



Structural, Geotechnical, and Traffic-Induced Mechanisms of Early Flexible Pavement Failure: Empirical study of the Ugep–Idomi Highway Strip, Cross River State, Nigeria

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ABSTRACT

The early deterioration of flexible highway pavements is a significant infrastructure issue in tropical developing areas. This research examines the structural, geotechnical, and traffic-related factors that contribute to pavement damage along the Ugep–Idomi road corridor in the Yakurr Local Government Area of Cross River State, Nigeria. Field studies included measuring the structural profile of exposed layers, conducting a six-day manual traffic volume survey, and collecting soil samples at depths of 3.28 ft (1.0 m) and 3.94 ft (1.2 m). Laboratory tests assessed index properties, particle size distribution, Atterberg limits, Modified Proctor compaction, and soaked California Bearing Ratio (CBR) values.

Physical measurements indicated in-situ layer thicknesses of 3.91 in (99.3 mm) for the surface course and 9.35 in (237.6 mm) for the sub-base course. Geotechnical analysis classified the subgrade material as low-plasticity silty clay (AASHTO A-4/A-6), with 59.4% passing the No. 200 sieve, a Liquid Limit of 25.5%, a Plastic Limit of 16.5%, and a Plasticity Index of 6.5%. The Modified Proctor compaction test resulted in a Maximum Dry Density (MDD) of 116.74 lb/ft³ (1.87 g/cm³) at an Optimum Moisture Content (OMC) of 12.5%, while the average soaked CBR was 8.3%. Traffic analysis showed an Average Daily Traffic (ADT) of 13,422 vehicles per day (northbound) and 13,128 vehicles per day (southbound), total 26,550 vehicles per day for the corridor. Structural assessment determined that a minimum sub-base thickness of 13.39 in (340.0 mm) is necessary based on current Equivalent Single Axle Load (ESAL) projections, indicating a structural deficiency of 4.04 in (102.6 mm), or a 30.2% shortfall. Key factors contributing to pavement distress included inadequate sub-base design, high moisture sensitivity of the subgrade, unmanaged capillary rise, heavy commercial traffic, and a complete lack of side drainage infrastructure. Recommendations for restoring the corridor's functionality include chemical stabilization, structural reconstruction using locally sourced high-strength aggregates, and the implementation of integrated drainage systems.

Keywords: Flexible pavement, pavement deterioration, subgrade strength, California bearing ratio (CBR), traffic loads. Road drainage.

INTRODUCTION

Flexible highway pavements are designed as layered structural systems that effectively distribute the loads from vehicle wheels to the underlying subgrade soils, ensuring that the shear strength and deformation limits of all structural components are not exceeded (Justo & Khanna, 2001; Oglesby, 1975). In West Africa, primary transport corridors often experience premature deterioration well before they reach their intended structural lifespan. This rapid decline is attributed to several factors, including insufficient compaction standards, unregulated axle overloads, intense seasonal rainfall, and inadequate surface and subsurface drainage (Bindra, 1982; Cedergren, 1974).

Dynamic loading from vehicles on saturated pavement systems increases hydrodynamic pore water pressures



in granular bases and fine-grained subgrades. This phenomenon accelerates the softening of the subgrade, causes fine particles to be pumped out, reduces inter-particle friction, leads to deep rutting, and ultimately results in the loss of the bituminous surface (Cedergren, 1974; Ola, 1983). The Ugep–Idomi corridor serves as a crucial commercial route in Cross River State, linking agricultural production areas to regional trade networks. The accelerated structural deterioration—evidenced by the complete breakdown of the wearing surface at key intersections—exposes the unbound layers beneath to rapid environmental degradation, prompting the comprehensive structural and geotechnical assessment conducted in this study.

Problem Statement

The significant structural deterioration along the Ugep–Idomi highway raises vehicle operating costs in the region, increases the risk of traffic hazards, and disrupts agricultural supply chains between rural and urban areas. It is essential to identify shortcomings in structural design, geotechnical limitations of the subgrade, and loading conditions to develop effective rehabilitation strategies for this corridor and similar tropical lateritic-subgrade roads in Nigeria.

Aim/Objectives

This research aims to assess the key engineering factors contributing to structural damage along the Ugep–Idomi corridor. The specific goals include:

- 1) Recording the physical patterns of pavement distress and measuring the structural layer profiles in situ;
- 2) Conducting geotechnical laboratory tests on subgrade soils to determine index and engineering parameters according to AASHTO standards;
- 3) Analysing traffic distribution and operational demands;
- 4) Developing engineering strategies related to structure, materials, and drainage to restore the full functionality of the pavement.

Scope and Relevance to Existing Literature

Highway engineering literature (Bindra, 1982; Justo & Khanna, 2001; Oglesby, 1975) provides the theoretical foundation for designing flexible pavement thickness based on subgrade CBR and cumulative ESAL demand. Cedergren (1974) addresses the issue of pavement distress caused by drainage. Ola (1983) explores the geotechnical properties of Nigerian lateritic soils pertinent to subgrade characterization, while Akwa et al. (2026) compare the engineering properties of quarry aggregates in Cross River State. This study combines these established theories with specific field and laboratory data to create a corridor-level assessment and rehabilitation plan for the Ugep–Idomi highway.

MATERIALS AND METHODS

Study Area

The research corridor is situated along the Ugep–Idomi highway in the Yakurr Local Government Area of Cross River State, Nigeria, connecting Idomi and the Ijiman Junction. This route serves as a major pathway for agricultural transport and commercial traffic between communities in the area.

The assessed corridor extends a total length of 2.0 km (6,562 ft), chained continuously from Chainage 0+000 at the Idomi terminus to Chainage 2+000 at the Ijiman Junction terminus. This chainage system provided the common spatial reference used for both the pavement-distress inspection stations (Section 2.2) and the geotechnical sampling stations (Section 2.2), allowing every field observation to be located and reproduced.

Field Reconnaissance and Subsurface Sampling

A comprehensive walkover survey was performed along the full 2.0 km corridor to document the type, severity and extent of pavement distress. Visual condition assessment was carried out at 80 inspection stations spaced at 25 m (82 ft) intervals along the chainage (Chainage 0+000 to 2+000), consistent with the total corridor length reported in Section 2.1. At each station, distress was logged against four defect categories — alligator/fatigue cracking, rutting, potholing, and ravelling/surface disintegration — and rated on a three-point severity scale (slight, moderate, severe) following conventional visual pavement-condition survey practice (Bindra, 1982). Soil samples were collected using a 2.99-inch (76 mm) diameter hand auger at five sampling stations spaced at 1,640 feet (500 m) intervals along the corridor, coinciding with locations of the most advanced surface distress identified during the walkover survey. At each station, samples were recovered from two depths — A1 at 3.28 feet (1.0 m) and A2 at 3.94 feet (1.2 m) — giving a total of ten (10) disturbed soil samples for laboratory testing (Table 1a). All samples were promptly sealed in moisture-proof containers, labelled by station chainage and depth, and transported to the laboratory for analysis.

Table 1a. Geotechnical Sampling Station Locations Along the Ugep–Idomi Corridor (n = 10 samples)

Station	Chainage	Distance from Idomi Terminus	Samples Collected
S1	0+000	0 m (0 ft)	A1 (1.0 m), A2 (1.2 m)
S2	0+500	500 m (1,640 ft)	A1 (1.0 m), A2 (1.2 m)
S3	1+000	1,000 m (3,281 ft)	A1 (1.0 m), A2 (1.2 m)
S4	1+500	1,500 m (4,921 ft)	A1 (1.0 m), A2 (1.2 m)
S5	2+000	2,000 m (6,562 ft)	A1 (1.0 m), A2 (1.2 m)

Five stations at 500 m spacing × two depths (A1, A2) per station = 10 disturbed samples.

Drainage and Capillary Rise Assessment

Surface and sub-surface drainage conditions were assessed qualitatively during the walkover survey described above, based on visual evidence of ponding, saturated subgrade exposure at failure sections, and the complete absence of engineered side drains along the corridor. Capillary rise into the pavement structure was inferred from these visual indicators and from the high fines content and natural moisture range recorded in the subgrade samples (Table 1); no piezometers, water-table observation wells, or other direct capillary-rise instrumentation were installed as part of this study. This is stated explicitly as a scope limitation of the present assessment, and instrumented sub-surface moisture and water-table monitoring is recommended as a direction for future research (see Recommendations).

Geotechnical Laboratory Testing

Laboratory tests were conducted on all ten (10) recovered samples according to standard soil-testing protocols (AASHTO T88 – particle size analysis, T89 – Liquid Limit, T90 – Plastic Limit and Plasticity Index, T99/T180 – Proctor compaction, and T193 – California Bearing Ratio), which included the following procedures:

- Moisture content and specific gravity:** The natural water content was assessed by drying the samples to a constant weight at temperatures between 221–248 °F (105–120 °C). Specific gravity (Gs) was measured using standard pycnometer bottle methods.
- Gradation and Atterberg limits:** Particle size distributions were analysed through wet sieve analysis down to the No. 230 (63 µm) sieve. The Liquid Limit (LL) was determined using the Casagrande mechanical apparatus, while the Plastic Limit (PL) was assessed by rolling a 0.12-inch (3 mm) thread, and the Plasticity Index (PI = LL – PL) was calculated.



c) Compaction and CBR: The moisture-density relationships were established using Modified Proctor compaction with a 9.92 lb (4.5 kg) rammer dropped from a height of 17.72 inches (450 mm). The soaked California Bearing Ratio (CBR) values were obtained through plunger penetration (1.95 inches / 49.6 mm diameter) after a 24-hour soaking period.

Traffic Survey and Layer Measurements

Traffic volume data were gathered through a six-day manual classified count covering 10-hour daily periods (08:00–18:00) in both directions [insert exact survey start and end dates]. Enumerators stationed at the Idomi and Ijiman Junction termini recorded vehicle movements in the field, aggregated into hourly and daily directional volumes as summarised in Table 2. Vehicles were classified into four categories — light utility vehicles/vans, private saloon cars, mass transit buses, and commercial heavy trucks — following standard axle-configuration-based classification. A supplementary classified spot-count sample of 164 vehicles (Table 2b) was additionally used to establish the proportional composition of the traffic stream by class and to assign representative axle-load equivalency factors (LEFs) for conversion of the six-day count into design ESALs (Section 2.5). The thickness of the pavement layers was measured directly at exposed failure cross-sections using calibrated depth gauges, at the same five stations used for soil sampling (Section 2.2, Table 1a).

Structural Analysis Framework

The required thickness of the sub-base was determined using standard flexible pavement design charts, which take into account the anticipated cumulative design traffic loading (measured in Equivalent Single Axle Loads, or ESALs) over a 20-year period, along with the average soaked subgrade California Bearing Ratio (CBR). This follows the traditional AASHTO design methodology (Justo & Khanna, 2001). The deficiency in structural thickness and the percentage shortfall were calculated by comparing the required thickness for design with the actual measured thickness in the field, as detailed in Section 3.

The classified traffic counts obtained in Section 2.4 were first converted to Equivalent Single Axle Loads (ESALs) using standard load-equivalency factors (LEFs) assigned to each vehicle class (Table 2b), and then projected over a 20-year design period following the AASHTO (1993) relationship:

$$ESAL(\text{design}) = ADT \times \%Heavy \times LEF(\text{avg}) \times 365 \times [(1+r)^n - 1]/r \times D \times L$$

where r is the assumed annual traffic growth rate, n is the 20-year design period, D is the directional distribution factor, and L is the lane distribution factor [insert the specific growth rate, directional and lane distribution factors adopted for this corridor]. Applying this procedure to the six-day classified count (Table 2) and the supplementary classification sample (Table 2b) yielded the projected cumulative design traffic loading of 32.2×10^6 ESALs over the 20-year analysis period reported in Section 3.

This cumulative ESAL value, together with the mean soaked subgrade CBR of 8.3% (Table 1), was applied to the AASHTO (1993) flexible-pavement design chart (nomograph) at [insert the design reliability level, overall standard deviation (S_o), and initial/terminal serviceability indices adopted] to obtain the minimum required structural number (SN) and the corresponding minimum sub-base thickness of 13.39 in (340.0 mm) reported in Section 3.

STRUCTURAL ANALYSIS AND CALCULATIONS

The design traffic loading and structural-number derivation summarised below follow the AASHTO (1993) procedure and input basis described in Section 2.5; the specific growth-rate, distribution-factor and reliability assumptions flagged there should be inserted prior to submission so the 32.2×10^6 ESAL figure and the resulting 340.0 mm requirement are fully reproducible.

Field profiling of the cross-section revealed an average actual sub-base course thickness (T_{actual}) of:

$$T_{\text{actual}} = 9.35 \text{ inches (237.6 mm)}$$

With a projected cumulative design traffic loading of 32.2×10^6 ESALs over a 20-year operational timeframe and a mean soaked subgrade CBR of 8.3%, standard flexible pavement design charts indicate that the minimum required sub-base thickness (T_{required}) should be:

$T_{\text{required}} = 13.39$ inches (340.0 mm)

The structural thickness deficiency (ΔT) is calculated as follows:

$\Delta T = \text{Required} - T_{\text{actual}} = 13.39 \text{ inches} - 9.35 \text{ inches} = 4.04 \text{ inches (102.6 mm)}$

The percentage structural shortfall is then calculated as:

$\text{Percentage Shortfall} = (\Delta T / \text{Required}) \times 100 = (4.04 / 13.39) \times 100 = 30.2\%$

This deficiency suggests that the existing sub-base layer is not adequately designed to meet the current traffic demands, providing a quantitative foundation for the distress mechanisms discussed in Section 4.

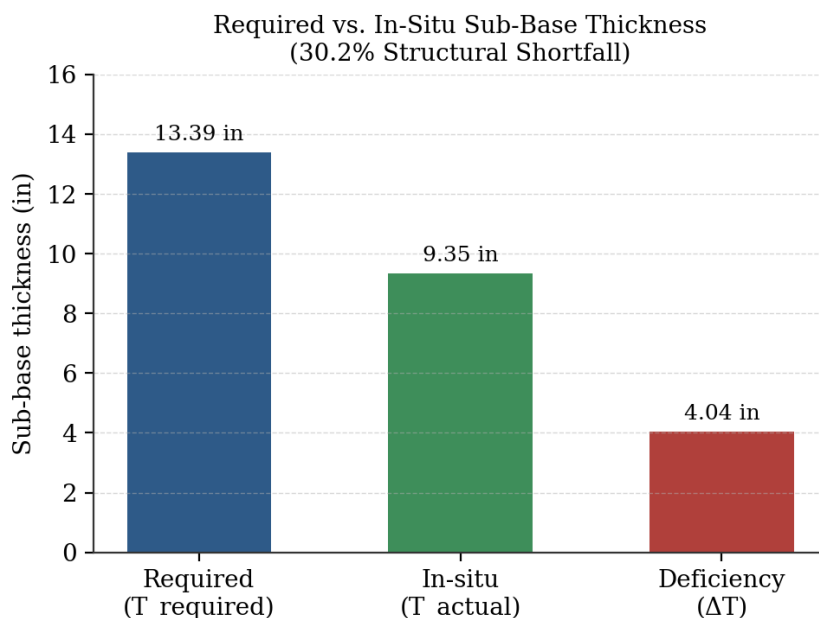


Figure 2. Required versus in-situ sub-base thickness, showing the 30.2% structural deficiency ($\Delta T = 4.04$ in / 102.6 mm).

RESULTS AND DISCUSSION

Geotechnical Subgrade Properties

Laboratory evaluations confirm that the subgrade material exhibits low shear strength and high sensitivity to moisture ingress. Table 1 summarizes the measured geotechnical parameters against their respective design evaluation criteria.

Table 1. Measured Subgrade Geotechnical Properties and Evaluation Criteria

Parameter / Test	Imperial Value	Metric Value	Design Evaluation / Standard
Auger sample depth A1	3.28 ft	1.0 m	Subgrade upper horizon
Auger sample depth A2	3.94 ft	1.2 m	Subgrade lower horizon
Natural moisture content	8.6% – 14.3%	8.6% – 14.3%	In-situ field moisture range



Specific gravity (Gs)	2.75 – 3.04	2.75 – 3.04	Typical lateritic mineral solids
Passing No. 200 sieve	59.40%	59.40%	High fine-grained silty clay content
Liquid Limit (LL)	25.50%	25.50%	Low plasticity response
Plastic Limit (PL)	16.50%	16.50%	Plasticity transition threshold
Plasticity Index (PI)	6.50%	6.50%	Classified as AASHTO A-4 / A-6
Maximum Dry Density (MDD)	116.74 lb/ft ³	1.87 g/cm ³	Modified Proctor standard
Optimum Moisture Content (OMC)	12.50%	12.50%	Ideal compaction target
Mean soaked CBR	8.30%	8.30%	Poor subgrade load-bearing support

Modified Proctor testing yields an MDD of 116.74 lb/ft³ (1.87 g/cm³) at an OMC of 12.5%. The high fine-particle content (59.4% passing the No. 200 sieve) restricts internal drainage, promoting high capillary retention and loss of stability under saturation. This behaviour is consistent with the moisture-sensitive lateritic subgrade profiles reported by Ola (1983) for comparable Nigerian soils, and the low Plasticity Index (6.5%) places the material at the AASHTO A-4/A-6 boundary, indicating marginal but workable subgrade quality that nonetheless requires stabilization under sustained traffic loading.

California Bearing Ratio (CBR) Performance

Plunger penetration resistance tests under soaked conditions indicate severe strength reduction. The mean soaked CBR value of 8.3% falls below standard pavement foundation recommendations for the traffic class observed on this corridor. Under sustained dynamic traffic loading, this low bearing capacity drives subgrade pumping, deep rutting, and secondary top-down cracking, corroborating the pore-pressure-driven failure mechanism described by Cedergren (1974) for saturated flexible pavement systems.

Operational Traffic Analysis

Traffic survey results demonstrate high operational demand along both directions of the corridor over the six-day observation period, as summarized in Table 2.

Table 2. Directional Daily Traffic Volume Distribution (6-Day Survey Period)

Observation Period	Idomi → Ijiman Jct. (veh/day)	Ijiman Jct. → Idomi (veh/day)	Combined Total (veh/day)
Day 1	12,888	12,675	25,563
Day 2	12,504	13,320	25,824
Day 3	13,536	15,168	28,704
Day 4	12,302	11,904	24,206
Day 5	13,368	13,104	26,472
Day 6	15,936	12,600	28,536
Mean ADT	13,422	13,128	26,550

The mean ADT of 26,550 vehicles/day underlines the substantial operational stress placed on the pavement structure. Unmonitored commercial vehicle axle weights further accelerate failure along sections already exhibiting structural thickness deficits, aligning with the ESAL-based structural demand established in Section 3.

Table 2b. Supplementary Vehicle Classification Sample (n = 164 vehicles) — Column Labels Provisional

Vehicle Category	Classified Count (veh)	Metric A	Metric B	Metric C
Commercial Heavy Trucks	32	8.4 months	138.5	45.2
Mass Transit Buses	48	6.2 months	112	32.4
Private Saloon Cars	64	4.1 months	84.5	18.1
Light Utility / Vans	20	5.5 months	96.2	24.6
Composite Average / Total	164	6.05 months	107.8	30.1

“Metric A/B/C” headings are placeholders. The classified-sample values above were supplied for inclusion but their column definitions (e.g., average vehicle service life, axle-load equivalency factor, %ESAL contribution) require the author's confirmation before this table is finalised for submission.

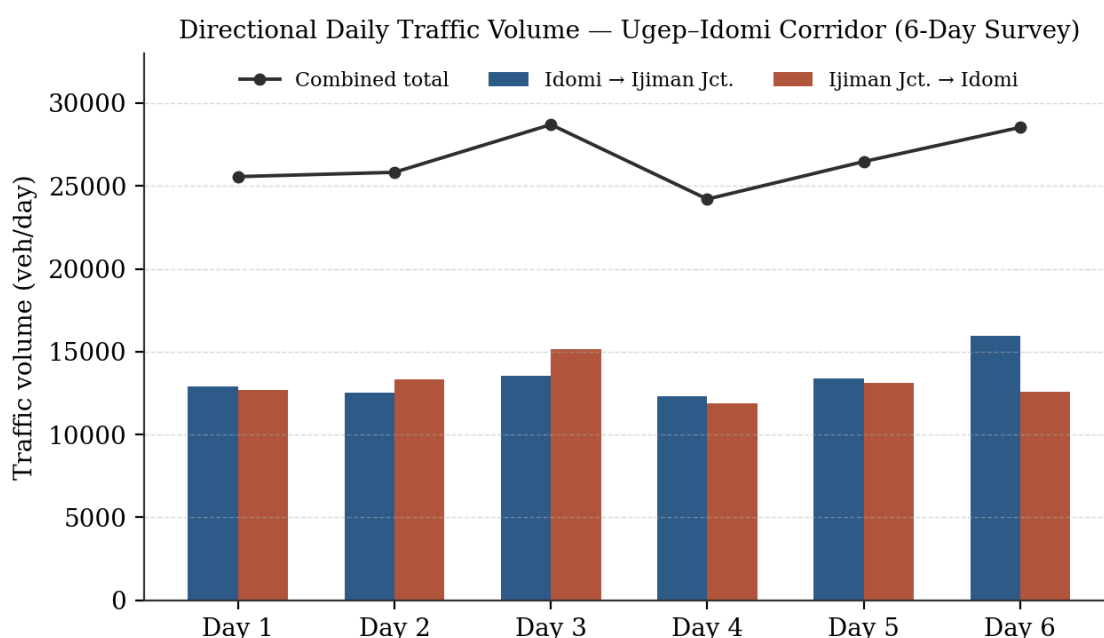


Figure 1. Directional daily traffic volume recorded over the six-day survey period, Ugep-Idomi corridor.

Comparative Regional Material Evaluation

To assess potential sub-base and structural quarry sources for reconstruction, aggregate properties from regional quarry deposits were evaluated against the in-situ subgrade material, following the comparative methodology of Akwa et al. (2026). Results are presented in Table 3.

Table 3. Comparative Engineering Properties of Regional Aggregates versus In-Situ Subgrade

Property / Parameter	Obudu Quarry (Leophina)	Akamkpa Quarry (Obasi)	Ugep-Idomi Subgrade Soil
Specific gravity (Gs)	2.62	2.74	2.75 – 3.04
Water absorption (%)	0.82%	0.45%	12.5% (optimum moisture)
Fine content (< No. 200)	1.10%	2.80%	59.40%
28-day compressive	2,942.8 psi	3,585.3 psi	N/A (unbound subgrade)

strength			
Strength dispersion (CV)	2.70%	0.60%	High in-situ variability
Haulage distance to site	≈115 mi (185 km)	≈53 mi (85 km)	In-situ source

Aggregates sourced from the Akamkpa deposit exhibit superior compressive strength (3,585.3 psi), exceptionally low water absorption (0.45%), and high mechanical consistency (CV = 0.6%). Combined with a significantly shorter haulage distance of 53 mi (85 km) compared to Obudu (115 mi / 185 km), Akamkpa aggregate represents the optimal crushed-stone source for sub-base and base reconstruction on cost and performance grounds alike.

Comparative Regional Aggregate Properties

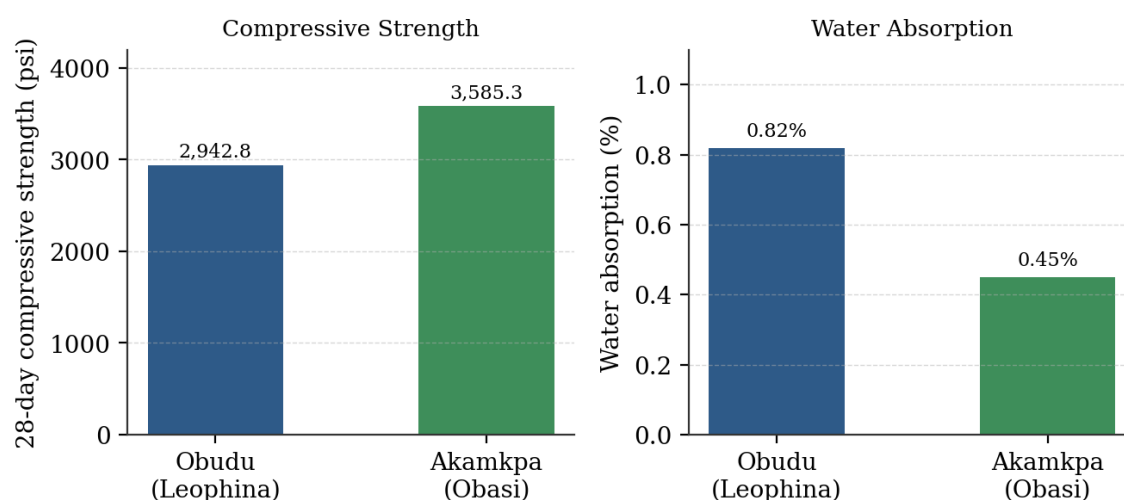


Figure 3. Comparative 28-day compressive strength and water absorption of candidate quarry aggregates.

Synthesis of Distress Mechanisms

The combination of structural, geotechnical, and traffic data reveals a cumulative failure mechanism: an inadequately designed sub-base (Section 3) interacts with a moisture-sensitive, fine-grained subgrade (Sections 4.1–4.2) under continuous heavy traffic loads (Section 4.3) and lacks any side drainage systems. This situation reflects the classic drainage-distress relationship outlined by Cedergren (1974) and aligns with reconstruction practices noted for similar Nigerian routes (Akwa et al., 2026), reinforcing the need for the integrated structural, chemical stabilization, and drainage solutions proposed below.

CONCLUSION

The significant premature distress observed along the Ugep–Idomi road corridor is the result of a mix of structural, geotechnical, and environmental factors:

- **Structural Thickness Deficit:** The actual sub-base thickness (9.35 in / 237.6 mm) falls short by 30.2% (4.04 in / 102.6 mm) compared to the design standard needed for the cumulative Equivalent Single Axle Load (ESAL) demand.
- **Subgrade Weakness:** The subgrade soil has 59.4% fines passing through the No. 200 sieve and a mean soaked California Bearing Ratio (CBR) of only 8.3%, making the foundation highly susceptible to moisture damage.
- **Traffic Loading:** High traffic volumes (26,550 vehicles/day average daily traffic) increase dynamic shear stresses on the structurally inadequate layers.
- **Drainage Infrastructure Deficits:** Insufficient surface runoff collection and uncontrolled sub-surface capillary rise lead to prolonged saturation of the unbound structural layers.



RECOMMENDATIONS

Structural Reconstruction: Redesign the flexible pavement section by removing damaged areas, adding a crushed-stone base layer, and increasing the thickness of the sub-base layer to at least 13.39 inches (340.0 mm). Use high-strength aggregate from Akamkpa, which has a compressive strength of 3,585.3 psi, for the structural layers.

Chemical Subgrade Stabilization: Apply a treatment of 4%–6% hydrated lime or Portland cement to the top 7.87 inches (200.0 mm) of the subgrade soil to decrease plasticity, reduce volumetric swelling, and raise soaked California Bearing Ratio (CBR) values above 15%.

Grade Elevation and Drainage Integration: Elevate the finished road profile by at least 3.28 feet (1.0 m) in low-lying areas to prevent capillary rise. Build continuous reinforced concrete side ditches and subsurface drainage drains to keep the water table at least 3.94 feet (1.2 m) below the subgrade level.

Compaction Control: Implement strict compaction controls in the field to achieve a minimum target density of 116.74 lb/ft³ (1.87 g/cm³) at 12.5% optimum moisture content during construction

Future Research: It is recommended to conduct longitudinal pavement performance monitoring and studies on axle-load enforcement to confirm the effectiveness of the proposed rehabilitation strategies amid ongoing traffic increases. A

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