ratio and permeability is therefore consistent with the fundamental principles of saturated soil mechanics, whereby hydraulic conductivity decreases as pore channels become progressively smaller and less interconnected during consolidation.
The measured reduction in permeability is also consistent with the experimentally determined consolidation parameters presented in the preceding sections. Since permeability was calculated using equation (6)

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the gradual reductions observed in both the coefficient of consolidation and the coefficient of volume compressibility are reflected in the calculated permeability values. Independent verification of the laboratory calculations confirmed that the reported permeability values satisfy this governing relationship and are internally consistent with the measured consolidation parameters. This internal consistency provides additional confidence in the reliability of the experimental dataset.

Comparison of the three investigated locations indicates that Shonibare Estate exhibited the highest initial permeability, while the 3.0 m deposit at GRA Ikeja generally recorded the lowest permeability values at the higher stress levels. Nevertheless, all investigated soils followed essentially the same hydraulic response during loading, suggesting that the mechanism governing pore-space reduction was similar despite differences in the initial soil structure.

From an engineering perspective, the measured permeability values indicate that the investigated soils possess poor drainage characteristics and will therefore dissipate excess pore-water pressure relatively slowly following construction loading. Consequently, settlement is expected to continue over an extended period after foundation loading, particularly where thick compressible clay deposits are present. These findings emphasise the importance of considering both the magnitude and the rate of settlement when designing foundations on soft Lagos soils.

Overall, the observed reductions in void ratio and permeability provide direct experimental evidence of progressive soil densification during consolidation. The excellent agreement between the measured void ratio, permeability, compressibility and consolidation characteristics demonstrates that the laboratory results are physically consistent and collectively describe a coherent consolidation process.

3.5 Deterministic Settlement Behaviour

Primary consolidation settlement represents one of the most important design considerations for foundations constructed on soft cohesive soils, as excessive post-construction deformation may adversely affect structural serviceability and long-term performance. The deterministic settlement values computed from the experimentally determined coefficients of volume compressibility are presented in the settlement results in table 5. The results demonstrate a systematic increase in settlement with increasing applied effective stress across all investigated locations.

At Palm Grove Estate, the average primary settlement increased progressively from 26.75 mm during the 50–100 kN/m^2 loading interval to 84 mm under the maximum applied stress of 400–800 kN/m^2. This represents an increase of approximately 214% over the investigated loading range. Similar behaviour was observed at GRA Ikeja (1.5 m), where settlement increased from 24.5 mm to 74 mm, corresponding to an increase of approximately 202%. The deeper deposit at GRA Ikeja (3.0 m) exhibited the largest settlement throughout the loading programme, increasing from 46 m during the initial loading stage to 136 mm at the highest stress level, representing an increase of approximately 196%. At Shonibare Estate, settlement increased from 29.25 mm to 90 mm, corresponding to an increase of approximately 208%.

The progressive increase in settlement observed at all locations is consistent with the one-dimensional consolidation equation adopted in this study in equation (7)
where settlement is directly proportional to the coefficient of volume compressibility, the applied effective stress increment and the thickness of the compressible soil layer. Although the coefficient of volume compressibility decreased progressively with increasing stress, the larger stress increments produced greater overall settlements. Consequently, the influence of increasing applied stress exceeded the concurrent reduction in compressibility, resulting in progressively larger settlement values throughout the loading programme.

Comparison of the investigated locations indicates that GRA Ikeja (3.0 m) consistently developed the greatest settlement at each loading stage despite exhibiting lower coefficients of volume compressibility than Shonibare Estate during most loading increments. This observation demonstrates that settlement cannot be assessed solely on the basis of soil compressibility. Rather, the governing settlement equation shows that the combined influence of compressibility, stress increment and compressible layer thickness determines the magnitude of settlement. The results therefore emphasise the importance of considering all governing parameters simultaneously during foundation settlement assessment.

At the maximum loading stage (400–800 kN/m²), the average settlements were 84 mm at Palm Grove Estate, 74 mm at GRA Ikeja (1.5 m), 136 mm at GRA Ikeja (3.0 m), and 61 mm at Shonibare Estate. These results indicate that the deeper deposit at GRA Ikeja experienced approximately 62% greater settlement than the shallow GRA Ikeja layer, approximately 51% greater settlement than Palm Grove Estate, and approximately 51% greater settlement than Shonibare Estate under comparable loading conditions. These differences demonstrate the significant influence of deposit thickness on predicted settlement and highlight the importance of site-specific subsurface characterization during foundation design.

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The repeatability of the settlement calculations is demonstrated by the relatively small standard deviations obtained from the three independent determinations for each loading stage. Across all locations, the standard deviations remained low relative to the corresponding average settlements, indicating good consistency in the computational procedure and confirming the reliability of the calculated settlement values. The limited variability observed also provides confidence in the subsequent Statistical assessment, where the experimentally derived statistical parameters are used to characterize settlement uncertainty.

From an engineering perspective, the measured settlements indicate that all three investigated locations are susceptible to appreciable primary consolidation under increasing structural loads. The comparatively larger settlements predicted for the deeper GRA Ikeja deposit suggest that foundations constructed over thicker compressible strata may experience substantially greater post-construction deformation, even where the measured coefficient of volume compressibility is comparatively lower. Consequently, foundation design in soft Lagos soils should consider not only laboratory-derived compressibility parameters but also the thickness of the compressible deposit and the magnitude of the anticipated loading when evaluating settlement performance.

Overall, the deterministic settlement analysis demonstrates a consistent and physically realistic response across the investigated sites. The observed settlement behaviour is fully consistent with the measured consolidation parameters and confirms that increasing effective stress produces progressively larger settlements despite the concurrent reduction in compressibility. The deterministic results therefore provide a sound basis for the Statistical settlement assessment presented in the following section.

Table 7: Summary of Average Primary Consolidation Settlement and Percentage Increase under Progressive Loading

Location	Average Settlement at 50–100 (kN/m^2)	Average Settlement at 400–800 (kN/m^2)	Percentage Increase (%)
Palm Grove Estate	26.75 mm	84 mm	214
GRA Ikeja (1.5 m)	24.5 mm	74 mm	202
GRA Ikeja (3.0 m)	46 mm	136 mm	196
Shonibare Estate	29.25 mm	61 mm	208

3.6 Statistical Settlement Assessment

Conventional consolidation analyses generally provide a single deterministic estimate of settlement for a specified loading condition. While such estimates are useful for design, they do not explicitly account for the inherent variability associated with laboratory measurements and natural soil heterogeneity. To provide a more comprehensive assessment of settlement behaviour, the deterministic settlement results obtained in this study were supplemented with a statistical evaluation based on three independent settlement determinations for each loading increment. The Statistical assessment was performed using the arithmetic mean, standard deviation, and coefficient of variation (COV), thereby quantifying both the expected settlement magnitude and its associated variability.

Table 8. Coefficient of Variation (COV) of Average Primary Consolidation Settlement under Progressive Loading

Location	Stress Range (kN/m^2)	Mean Settlement (mm)	Standard Deviation (mm)	COV (%)
Palm Grove Estate	50–100	26.75	3.06	11.44
	100–200	42.5	6.11	14.38
	200–400	61	8.08	13.25
	400–800	84	14.22	16.93

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Location	Stress Range (kN/m^2)	Mean Settlement (mm)	Standard Deviation (mm)	COV (%)
GRA Ikeja (1.5 m)	50–100	24.5	4.16	16.98
	100–200	39.5	7.77	19.67
	200–400	55	6	10.91
	400–800	74	7.02	9.49
GRA Ikeja (3.0 m)	50–100	46	4.51	9.8
	100–200	74	7.02	9.49
	200–400	104	15.87	15.26
	400–800	136	2.082	15.31
Shonibare Estate	50–100	29.25	2.08	7.11
	100–200	46	4.51	9.8
	200–400	67	10.07	15.03
	400–800	90	12	13.33

while the calculated coefficients of variation are summarized in Table 7. The COV was computed as

$$COV = \frac{\sigma}{\mu} \times 100 \quad (8)$$

where σ is the standard deviation of settlement and μ is the corresponding mean settlement.

The calculated coefficients of variation ranged from 7.11% to 19.67% across all investigated locations and loading stages. The lowest variability was observed at Shonibare Estate during the 50–100 kN/m² loading interval, where the COV was 7.11%, indicating excellent repeatability of the settlement determinations. Conversely, the highest variability occurred at GRA Ikeja (1.5 m) within the 100–200 kN/m² loading interval, where the calculated COV reached 19.67%. Nevertheless, all calculated coefficients of variation remained below 20%, indicating that the observed variability is consistent with the natural heterogeneity expected in soft cohesive soils and does not compromise the reliability of the experimental results with fall within the range reported by (Phoon, K.-K., & Kulhawy, 1999; Phoon & Kulhawy, 2025); (Löfman & Tanttu, 2025).

Although the absolute standard deviation generally increased with increasing settlement magnitude, the coefficient of variation remained within a relatively narrow range throughout the loading programme. This observation indicates that the increase in standard deviation primarily reflects the larger settlements developed under higher stress levels rather than increased uncertainty in the experimental measurements. Consequently, the relative variability of the settlement predictions remained reasonably stable despite the progressive increase in applied stress.

Comparison of the investigated locations reveals distinct patterns in settlement variability. Palm Grove Estate exhibited COV values ranging from 11.44% to 16.93%, indicating moderate variability throughout the loading programme. The shallow deposit at GRA Ikeja (1.5 m) showed slightly greater variability during the early loading stages, with COV values between 16.98% and 19.67%, before decreasing to 9.49% at the highest loading stage. The deeper GRA Ikeja (3.0 m) deposit demonstrated comparatively stable behaviour, with coefficients of variation ranging from 9.49% to 15.31%, despite producing the largest deterministic settlements. Shonibare Estate exhibited the lowest overall variability, with COV values between 7.11% and 15.03%, suggesting relatively consistent settlement behaviour across the applied loading range.

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The statistical assessment demonstrates that the relative variability of settlement remained modest for all investigated soils. This finding is particularly significant because the deterministic settlement values varied considerably between loading stages and locations, whereas the corresponding COV values remained comparatively uniform. The results therefore indicate that the observed differences in settlement are primarily attributable to the effects of stress level and soil compressibility rather than inconsistencies in the laboratory measurements.

From an engineering perspective, the Statistical characterization provides additional insight beyond deterministic settlement analysis by quantifying the uncertainty associated with the predicted settlement values. Rather than interpreting settlement as a single fixed quantity, the statistical descriptors define the range within which settlement is likely to occur under the investigated loading conditions. Such information is valuable for foundation design because it enables engineers to evaluate not only the expected magnitude of settlement but also the confidence that may be placed in the predicted response.

The Statistical assessment confirms the robustness of the experimental programme. The relatively low coefficients of variation obtained across all investigated locations demonstrate good repeatability of the laboratory measurements and indicate that the experimentally derived consolidation parameters provide a reliable basis for settlement prediction in the investigated soft soils. The statistical characterization presented herein therefore complements the deterministic analysis and enhances the interpretation of consolidation behaviour by explicitly accounting for the inherent variability associated with geotechnical materials.

3.7 Engineering Implications for Foundation Design on Soft Lagos Soils

The consolidation characteristics obtained in this study have important implications for the design and performance assessment of shallow and deep foundations constructed on soft cohesive soils within Lagos. The experimentally determined consolidation parameters demonstrate that the investigated soils exhibit moderate to high compressibility, low hydraulic conductivity, and progressive settlement under increasing effective stress. (Otuoze et al., 2021) equally stated that these characteristics indicate that post-construction settlement should be considered explicitly during foundation design, particularly for structures subjected to sustained service loads.

The measured coefficients of volume compressibility decreased systematically with increasing effective stress, while the corresponding settlements increased throughout the loading programme. This behaviour demonstrates that settlement prediction cannot be based solely on compressibility parameters. Rather, reliable settlement assessment requires simultaneous consideration of the coefficient of volume compressibility, the applied effective stress increment, and the thickness of the compressible soil layer, as expressed by the one-dimensional consolidation equation. Consequently, foundation design should be based on an integrated evaluation of all governing consolidation parameters rather than relying on a single soil property.

The experimentally determined permeability values, which remained within the order of 10^{-10}–10^{-11}m/s, indicate poor drainage characteristics for the investigated soils. Under field conditions, such low hydraulic conductivity is expected to delay the dissipation of excess pore-water pressure, resulting in gradual consolidation over time rather than immediate settlement following construction. For heavily loaded buildings and infrastructure founded on similar soils, the long-term serviceability performance can therefore be governed by consolidation settlement rather than ultimate bearing capacity alone. Consequently, settlement analysis should form an integral component of geotechnical foundation design for soft Lagos soils. Among the investigated locations, the deeper GRA Ikeja (3.0 m) deposit consistently developed the largest calculated settlements despite exhibiting comparatively lower coefficients of volume compressibility than Shonibare Estate. This observation reinforces the importance of considering the thickness of compressible strata during settlement evaluation. It further demonstrates that deterministic comparison of laboratory compressibility values alone may not adequately represent the actual field settlement response.

The Statistical assessment provides an additional dimension to conventional settlement analysis by explicitly quantifying the variability associated with laboratory-derived settlement predictions. The calculated coefficients of variation, ranging from 7.11% to 19.67%, indicate relatively low to moderate variability across the investigated sites. These results suggest that the experimentally derived settlement values are sufficiently consistent for engineering applications while simultaneously acknowledging the inherent variability associated with natural geomaterials. Incorporating statistical descriptors into settlement evaluation therefore provides engineers with a more realistic representation of expected field behaviour than deterministic values alone.

From a practical design perspective, the findings suggest that foundation selection within the investigated areas should be based not only on bearing capacity requirements but also on anticipated long-term settlement performance. For lightly loaded structures, conventional shallow foundations may remain suitable where predicted settlements satisfy serviceability criteria. However, for heavily loaded buildings or

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structures particularly sensitive to differential settlement, alternative foundation solutions or ground improvement measures may be necessary where excessive long-term consolidation is anticipated. The present study does not evaluate specific foundation systems; rather, it provides experimentally derived consolidation parameters that can support informed geotechnical design decisions for comparable soft soil conditions in Lagos.

Overall, the results demonstrate that combining deterministic consolidation analysis with statistical characterization of settlement variability provides a more comprehensive framework for evaluating foundation performance on soft cohesive soils. This integrated approach enhances confidence in settlement prediction and offers a practical basis for incorporating laboratory-derived consolidation parameters into serviceability-based foundation design.

4.0 Conclusions

This study investigated the consolidation behaviour and settlement characteristics of soft cohesive soils obtained from Palm Grove Estate, GRA Ikeja, and Shonibare Estate in Lagos, Nigeria. One-dimensional consolidation tests were conducted in accordance with ASTM D2435/D2435M to determine the coefficient of volume compressibility (mv), coefficient of consolidation (Cv), coefficient of permeability (k), void ratio (e), and primary consolidation settlement under progressive vertical loading. In addition to conventional deterministic settlement evaluation, a statistical assessment based on the mean, standard deviation, and coefficient of variation (COV) was performed to quantify the variability associated with the experimentally determined settlement values.

The experimental results consistently demonstrated that the investigated soils underwent progressive densification with increasing effective stress. The coefficient of volume compressibility decreased by approximately 60–63% across the investigated loading range, indicating a gradual reduction in soil compressibility as consolidation progressed. Similarly, the coefficient of consolidation decreased by approximately 32–41%, while the calculated permeability reduced by approximately 70–75%. These reductions occurred concurrently with a continuous decrease in void ratio, confirming that progressive loading resulted in reduced pore space, lower hydraulic conductivity, and increased resistance of the soil skeleton to further compression.

Deterministic settlement analysis showed a systematic increase in settlement with increasing applied stress despite the reduction in compressibility. Among the investigated locations, the 3.0 m deposit at GRA Ikeja consistently developed the largest calculated settlements, reaching an average value of 136 mm under the maximum applied loading condition. Palm Grove Estate, GRA Ikeja (1.5 m), and Shonibare Estate recorded corresponding maximum average settlements of 84 mm, 74 mm, and 61mm, respectively. These findings demonstrate that settlement behaviour cannot be interpreted solely from the coefficient of volume compressibility, but must be evaluated by considering the combined influence of compressibility, effective stress increment, and the thickness adopted for settlement calculations.

The statistical characterization of settlement variability demonstrated that the calculated coefficients of variation ranged from 7.11% to 19.67% across all investigated loading stages. These values indicate low to moderate variability in the laboratory-derived settlement predictions, with all calculated COV values remaining below the commonly accepted threshold of 20% for good repeatability in geotechnical laboratory investigations which is also stated by (Phoon, K.-K., & Kulhawy, 1999; Phoon & Kulhawy, 2025). The relatively small variability observed confirms the consistency of the laboratory measurements and provides additional confidence in the experimentally derived consolidation parameters.

An important outcome of this investigation is the strong internal consistency observed among the independently evaluated consolidation parameters. The measured reductions in void ratio corresponded closely with the progressive reductions in compressibility, permeability, and consolidation rate, while the calculated settlement values remained fully consistent with the governing one-dimensional consolidation relationship adopted in this study. Independent verification of the permeability calculations confirmed that the reported values satisfy the theoretical relationship of equation (6)
while the settlement calculations were found to be consistent with equation (7)
using the representative layer thickness adopted in the study. This agreement between the measured laboratory parameters and the governing consolidation equations enhances confidence in the reliability and internal consistency of the experimental dataset.

From an engineering perspective, the results indicate that the investigated soils possess relatively low permeability, moderate to high compressibility, and appreciable long-term settlement potential under increasing structural loading. These characteristics highlight the importance of performing comprehensive settlement analyses during foundation design for structures founded on similar soft cohesive soils within the investigated areas. The findings further demonstrate that satisfactory assessment of foundation performance

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requires simultaneous consideration of soil compressibility, drainage characteristics, applied loading, and compressible layer thickness rather than reliance on a single consolidation parameter.

The principal scientific contribution of this study lies in integrating experimentally determined consolidation parameters with a statistical characterization of settlement variability using only laboratory-derived data. Unlike conventional consolidation studies that report single deterministic settlement values, the present work demonstrates that uncertainty in settlement prediction can be quantified through the combined use of the mean, standard deviation, and coefficient of variation without requiring additional field instrumentation. This approach provides a practical framework for improving confidence in settlement prediction while remaining readily applicable to routine geotechnical investigations.

Although the present investigation was limited to three representative locations within Lagos, the methodology developed in this study can be applied to similar soft cohesive soil deposits where reliable laboratory consolidation data are available. Future research should extend this framework by incorporating a larger number of sampling locations, additional geological formations, and field monitoring data to validate the laboratory-derived settlement predictions under actual foundation loading conditions. Integration of the present methodology with reliability-based design approaches and Statistical analysis would further enhance its application in modern geotechnical engineering practice.

This study demonstrates that integrating deterministic consolidation analysis with statistical characterization of settlement variability provides a more comprehensive interpretation of consolidation behaviour than deterministic analysis alone. The proposed framework improves the assessment of both the expected magnitude of settlement and the associated uncertainty, thereby providing engineers with a more robust basis for serviceability-based foundation design on soft cohesive soils in rapidly developing urban environments.

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