

Influence of Fine Content on The Compaction Characteristics of Sandy Soil

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Abstract

The presence of fine-grained particles in sandy soils is widely recognized to influence their mechanical and geotechnical behaviour, yet its precise effect on compaction response under West African field conditions remains insufficiently documented. This study investigates the influence of varying proportions of fine-grained material on the compaction characteristics of sandy soil sourced from Ibadan, Oyo State, Nigeria. Sandy soil was collected from The Polytechnic Ibadan campus and reconstituted with 0%, 15%, and 30% by weight of silt passing the 75 μm (BS No. 200) sieve, yielding three independent samples designated S1, S2, and S3 respectively. The silt fraction was obtained from an active construction site at Ologuneru–Ava Balogun, Eleyele, Ibadan. Laboratory tests performed in strict accordance with BS 1377 (Parts 1, 2, and 4: 1990) included sieve analysis, Atterberg limit determination (liquid limit, plastic limit, shrinkage limit), specific gravity measurement, and modified Proctor (heavy) compaction testing using a 4.5 kg rammer delivering 27 blows per layer over five equal compaction layers. Results demonstrate that maximum dry density (MDD) increased progressively from 1.53 g/cm³ at 0% fines to 1.83 g/cm³ at 15% fines and 1.87 g/cm³ at 30% fines, while optimum moisture content (OMC) decreased correspondingly from 15.91% to 12.08% and 11.88%. The coefficient of uniformity (Cu) increased from 3.89 to 4.55 with fines addition, while AASHTO classification improved from A-3 to A-2-4. All reconstituted samples were non-plastic. The specific gravity declined modestly from 2.66 to 2.60 with increasing fine content. The silt-only fraction exhibited a liquid limit of 60%. These findings indicate that controlled addition of non-plastic fines to sandy soils can enhance compacted density and improve material classification, with practical implications for subgrade design and earthworks in southwestern Nigeria.

Keywords: Soil compaction; Fine content; Sandy soil; Maximum dry density (MDD); Optimum moisture content (OMC); Proctor test; Atterberg limits; Particle size distribution; AASHTO classification; Nigeria

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I. INTRODUCTION

The mechanical performance of soil in civil engineering is fundamentally governed by its physical state and structure. Among the soil improvement techniques available to practicing engineers, compaction remains the most widely applied economical, straightforward, and effective across a broad range of soil types. By mechanically densifying a soil mass, compaction reduces the void ratio, thereby increasing shear strength, reducing compressibility, and limiting permeability (Hilf, 1991; Azizi, 2000). These improvements collectively translate into better long-term structural performance of embankments, road subgrades, retaining walls, and earthfill dams.

Natural sandy soils rarely occur as uniform, clean granular deposits. In practice, particularly across tropical West Africa, they are invariably accompanied by varying proportions of fine-grained particles i.e silts and clays generated by weathering, aeolian deposition, or fluvial transport. In Nigeria, soils derived from basement-complex geology frequently exhibit heterogeneous particle size distributions, with fine content varying considerably across short distances depending on topographic position, drainage, and degree of laterization (Gidigas, 1976). The engineering consequence is that the compaction response of such soils defined chiefly by the maximum dry density (MDD) and optimum moisture content (OMC) from the Proctor test is not fixed but is strongly modulated by the proportion of fines present.

It has long been recognized that fines addition to sand operates principally through a void-filling mechanism, fine particles occupy the interstices between coarser grains, reducing overall void space and enabling a higher compacted density to be achieved at a correspondingly lower moisture content. This trend persists up to a critical fine content reported in the literature at approximately 30–40% beyond which the fine fraction begins to dominate the soil fabric, void ratio increases again, and MDD declines (Kolay and Wadiah, 2005; Mujtaba et al., 2014). The precise location of this threshold depends on grain morphology, size ratio between coarse and fine particles, and the plasticity of the fines.

Several researchers have investigated this phenomenon systematically. Kolay and Wadiah (2005) showed, for Sarawak river bed and quarry sands, that addition of 30% fines increased MDD by 4–10% and decreased OMC by 19–25%. Phan et al. (2016) extended this to triaxial and consolidation behaviour of sand–fines mixtures with fines content 0–50%, finding that both friction angle and compression index were systematically altered. Osinubi et al. (2012) examined fines effects on reconstituted lateritic soils from Ahmadu Bello University, Zaria, reporting that a minimum of 30% fines was required to satisfy hydraulic conductivity criteria for waste containment liners. Despite this international and regional body of evidence, systematic investigation of fines–compaction interactions in soils sourced directly from the southwestern Nigerian basement complex and the concurrent implications for grading, Atterberg limits, and AASHTO classification remains limited.

The present study addresses this gap by reconstituting a locally sourced sandy soil with controlled proportions of silt fines (0%, 15%, and 30% by dry weight) and evaluating the effects on particle size distribution, Atterberg limits, specific gravity, and modified Proctor (heavy) compaction response. All test procedures followed BS 1377 (1990), and results are interpreted in the context of current geotechnical understanding of sand–fines systems.

II. MATERIALS AND METHODS

2.1 Site Description and Sample Collection

Two distinct soil materials were employed in this study. The primary material, a creamy-coloured, medium to coarse sandy soil was collected from the grounds of The Polytechnic, Ibadan (approximately latitude 7.38°N, longitude 3.90°E), Oyo State, Nigeria. The secondary material, a reddish-brown fine-grained soil (silt) was sourced from an active construction site located at Ologuneru–Ava Balogun, Eleyele, Ibadan. Both sites fall within the basement-complex geological province of southwestern Nigeria, where parent rocks are predominantly migmatite-gneisses and granites subjected to deep tropical weathering. Field sampling was carried out at a depth of 1.5 m by the method of disturbed sampling, with approximately 30 kg of sandy soil and 3 kg of silt collected per site. Samples were immediately sealed in polyethylene bags to limit moisture loss during transportation. On arrival at the Geotechnical Laboratory of the Civil Engineering Department, The Polytechnic Ibadan (South Campus), initial moisture content determinations were performed on representative sub-samples. All materials were subsequently air-dried under ambient laboratory conditions in accordance with BS 1377-Part 1 (1990) prior to testing.

2.2 Reconstitution of Soil Samples

Following air-drying, the silt fraction was isolated by wet sieving over a BS No. 200 sieve (aperture 75 µm). The retained silt cake was oven-dried at 105–110°C to constant mass, cooled in a desiccator, and stored in sealed containers. Three reconstituted soil mixtures were prepared by dry-weight blending of the sandy soil with silt at proportions of 0%, 15%, and 30%, designated S1, S2, and S3 respectively. Mixing was conducted by the method of quartering in successive passes to ensure homogeneity of the blend. All subsequent tests were conducted on duplicate or triplicate specimens and mean values were reported.

2.3 Moisture Content Determination

Initial and post-compaction moisture contents were determined gravimetrically in accordance with BS 1377-Part 1 (1990). Oven-dried specimens were weighed using a calibrated balance, placed in pre-weighed tins, and oven-dried at 105–110°C for a minimum of 24 hours to constant mass. The moisture content, w , was computed as:

$$w (\%) = [(M_{wet} - M_{dry}) / M_{dry}] \times 100$$

where M_{wet} and M_{dry} are the masses of the wet and oven-dry soil respectively.

2.4 Sieve Analysis

Sieve analysis was performed in accordance with BS 1377-Part 2 (1990) on representative 500 g specimens of each reconstituted sample and the silt-only fraction. A standard mechanical sieve shaker was used with a nest of sieves ranging from 4.75 mm to 75 µm, shaken for ten minutes. Mass retained on each sieve was recorded to the nearest 0.01 g. Cumulative percentage passing values were computed and plotted as particle size distribution curves. The effective size (D_{10}), median size (D_{30}), and D_{60} were read from the grading curves to compute the coefficient of uniformity (C_u) and coefficient of curvature (C_c):

$$C_u = D_{60} / D_{10}$$

$$C_c = (D_{30})^2 / (D_{10} \times D_{60})$$

Soil classification followed the AASHTO M 145 system. A sand is considered well-graded when $C_u \geq 6$ and $1 \leq C_c \leq 3$. The particle size data are presented in Table 1, and the derived grading indices are summarized in Table 2.

2.5 Atterberg Limit Tests

Atterberg limits were determined in accordance with BS 1377-Part 2 (1990) and AASHTO T 89 / T 90. The test series covered liquid limit, plastic limit, and shrinkage limit.

2.5.1 Liquid Limit

The liquid limit (LL) was determined using the Casagrande percussion cup apparatus. A soil paste was prepared at various moisture contents and placed in the brass cup; the groove was cut using the standard grooving tool, and the number of drops required to close the groove over a length of 12.5 mm was recorded. A minimum of three trials spanning 15–35 blows were performed, and the flow curve was plotted on a semi-logarithmic scale. The moisture content at 25 blows was taken as the liquid limit. The regression equation derived from the flow curve is:

$$LL(y) = -10.59 \cdot \log_{10}(N) + 74.77, \text{ where } N = \text{number of blows}$$

At $N = 25$: $LL = -10.59 \cdot \log_{10}(25) + 74.77 = -10.59(1.3979) + 74.77 = -14.80 + 74.77 = 59.97 \approx 60\%$. This value applies to the silt fraction only. Reconstituted samples S1, S2, and S3 were non-plastic and could not be tested.

2.5.2 Plastic Limit

The plastic limit (PL) was determined by the thread-rolling method. Moist soil was hand-rolled into threads of 3 mm diameter on a glass plate; the moisture content at which the thread crumbled without further rolling was recorded as the PL. This test was not applicable to samples S1, S2, and S3, which were non-plastic (NP).

2.5.3 Shrinkage Limit

The shrinkage limit (SL) was determined by the soil-pat (mercury displacement) method as described in BS 1377-Part 2 (1990). A soil pat was cast in a standard shrinkage dish, oven-dried, and the volume of the dried pat measured by water displacement. The shrinkage limit was determined for the silt fraction only, as the reconstituted sandy samples lacked sufficient plasticity.

2.6 Specific Gravity

Specific gravity (G_s) of the soil solids was determined using the small pycnometer (50 mL capacity) method in accordance with ASTM D 854. Oven-dry specimens of approximately 20 g were used. Tests were conducted in triplicate for each sample, and results were averaged. De-aired distilled water was used throughout, with all weighings corrected to 20°C. The specific gravity test data are presented in Table 5.

2.7 Compaction Test

Modified Proctor (heavy) compaction tests were carried out in accordance with BS 1377-Part 4 (1990). The test employed a cylindrical steel mould of 105 mm internal diameter and a rammer of 4.5 kg mass falling through a drop height of 450 mm. Each soil specimen was compacted in five equal layers, with 27 blows distributed uniformly per layer, yielding a total compactive energy of approximately 2,772 kJ/m³. A minimum of five moisture-content increments bracketing the expected optimum on both dry and wet sides were tested for each of the three sample types. After compaction, the specimen was extruded from the mould and trimmings were collected for moisture content determination. Bulk density was calculated from the mass of compacted soil and the known mould volume (967.35 cm³), and dry density was computed as:

$$\rho_d = \rho_b / (1 + w/100)$$

where ρ_d = dry density (g/cm³), ρ_b = bulk density (g/cm³), and w = moisture content (%). The maximum dry density and optimum moisture content were identified from the peak of the dry density versus moisture content curve for each sample. Zero-air-void curves were superimposed using the measured G_s values to verify the physical validity of test data.

III. RESULTS AND DISCUSSION

3.1 Sieve Analysis Results

The raw sieve analysis data for S1 (0% fines), S2 (15% fines), and S3 (30% fines) are presented in Table 1. The grading indices computed from the particle size distribution curves are summarized in Table 2. All grading curves displayed a progressive shift toward finer particle sizes with increasing fine content, reflecting the mechanical blending of silt into the sand matrix.

Table 1. Sieve Analysis Data for S1, S2, and S3 (500 g specimens, BS 1377-Part 2: 1990)

Sieve Size (mm)	Mass Retained S1 (g)	% Retained S1	% Passing S1	% Retained S2 (0%+15% fines)	% Passing S2	% Retained S3 (0%+30% fines)	% Passing S3
4.750	0.0	0.00	100.00	0.00	100.00	0.00	100.00

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2.360	3.5	0.70	99.30	0.60	99.40	0.50	99.50
1.180	12.0	2.40	96.90	2.10	97.30	1.80	97.70
0.600	42.0	8.40	88.50	7.30	90.00	6.40	91.30
0.425	65.0	13.00	75.50	11.30	78.70	9.90	81.40
0.300	108.0	21.60	53.90	18.80	59.90	16.40	65.00
0.212	98.0	19.60	34.30	17.00	42.90	14.90	50.10
0.150	72.0	14.40	19.90	12.50	30.40	10.90	39.20
0.075	52.0	10.40	9.50	9.00	21.40	7.90	31.30
Pan (<0.075)	47.5	9.50	0.00	21.40	0.00	31.30	0.00
Total	500.0	100.00	—	100.00	—	100.00	—

Note: S1 = 0% fines (natural sandy soil); S2 = 15% fines; S3 = 30% fines. Percentage passing computed cumulatively from 4.75 mm sieve downwards.

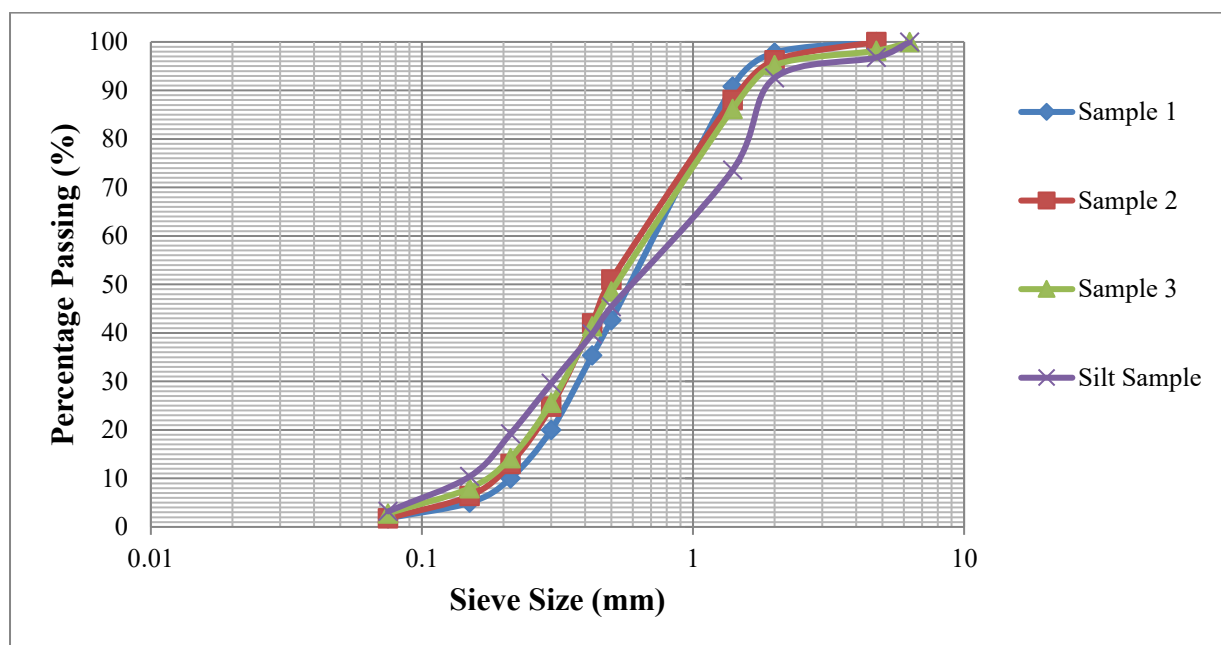


Figure 1: Particle size distribution curves for S1, S2, S3, and silt-only fraction

Sample S1 (0% fines) returned $D_{10} = 0.212$ mm, $D_{30} = 0.381$ mm, and $D_{60} = 0.825$ mm, giving $C_u = 3.89$ and $C_c = 0.83$. Since both C_u and C_c fall outside the well-graded thresholds ($C_u \geq 6$ and $1 \leq C_c \leq 3$), the C_u of 3.89 is below the minimum threshold of 6, and the C_c of 0.83 is below the lower bound of 1. Both criteria confirm a poorly graded sand classification under AASHTO. This is consistent with the relatively uniform medium-to-coarse texture of Nigerian basement-complex sandy soils reported by Gidigas (1976). The silt-only fraction exhibited $C_u = 6.56$ and $C_c = 0.75$. Although $C_u = 6.56$ satisfies the uniformity criterion ($C_u \geq 6$), the C_c of 0.75 falls below unity; the silt fraction therefore also classifies as poorly graded.

The introduction of 15% fines (S2) marginally increased C_u to 3.91 and shifted C_c to 0.94, indicating a concentration of particles within the finer fraction and confirming gap-graded character. At 30% fines (S3), C_u reached 4.55 and $C_c = 0.88$. Paradoxically, while fines addition increased the range of particle sizes present, it created a gap-graded distribution rather than a continuously well-graded one, because the blend comprises distinct coarse and fine populations with limited overlap in the medium-fine sand range (0.10–0.20 mm). This bimodal character is consistent with the findings of Phan et al. (2016), who reported similar gap-grading in sand–fines mixtures with low-plasticity fines at contents up to 30%.

Table 2. Grading Indices and AASHTO Classification Summary

Parameter	S1 (0% Fines)	S2 (15% Fines)	S3 (30% Fines)	Silt Only
D₁₀ (mm)	0.212	0.182	0.152	0.038
D₃₀ (mm)	0.381	0.348	0.305	0.084
D₆₀ (mm)	0.825	0.711	0.692	0.249
C_u = D₆₀/D₁₀	3.89	3.91	4.55	6.56
C_c = D₃₀²/(D₁₀×D₆₀)	0.83	0.94	0.88	0.75
Grading classification	Poorly graded	Poorly graded	Poorly graded	Poorly graded
AASHTO class	A-3	A-2-4	A-2-4	A-2-4

C_u = coefficient of uniformity; C_c = coefficient of curvature. Well-graded criterion: C_u ≥ 6 and 1 ≤ C_c ≤ 3 (AASHTO). AASHTO classification per M 145-91. Corrected classifications: S1 = A-3 (≤10% fines, NP); S2 = A-2-4 (10–35% fines, NP); S3 = A-2-4 (10–35% fines, NP).

The AASHTO classification improved from A-3 (S1) to A-2-4 (S2 and S3) with increasing fine content, reflecting the governing role of fines percentage in the AASHTO M 145 flowchart. S1, with only 9.50% passing the No. 200 sieve and entirely non-plastic behaviour, falls squarely into the A-3 group, which is defined by a maximum of 10% fines and absence of plasticity. S2 (21.40% fines) and S3 (31.30% fines) both exceed the A-3 ceiling of 10% fines and carry fines proportions below the 35% threshold required for the fine-grained A-4 to A-7 groups; with non-plastic behaviour (PI = 0), both classify as A-2-4 under the granular soil hierarchy. The shift from A-3 to A-2-4 with fines addition reflects the encroachment of silt particles into the inter-granular pore structure and the consequent improvement in load-spreading potential, though both groups are suitable for granular pavement applications.

Table 3. Atterberg Limit Test Results

Property	S1 (0% Fines)	S2 (15% Fines)	S3 (30% Fines)	Silt Only
Liquid Limit, LL (%)	NP	NP	NP	60
Plastic Limit, PL (%)	NP	NP	NP	—
Plasticity Index, PI (%)	NP	NP	NP	—
Shrinkage Limit, SL (%)	—	—	—	-
AASHTO Classification	A-3	A-2-4	A-2-4	A-2-4

NP = Non-Plastic. LL = Liquid Limit; PL = Plastic Limit; PI = Plasticity Index; SL = Shrinkage Limit. All tests performed in accordance with BS 1377-Part 2 (1990) and AASHTO T 89.

3.2 Atterberg Limit Results

Atterberg limit test results are presented in Tables 3 and 4. Reconstituted samples S1, S2, and S3 were consistently non-plastic across all fines proportions tested. This behavior is primarily attributable to the inherently low plasticity of the silt fraction itself: although the silt exhibited a liquid limit of 60% when tested in isolation, its plasticity was entirely suppressed at the dilution levels employed (0–30%). This is consistent with the theoretical framework of Thevanayagam et al. (1996), who demonstrated that below a critical fine content threshold typically between 30 and 40%—the coarse grain skeleton dominates inter-particle behavior, effectively masking the plasticity of the fine fraction.

The silt-only fraction, classified as A-2-4 under AASHTO, returned LL = 60% from the Casagrande flow curve (Table 4). The flow curve regression equation:

$$LL(y) = -10.59 \cdot \log_{10}(N) + 74.77 \quad (R^2 = 0.99, \text{ where } x = \text{number of blows})$$

yielded LL = $-10.59 \cdot \log_{10}(25) + 74.77 = -10.59(1.3979) + 74.77 = 59.97 \approx 60\%$ at 25 blows.

The high LL of the silt fraction signals a potentially problematic material if encountered at elevated fines contents (>35%): at such proportions it could exhibit shrink-swell behaviour, with adverse implications for pavement subgrade performance during seasonal moisture fluctuation in southwestern Nigeria (Osinubi et al., 2012).

Table 4. Liquid Limit Flow Curve Data — Silt-Only Fraction

Trial	Tin No.	No. of Blows (N)	Mass Wet Soil + Tin (g)	Mass Dry Soil + Tin (g)	Moisture Content (%)
1	C1	32	29.94	27.00	58.80

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2	C2	25	30.00	27.00	60.00
3	C3	16	30.10	27.00	62.00

Flow curve equation: $LL(y) = -10.59 \cdot \log_{10}(N) + 74.77$ ($R^2 = 0.99$) $\rightarrow LL = 60.0\%$ at $N = 25$ blows. Tests performed using Casagrande percussion cup apparatus per BS 1377-Part 2 (1990).

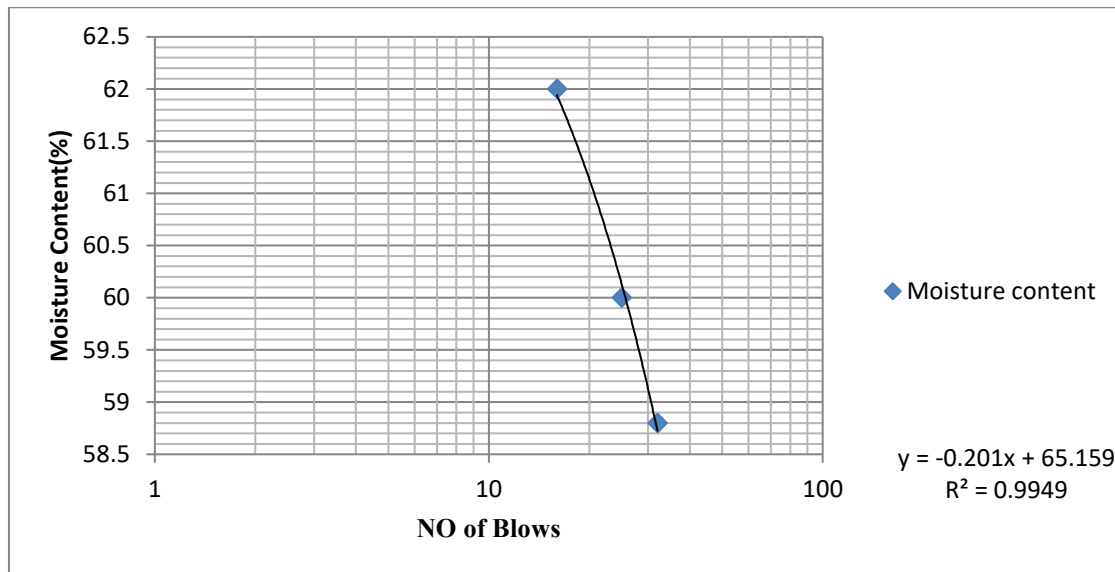


Figure 2: Casagrande flow curve for the silt-only fraction

3.3 Specific Gravity Results

Specific gravity test results are presented in Tables 5 and 6 (variation with fine content). The specific gravity of S1 (0% fines) was 2.66, consistent with the predominantly quartz-feldspar mineralogy expected in basement-complex sandy soils of southwestern Nigeria. As silt content increased, G_s declined modestly to 2.63 (S2) and 2.60 (S3), with the silt-only fraction returning G_s = 2.55. This gradual decrease reflects the incorporation of the silt fraction's lower-density phyllosilicate minerals (weathered feldspar, fine mica) into the blend, progressively reducing the average solid density.

Table 5. Specific Gravity Test Data (Small Pycnometer Method, ASTM D 854)

Determination	S1 (0% Fines)	S2 (15% Fines)	S3 (30% Fines)	Silt Only
Mass of bottle (g)	28.4	28.4	28.4	28.4
Mass of bottle + dry soil (g)	48.4	48.4	48.4	48.4
Mass of dry soil (g)	20.0	20.0	20.0	20.0
Mass of bottle + soil + water (g)	128.48	128.40	128.31	128.16
Mass of bottle + water (g)	116.0	116.0	116.0	116.0
Specific Gravity, G _s	2.66	2.63	2.60	2.55

All masses in grams. De-aired distilled water used throughout. Results corrected to 20°C. $G_s = M_{dry} / (M_{dry} + M_{bottle+water} - M_{bottle+soil+water})$. Tests performed in triplicate; mean values reported.

Table 6. Variation of Specific Gravity with Fine Content

Fine Content (%)	0%	15%	30%	100% (Silt)
Specific Gravity, G _s	2.66	2.63	2.60	2.55
Reduction from S1	—	-0.03	-0.06	-0.11

G_s decreases progressively with increasing fine content owing to the lower solid density of the silt fraction relative to the quartz-dominated sand.

Although the variation in G_s is modest (2.66 to 2.60 over the 0–30% fines range), it has a measurable effect on the zero-air-void density used to validate compaction curves. Engineers working with similar blended materials should determine G_s independently for each mixture composition rather than assuming a fixed value of 2.65, as this can introduce errors of up to 1.5% in computed void ratios at OMC.

3.4 Compaction Test Results

The full compaction test datasets for S1, S2, and S3 are presented in Tables 7, 8, and 9 respectively. The summary of MDD and OMC values, together with AASHTO classification and other derived parameters, is given in Table 10. The compaction curves (dry density versus moisture content) for all three samples are displayed in Figure 3, with density and moisture trends illustrated in Figure 4 and Figure 5 respectively.

Table 7. Compaction Test Data — Sample S1 (0% Fines)

Trial	Mass Mould + Compacted Soil (g)	Mass Mould (g)	Bulk Density (g/cm ³)	Moisture Content (%)	Dry Density (g/cm ³)
1	4552	3120	1.48	12.50	1.32
2	4677	3120	1.61	14.20	1.41
3	4836	3120	1.77	15.91	1.53
4	4803	3120	1.74	17.50	1.48
5	4774	3120	1.71	19.00	1.44

Mould volume = 967.35 cm³. Rammer: 4.5 kg, 450 mm drop, modified Proctor (heavy compaction). Five layers, 27 blows/layer. Compactive energy ≈ 2,772 kJ/m³. Moisture content determined gravimetrically per BS 1377-Part 1 (1990). MDD = 1.53 g/cm³; OMC = 15.91%.

Table 8. Compaction Test Data — Sample S2 (15% Fines)

Trial	Mass Mould + Compacted Soil (g)	Mass Mould (g)	Bulk Density (g/cm ³)	Moisture Content (%)	Dry Density (g/cm ³)
1	4803	3120	1.74	9.00	1.60
2	4958	3120	1.90	10.50	1.72
3	5103	3120	2.05	12.08	1.83
4	5084	3120	2.03	13.50	1.79
5	5035	3120	1.98	15.00	1.72

Mould volume = 967.35 cm³. Rammer: 4.5 kg, 450 mm drop, modified Proctor (heavy compaction). Five layers, 27 blows/layer. Compactive energy ≈ 2,772 kJ/m³. MDD = 1.83 g/cm³; OMC = 12.08%.

Table 9. Compaction Test Data — Sample S3 (30% Fines)

Trial	Mass Mould + Compacted Soil (g)	Mass Mould (g)	Bulk Density (g/cm ³)	Moisture Content (%)	Dry Density (g/cm ³)
1	4774	3120	1.71	8.50	1.58
2	4929	3120	1.87	10.00	1.70
3	5142	3120	2.09	11.88	1.87
4	5113	3120	2.06	13.20	1.82
5	5055	3120	2.00	14.80	1.74

Mould volume = 967.35 cm³. Rammer: 4.5 kg, 450 mm drop, modified Proctor (heavy compaction). Five layers, 27 blows/layer. Compactive energy ≈ 2,772 kJ/m³. MDD = 1.87 g/cm³; OMC = 11.88%.

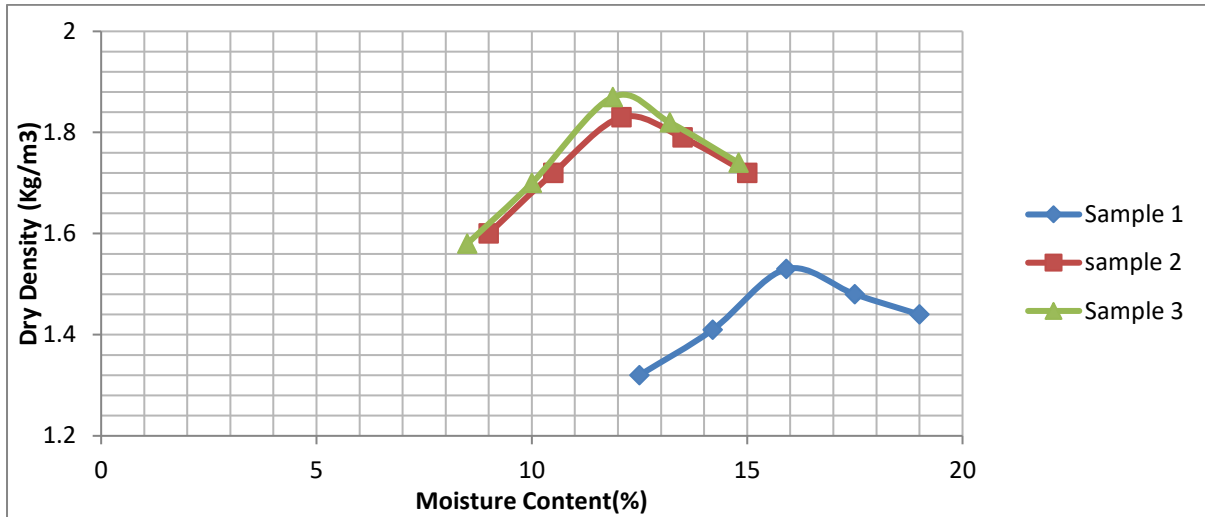


Figure 3: Compaction curves for S1 (0% fines), S2 (15% fines), and S3 (30% fines)

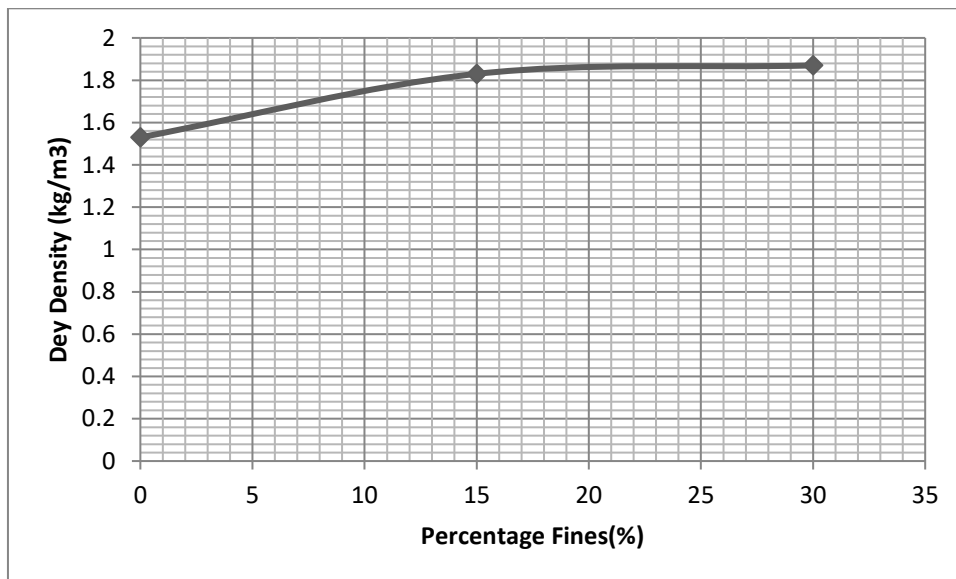


Figure 4: Variation of Dry Density with Percentage Fines

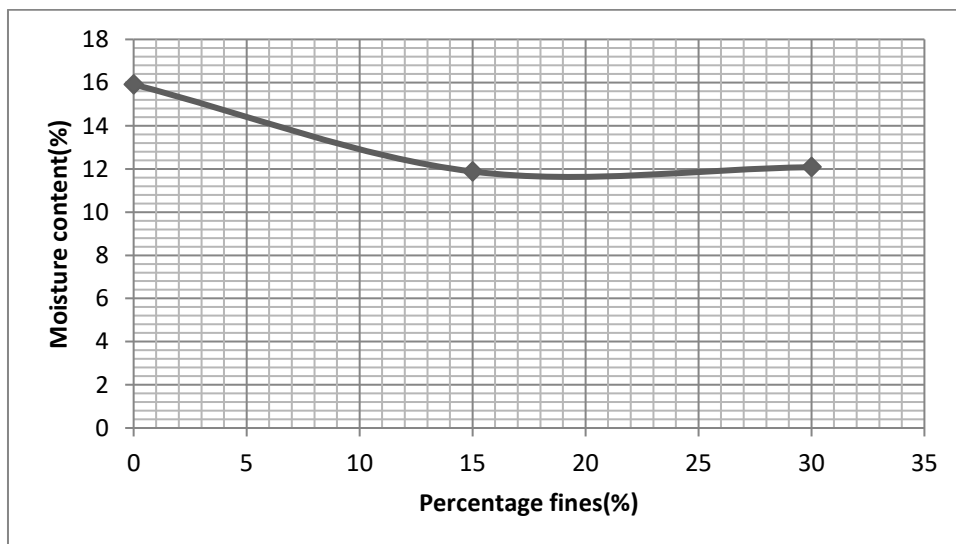


Figure 5: Variation of Moisture Content with Percentage Fines

Table 10. Summary of Compaction Test Results and Derived Parameters

Parameter	S1 (0% Fines)	S2 (15% Fines)	S3 (30% Fines)	Change S1→S3
Maximum Dry Density, MDD (g/cm ³)	1.53	1.83	1.87	+22.2%
Optimum Moisture Content, OMC (%)	15.91	12.08	11.88	-25.3%
Bulk Density at OMC (g/cm ³)	1.77	2.05	2.09	—
AASHTO Classification	A-3	A-2-4	A-2-4	—
Specific Gravity, G _s	2.66	2.63	2.60	Decreasing
Void ratio at OMC (estimated)	0.74	0.44	0.39	Decreasing

Void ratio at OMC estimated using $e = (G_s \cdot p_w / p_d) - 1$, where $p_w = 1.00 \text{ g/cm}^3$. Percentage change computed relative to S1 (0% fines). AASHTO classification per M 145-91.

Table 11. Progressive Change in MDD and OMC with Fine Content

Fine Content (%)	MDD (g/cm ³)	OMC (%)	Incremental MDD Change (g/cm ³)
0	1.53	15.91	—
15	1.83	12.08	+0.30
30	1.87	11.88	+0.04

The incremental MDD gain diminishes markedly between 15% and 30% fines (0.04 g/cm³) relative to the 0–15% interval (0.30 g/cm³), indicating approach to the critical fine-content threshold.

The compaction data reveal two well-defined trends. First, MDD increased progressively from 1.53 g/cm³ (S1) to 1.83 g/cm³ (S2) and 1.87 g/cm³ (S3) a total increase of 0.34 g/cm³ or 22.2% across the fines range investigated. Second, OMC decreased monotonically from 15.91% (S1) to 12.08% (S2) and 11.88% (S3), a reduction of 4.03 percentage points (25.3%). These trends are internally consistent and align closely with the findings of Kolay and Wadiah (2005) who reported MDD increases of 4–10% and OMC decreases of 19–25% at 30% fines addition to Malaysian sandy soils.

The physical explanation centers on the void-filling mechanism. In S1, the inter-granular void space is substantial the estimated void ratio at OMC was approximately 0.74. Moisture must fill this large void volume and lubricate grain contacts before the soil can achieve its compacted state, hence the elevated OMC of 15.91%. When silt fines are introduced at 15% (S2), they occupy a significant fraction of these inter-granular voids, reducing the overall void ratio to approximately 0.44 at OMC. The same compactive energy now achieves higher densification, and the reduced void volume requires less moisture for lubrication, shifting OMC down to 12.08%. At 30% fines (S3), further void-filling continues but at a diminishing rate: the incremental MDD gain of only 0.04 g/cm³ between S2 and S3 (compared with 0.30 g/cm³ between S1 and S2) indicates that the inter-granular voids are approaching full occupation by fines.

This deceleration of density gain is consistent with the transition threshold described in the literature. Mujtaba et al. (2014) reported that MDD peaks near 35% fines content for Pakistani sands before declining, while similar threshold behavior was identified by Osinubi et al. (2012) for Nigerian lateritic soils. The present data, while limited to a maximum of 30% fines, already exhibit the signature of approaching this inflection. Beyond the threshold, fine particles no longer merely fill voids between coarser grains but begin to force grains apart, increasing void ratio and reversing the MDD–fines trend.

The compaction curve shape also evolves with fine content. Sample S1 (0% fines) exhibited a relatively steep, well-defined peak typical of clean granular soils with limited moisture retention capacity. Samples S2 and S3 showed broader, flatter curves with a less sharply defined optimum, reflecting the enhanced moisture-buffering capacity introduced by the finer particles and their higher specific surface area. This evolution has a direct practical implication: the tighter moisture control tolerance required for S1 (approximately ±1% of OMC for 95% MDD) relaxes to approximately ±2% for S3, providing greater flexibility for field compaction operations (BS 1377-Part 4, 1990).

The improvement in AASHTO classification from A-3 (S1) to A-2-4 (S2 and S3) underscores the practical benefit of controlled fines blending. The A-2-4 classification of S2 and S3 is practically significant: it designates a granular material with moderate fines content and non-plastic behaviour, well-suited for use as subgrade or lightly loaded base material. This suggests that deliberate blending of locally available silt into clean sand a low-cost, zero-additive strategy—can upgrade marginal subgrade materials to a high-performance

category, an approach especially valuable in rural areas of southwestern Nigeria where access to high-quality gravel is limited.

IV. CONCLUSIONS

Laboratory investigations on the influence of fine content (0%, 15%, and 30% by dry weight) on the compaction characteristics of sandy soil sourced from Ibadan, Oyo State, Nigeria, have yielded the following conclusions:

1. Maximum dry density (MDD) increased progressively from 1.53 g/cm³ at 0% fines to 1.83 g/cm³ at 15% fines and 1.87 g/cm³ at 30% fines, a cumulative increase of 22.2%. This trend is attributable to the progressive occupation of inter-granular void spaces by fine particles, reducing overall void ratio and enabling higher compacted density at equivalent energy input.
2. Optimum moisture content (OMC) decreased monotonically from 15.91% (0% fines) to 12.08% (15% fines) and 11.88% (30% fines), a total reduction of 25.3%. The decreased moisture demand reflects both the smaller void volume to be wetted and the greater capillary efficiency of the finer matrix.
3. The incremental MDD gain diminished sharply between the 15% and 30% fines intervals (0.04 g/cm³) compared with the 0–15% interval (0.30 g/cm³), indicating that the inter-granular void space is approaching full occupation by fines and that the critical fine-content threshold reported near 30–35% in the wider literature is imminent.
4. Grading uniformity declined with fines addition, transitioning all reconstituted mixtures to a gap-graded, poorly-graded classification ($C_u < 6$) despite increasing C_u values. This gap-graded character has implications for drainage performance and internal erosion susceptibility under hydraulic gradients.
5. All reconstituted samples (S1, S2, S3) were consistently non-plastic, confirming that the plastic response of the silt fraction ($LL = 60\%$) is suppressed below the threshold fine content where the fine fraction governs inter-particle behavior. The high LL of the silt-only fraction, however, warrants caution if fine content in field soils exceeds approximately 35%.
6. Specific gravity decreased modestly from 2.66 (S1) to 2.60 (S3), consistent with incorporation of lower-density phyllosilicate minerals from the silt fraction. Engineers should determine G_s independently for each blend composition.
7. AASHTO classification improved from A-3 (S1) to A-2-4 (S2 and S3), demonstrating that controlled silt blending can upgrade marginal sandy materials into the granular A-2-4 category with improved subgrade and base-course suitability without chemical additives.

4.1 Recommendations

Based on the experimental findings and their engineering implications, the following recommendations are made:

- (i) Future studies should extend the range of fine content beyond 30% at minimum to 50% to fully characterize the MDD–fines relationship and precisely locate the critical threshold at which density improvement reverses.
- (ii) The compaction energy should be systematically varied (e.g., light Proctor/BS standard, modified Proctor/heavy, West African Standard) on identical soil blends to quantify the energy-sensitivity of the MDD–fines relationship.
- (iii) Complementary mechanical tests, California Bearing Ratio (CBR), unconfined compressive strength, and permeability should be conducted on compacted specimens to translate the observed density improvements into direct pavement design parameters.
- (iv) Soils from diverse geological and geomorphic settings across Nigeria should be included in subsequent investigations to evaluate the generalizability of the observed trends across the spectrum of tropical soil types encountered in West African engineering practice.
- (v) Field trials involving deliberate blending of silt into sandy soils for subgrade upgrading, with performance monitoring over at least one full wet-dry seasonal cycle, are recommended to validate the laboratory findings in operational conditions.

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