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Geotechnical Influence Factors in Empirical Design of Highway Pavement: The A123 Ilorin – Lokoja Highway, Nigeria Case Studies

F. A. Abija,[1,6]* A. M. Fakeye[2], O. O. Ige[3], and A. I. Ifedotun[4,6]

Abstract

Site investigation and application of geological and geotechnical influence factors on the highway were investigated. Method involved field sampling, geotechnical laboratory and x-ray diffraction analysis and use of SRTM extracted slope and drainage parameters; and their integration in a GIS based multi-criteria decision analysis to derive a subgrade suitability map as a design tool. The suitability criteria classified the highway into four (4) design sections. Section one for very low suitability material consisting of clays with x-ray diffraction mineralogical intensity > 11cts, CBR ranging from 0 – 3%, A6/7 AASHTO class with maximum dry density ranging from 1 – 10kg/m^3 and optimum moisture content varying from 1 – 10%. A total compacted highway thickness ≥ 700mm is recommended. Design section two (2) comprising the low suitability soils is characterized by materials with XRD mineralogical intensity varying from 10cts – 11cts and CBR strength range of 4 – 10%. Adopting the lowest CBR of 4% in the empirical design would require ≥ 480mm compacted thickness. Design section three for moderate suitability soils with characteristically A-4 (silts) and CBR range of 10 – 15% is recommended to have a compacted thickness ≥ 300mm and design section four (4) for the high suitability areas. Design section 4 is characterized by A-2– suitable (very high for fair to poor quality) AASHTO materials with CBR >15%. Composite permeable pavement and soil improvement, use granular subbase and base course materials, and use of geosynthetic materials for roadbed drainage is recommend for climate resilient pavement crust.

Keywords: clay minerals, influence factors, Analytic hierarchy process, site suitability map, composite and permeable pavement

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INTRODUCTION

The Ilorin-Kabba section of the A123, Ilorin - Lokoja highway is located within latitude 7°25'N - 8°40'N and longitude 4°30'E – 6°45'E covering an approximate area of 15,612km^2 (Figure 1). It is a Trunk A (federal) highway providing transportation from Nigeria's South-West to the federal capital. This puts the road under heavy vehicular axial load that causes the constructed pavement structure to deteriorate frequently with intermixed sectional failures as evident from several failed sections (Figure 2). Road pavement infrastructures and the transportation sector accounts for over 90% of the movement of goods and commuters in Nigeria. The country also lacks a functional rail system putting much pressure on the already inadequate road network. The rate of pavement failure along this highway and infrastructural failures in Nigeria generally, calls for concerted research efforts to proffer explanation for the causative factors and or mechanisms; and recommend the most plausible design alternatives for sustainability. Highway pavements are founded on in situ subgrade soils which are weathering products of parent rocks [1-6].

The mineralogy of the parent rocks significantly affects the engineering properties and behavior of their derived soils. Research revealed that roads constructed over igneous rock terrains were more durable than those constructed over metamorphic rock terrains in the basement complex region of Southwest Nigeria. Investigations into pavement failures along the Calabar–Itu highway, Nigeria, found a higher failure rate in locations underlain by shale or marl-derived subgrades compared to sections underlain by weathered basement or sandy subgrades. On failures along the Kano-Kazaure highway, Nigeria, it was reported that residual soils derived from granitic rocks exhibited very good geotechnical properties; those derived from schistose and quartzite rocks had intermediate properties, while transported loose silty fine sand of the Chad Formation showed poor geotechnical properties along the failed sections. Other studies have linked pavement failures to poor and inadequate geotechnical design parameters in various regions of Nigeria, including parts of the Niger Delta, the Port Harcourt-Enugu expressway, Lokpaukwu, Lokpanta and Leru areas, the F209 highway at Ado-Ekiti, the Lagos-Ibadan expressway, the Port-Harcourt–Patani–Warri road, Igbara-Oke–Ibuji road, Jos–Plateau road, Sagamu-Papalanto road, and poor subbase conditions along the Ibadan-Iseyin road. Field observations and laboratory experiments also showed that road failures can arise from inadequate knowledge of the geotechnical characteristics and behavior of residual soils on which the roads are built, due to the non-recognition of the influence of geology and geomorphology, and failure to incorporate the same [7-15].

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It was also reported that roads underlain by kaolinitic soils were more stable, with stability increasing as the amount of kaolinite increased. The stable sections of the Lagos–Ibadan expressway, Nigeria, were found to have higher maximum dry density, unsoaked CBR, uniaxial compressive strength, and lower amounts of clay, optimum moisture content, and linear shrinkage. On the impact of geology on the stability of the Minna–Lambatta road, North Central Nigeria, soils underlain by migmatitic rocks exhibited lower strength (CBR), maximum dry density, and higher optimum moisture content along the failed sections compared to those underlain by granitic and granodioritic rocks. Further research on road pavement failure due to inadequate and poor geotechnical input into design includes cases in the United States, where drainage failure and the presence of collapsible soils led to pavement issues along U.S. Route 1A and Interstate 15.

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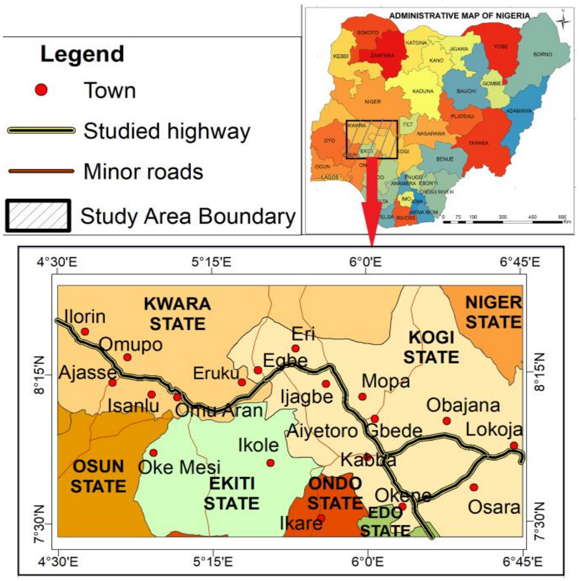

Figure 1. Administrative Map of the study area.

Figure 2. Some failed sections of the A123 Ilorin – Lokoja federal highway.

The design, construction, cost, and performance of roads are intricately linked to the integration and synthesis of design influence factors. However, the alignment for many highway projects does not always follow site topography, emphasizing the importance of engineering geological mapping. This process evaluates and documents site-specific geomorphological, geologic, hydrologic, and geotechnical conditions related to the design, construction, maintenance, and planning of engineered structures. The need for simple techniques to predict failure ahead of time has been emphasized, and geotechnical maps are instrumental in selecting the optimal alignment for highways, designing pavement structures, and ensuring resilience and sustainability in pavement construction. Tools such as the analytic hierarchy process (AHP) help synthesize geological and geotechnical data into practical formats, with applications in highway route selection, mine road design, landfill siting, geohazard assessment, and more [26-34].

GEOLOGY AND GEOHYDROLOGY OF THE STUDY AREA

The study area is underlain by Precambrian rocks of the Basement Complex, including the migmatite-gneiss complex, banded gneiss, meta-sedimentary suite, and older granite series. The highway traverses migmatite–gneiss, flaggy quartzite, undifferentiated schists, and porphyritic granite. Two main types of gneisses in the area are fine-grained biotite gneiss and banded gneiss. The older granites, which do not host mineralization, include diorites, granodiorite, granitoid, and charnockites, and are classified as migmatite granite, granite gneiss, and various other types of granites. These rock formations play a critical role in determining the geotechnical behavior of the soils and the overall stability of the highway pavement Figure 3 [35-39].

The Schist Belts, comprising metasedimentary and metavolcanic rocks, are composed of low-grade metasediments-dominated belts that trend N-S in the western part of Nigeria. These belts are considered to be Upper Proterozoic supracrustal rocks that have been infolded into the migmatite-gneiss-quartzite complex. The lithology consists of coarse to fine-grained clastics, pelitic schists, phyllites, banded iron formations, carbonate rocks, and mafic metavolcanic amphibolite. The Migmatite-Gneiss Complex occupies about 60% of the surface area of Nigeria's basement and records three major geological events. The earliest, around 2,500 Ma, involved crust-forming processes, followed by the Eburnean event around 2,000 Ma, and finally, the Pan African event in the age range of 900 to 450 Ma, which gave rise to granite gneisses, migmatite, and other lithological units [40-44].

The geomorphology of the area shows ground elevations varying from 200 to 800m above mean sea level, ranking moderately high to high elevation. The climate is dry to wet, described as hot and humid, and falls within Zone 3 of Nigeria's climatological zones. Geohydrologically, the area is drained by tributaries of the Niger and Benue rivers. Groundwater is controlled by rock fracturing and the thickness of the weathered zone, which influences porosity, transmissivity, and storage. Rainfall, ranging from 1,183 to 1,786 mm with a mean annual rainfall of 1,200 mm, constitutes the main source of groundwater recharge, with contributions from streams and rivers [45-47].

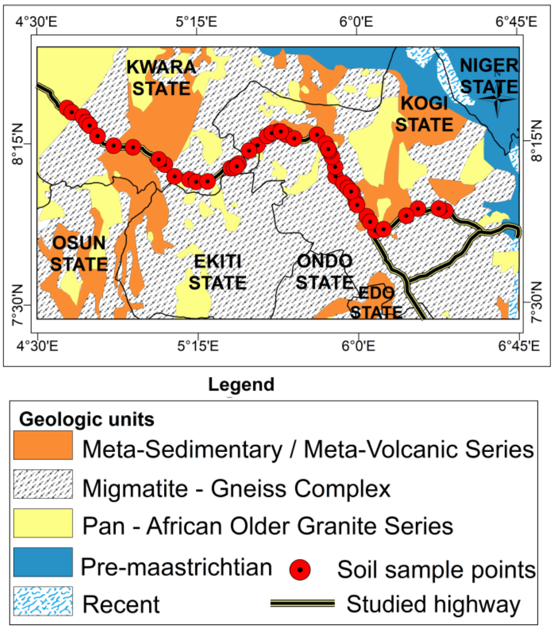

Figure 3. Geologic map of the study area extracted from geologic map of Nigeria (NGSA, 2004).

MATERIALS AND METHODS

Field Investigations

Field investigations involved excavation of trial pit along the failed sections and observation of local geology of the area were carried out in the months of May - June, 2019. The soil strata from excavated borrowed pit were also studied. Soil sampling was done to a representative depth of 1.2m – 1.5m depth and 5 – 10m distance away from the highway right of way within which subgrade samples were collected and visually inspected and described in the field. Soil profile was also examined in the trial pits. All the trial pit locations were selected at intervals of 3 – 5km distance both at stable and failed sections. Visual examination, description of fresh soil samples and the variability of the ground mass were noted at locations especially where changes were observed on soil strata. In addition, vertical variations in soil profile were observed in areas where construction activities had occurred with apparent cuttings and open excavations. Furthermore, sample locations on bedrocks, inaccessible valleys/hills, marshy areas or reserved areas were rejected and replaced with other locations. Strategic soil sampling collection followed a 3 by 5km interval distance at a depth of 0.8 – 1.5m from both failed and stable portions of the highway with coordinates readings of each sample point. All soil samples were carefully labeled in sample bags to prevent contamination and loss of moisture. Prior to laboratory analyses, the soil samples were air-dried at 30 – 35ºC for two weeks and gently sieved with 2mm sieve. Fifty soil samples were collected from 5m – 10m distance away from the highway right of way to ensure the trial pits are from borrowed fills used during construction [48-50].

Laboratory Analyses

Geotechnical analysis of the soil samples was carried out at the laboratory of the Nigerian Building and Road Research Institute (NBRRI). The analysis of the clay fraction was done by the hydrometer method, while wet sieving was used for the other fractions. Classification and index tests were conducted in accordance with BS 1377. Soil activity (Ac) was obtained as the ratio of the plasticity index (PI) to the clay fraction. Heavy compaction tests, including maximum dry density (MDD), optimum moisture content (OMC), and California Bearing Ratio (CBR), followed the modified Standard Proctor method as specified by BS 1377.

Mineralogical and spectroscopic analyses were performed at the Department of Chemical Sciences Laboratory, University of Johannesburg, Doornfontein Campus, South Africa. The soil sample pool consisted of 89 samples from Section A and 42 samples from Section B, taken from depths of 30–60 cm and 60–150 cm at intervals of 3–5 km. All soil samples were air-dried at 35–40°C for two weeks to partially remove natural water and were sieved to 2mm. X-ray diffraction (XRD) analysis was carried out on each sample using a Bruker D8 Advance X-ray diffractometer with monochromatic Cu-Kα1 radiation (λ = 1.54Å) in the range of 10° to 90°. XRD is a rapid analytical technique extensively used for phase identification of crystalline materials based on constructive interference of X-rays with the crystalline sample. The diffractograms, with corresponding intensity and 2θ values, were analyzed using Match 3 software packages for pattern fitting with established Mineral Power Diffraction File Data Book [51-54].

Analytic Hierarchy Process

The engineering geological and geotechnical influence factors, which include geology and mineralogy, California Bearing Ratio (CBR), percent fines, liquid limit, plasticity index, AASHTO classification, ground slope, stream order, maximum dry density, and optimum moisture content, were utilized in the multi-criteria decision-making tools suited for problems with spatial nature. The method assesses the relationship between these factors and establishes their relative importance through pairwise comparison, giving equal importance to all factors in the final decision, using a pairwise comparison scale in the ArcGIS environment. The procedural steps include defining the unstructured problem, developing the hierarchy, pairwise comparison, estimating the relative weights, checking the consistency, and obtaining the overall rating. All the equations for the calculations are embedded in the AHP tool of ArcGIS [55-57].

Geotechnical Characteristics

The geotechnical properties of the soils reveal a dominance of fines fraction (<0.075mm and passing sieve No. 200) with clay content ranging from 10% to 71%, silt fraction from 10.2% to 50.8%, while sand fractions vary from 44% to 85%. The natural moisture content exceeds the average range of 5–15%, with a minimum value of 2.4% and a maximum value of 22.7%. The high fines content and overall moisture content in the subgrades suggest high water retention capacity. The liquid limit ranges from 16.5% to 53%, plastic limit from 4.7% to 36.9%, and plasticity index from 3.8% to 24.4%, indicating inorganic soils of low to moderately high plasticity, compressibility, and low to high activity. The Unified Soils Classification System (USCS) identifies the soils as predominantly silty, clayey sands (SC, SM, SC-SM) mixtures, while the AASHTO specification classifies the materials as predominantly A-2 and A-6 types, depicting fair to poor quality and unsuitable materials. The optimum moisture content of the subgrade materials varies from 8.12% to 25%, with a maximum dry density range of 0.89 kg/m³ to 2.61 kg/m³. The strength of these subgrade materials, indicated by the 48-hour soaked CBR, ranges from 1.09% to 12.3%, while the unsoaked CBR varies from 2.08% to 30.4% [58-60] Table 1.

Table 1. Summary of geotechnical properties of soils.

	Sand %	*Silt %*	*Clay %*	*LL %*	*PL %*	*I_p %*	*W_n %*	*Ac*	*OMC %*	*MDD kg/m³*	*CBRu %*	*CBRs %*
Minimum	44	10.2	10	16.5	4.7	3.8	2.4	0.1	8.12	0.89	2.08	1.09
Maximum	85	50.8	71	53	36.9	24.4	22.7	8.5	25	2.61	30.4	12.3
Range	41	40.6	61	36.5	32.2	20.6	20.3	8.4	16.9	1.72	28.3	11.2
Mean	63.2	20.8	31.2	31.3	17.3	13.8	12.0	1.85	14.5	1.68	8.69	3.87
Standard Deviation	9.89	8.95	13.8	8.87	6.84	4.79	4.23	0.32	3.76	0.23	6.19	2.60
CL	2.81	2.54	3.93	2.52	1.94	1.36	1.32	1.34	1.07	0.07	1.76	0.74

Engineering Geological and Geotechnical Influence Factors

Clay materials derive their capacity to resist deformation by mobilizing shear resistance within the soil mass. Deformation due to imposed stress is resisted by frictional forces between particles as they move or attempt to move with respect to each other. In some cases, cements or electrostatic forces may also contribute to strength. Hence, strength and stiffness are influenced by mineralogy, grain size, structure, inter-granular cementation, moisture content, and inter-particle pressures. The proportion of clay minerals of the Na-montmorillonite group reflects the magnitude of the problems a soil may pose as a foundation for civil engineering structures or as a construction material.

Therefore, five mineralogical suitability classes were adopted for the mineral composition of the subgrades based on laboratory XRD data:

- 0–3 cts (very high suitability),
- 4–6 cts (high suitability),
- 7–9 cts (moderate suitability),
- 10–11 cts (low suitability),
- 11 cts (very low suitability).

The area is largely covered by high to very high suitability minerals.

The strength of subgrades and subbases used in highway design and construction is measured by the California Bearing Ratio (CBR) under soaked and unsoaked laboratory conditions to simulate field conditions. This strength index test is conducted for the wettest moisture condition at the expected field density likely to occur during the pavement's lifespan. Most premature road failures are attributed to weak subgrades, and a minimum 96-hour soaked CBR of not less than 15% is specified for the design of road pavement structures.

Taking into consideration the limit for the specified CBR, the factor criteria classes were:

- 0–3% for extremely weak and very highly unsuitable material (very low suitability),
- 4–10% for low suitability,
- 10–15% for high suitability,
- 15% for strong and highly suitable materials (very high suitability). (Figure 4-5).

The behaviour of clays depends on their particle size distribution, mineralogy and moisture content which influence their state of consistency. The classes of factor criteria for the fines fraction were classified as 0 – 10% as very highly suitable, 11% – 20% as high suitability, 21% – 35% as low suitability, and >35% as very low suitability (unsuitable) materials (Figure 6). Based on the subgrade specification of Nigeria's federal ministry or works (2011) which states that the Liquid limit shall not exceed 50% and percentage fines ≤ 35%, plasticity index ≤ 30%, influence factor criteria for the stated subgrade geotechnical parameters set as liquid limit 1% – 25% as Very high suitability, 25% - 50% of low suitability and > 50% of very low suitability (Figure 7). Plasticity index (I_p) classes were 1% – 15% (very high suitability), 16% – 30% (moderate suitability class) and > 30% (very low suitability or simply unsuitable materials (Figure 8 -10).

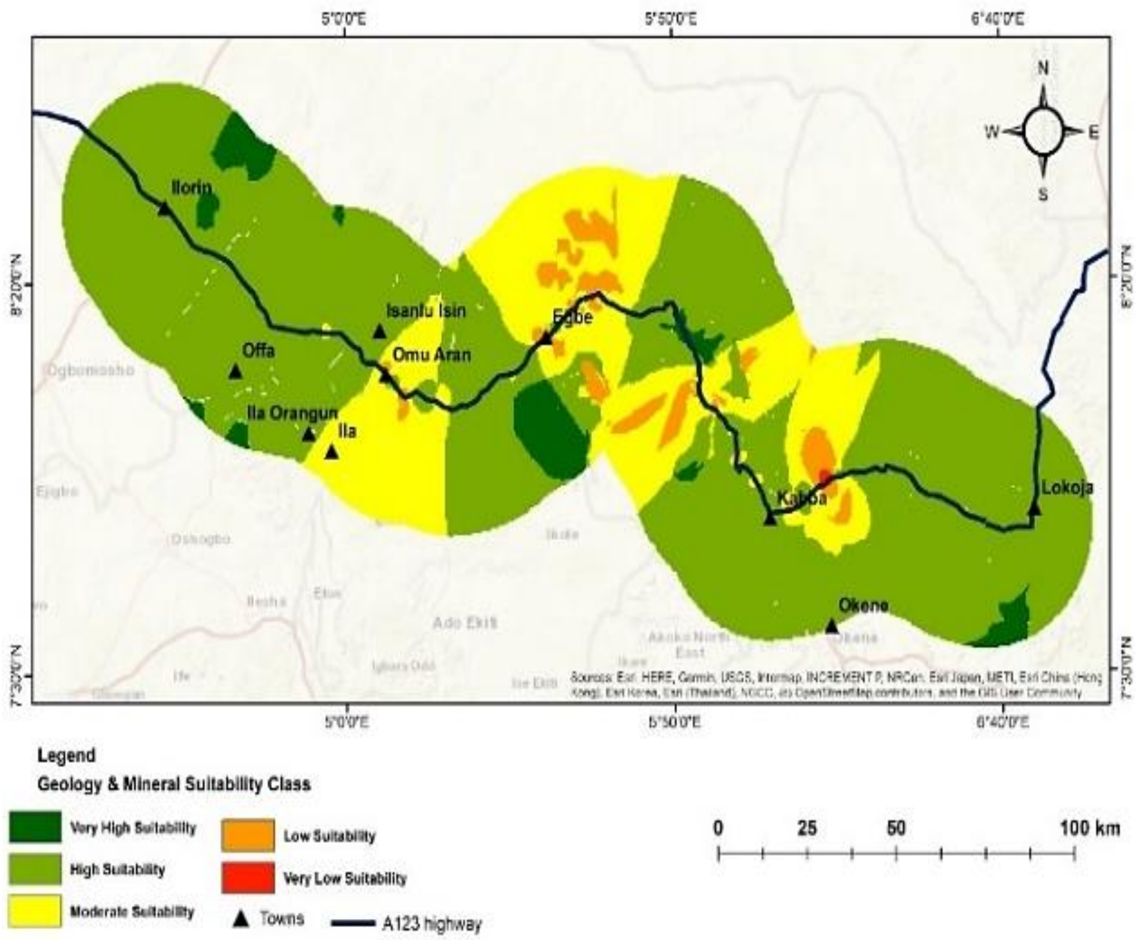

Figure 4. Map of the geology and mineralogical suitability classes of the study area.

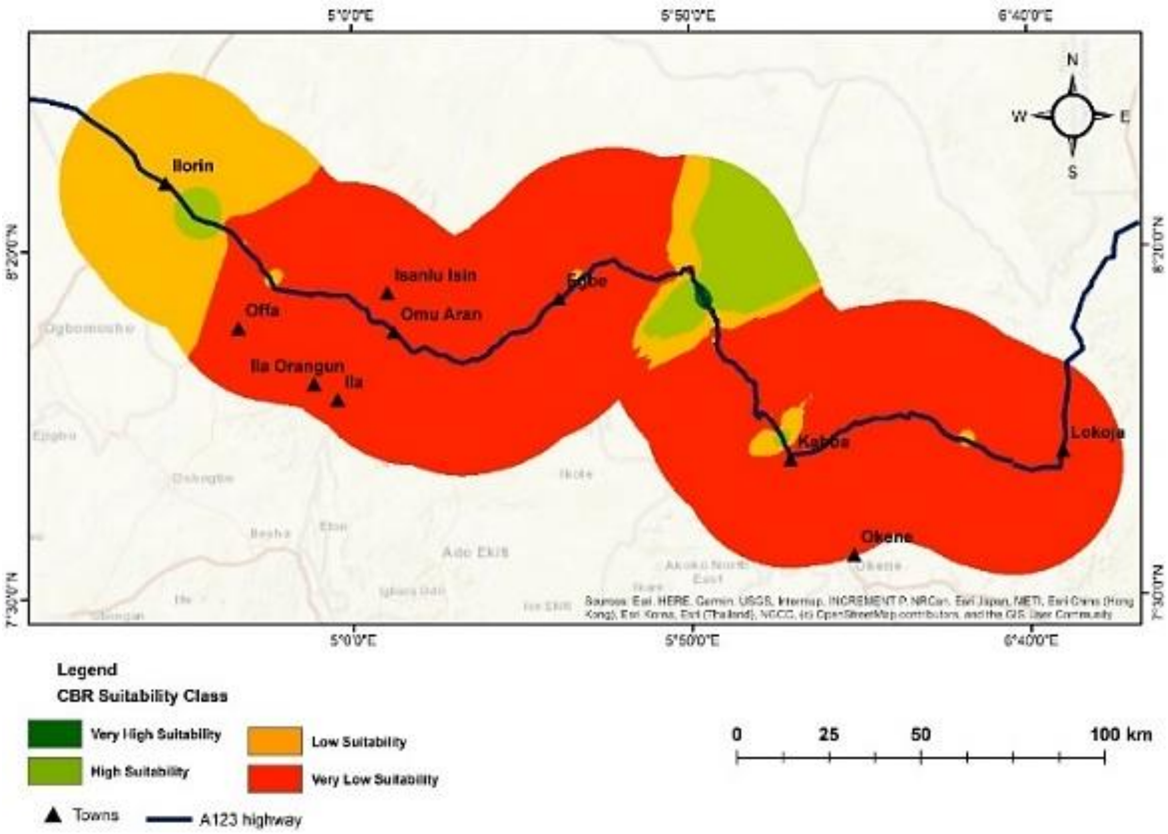

Figure 5. Map of the material strength suitability classes of the study area.

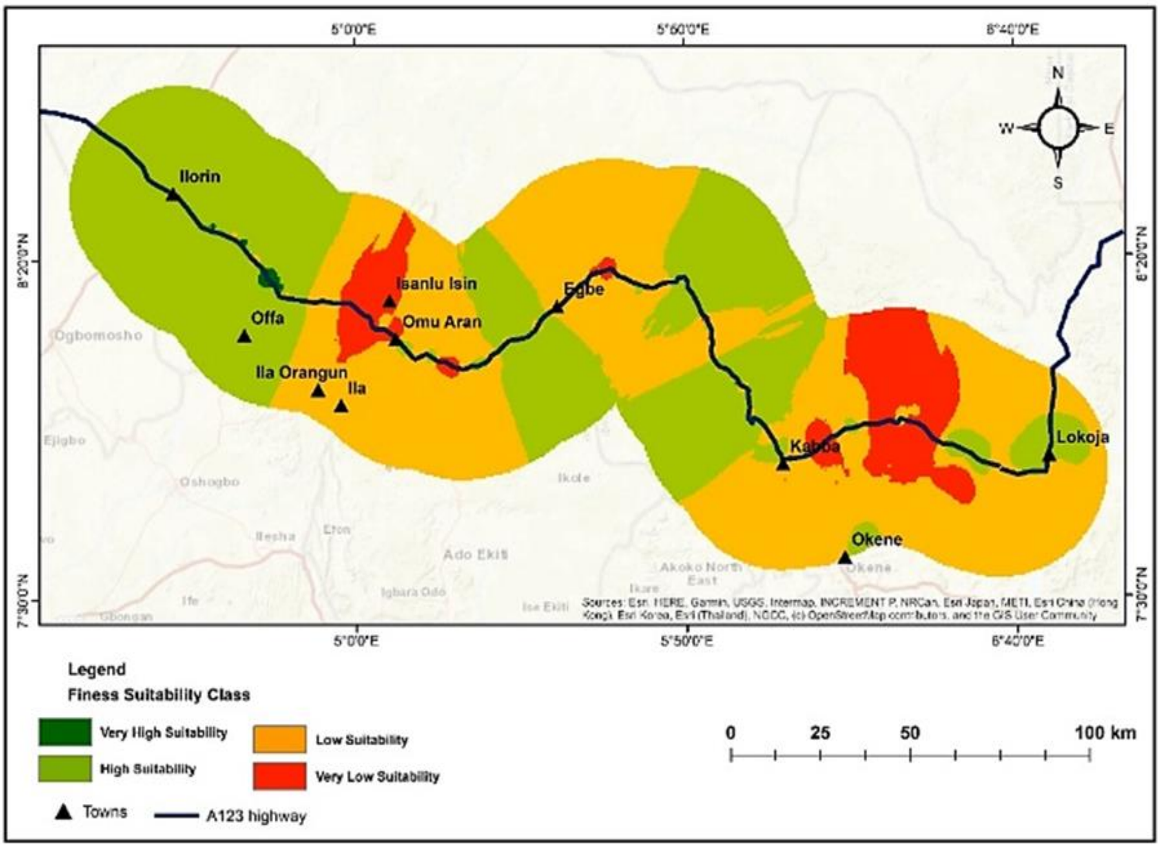

Figure 6. Map of the percent fines material suitability classes of the study area.

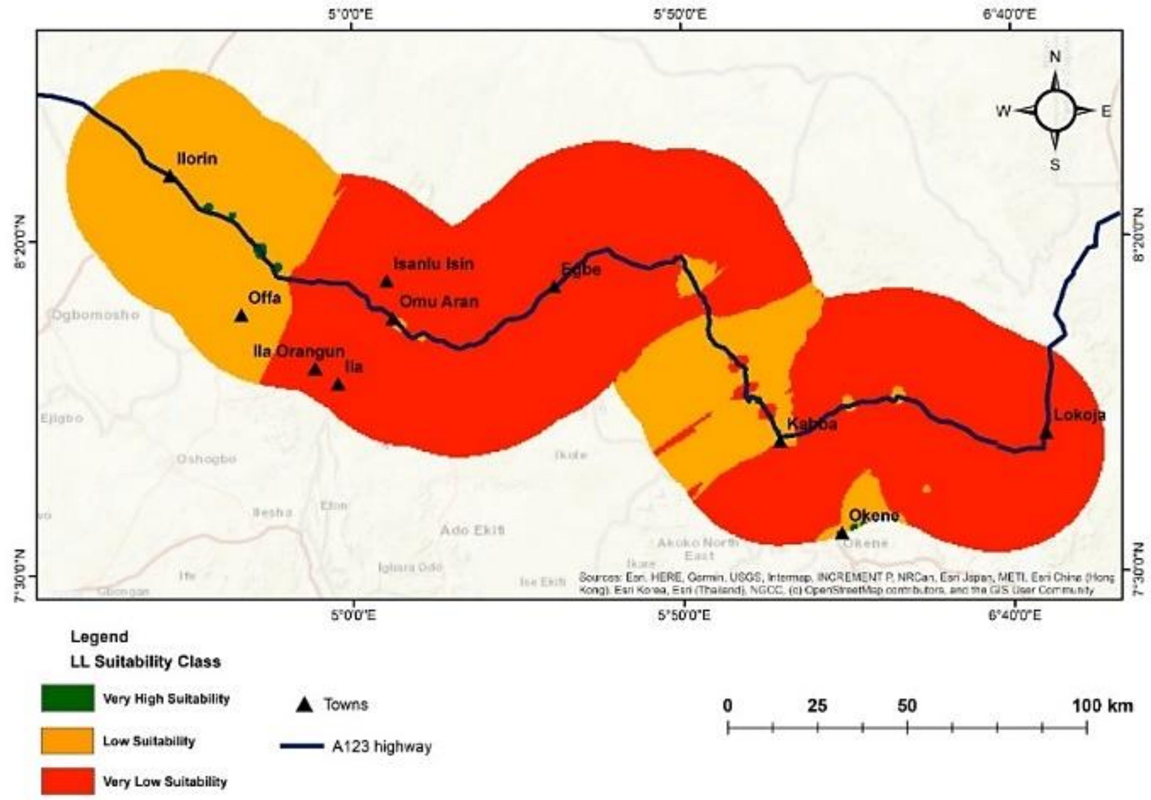

Figure 7. Map of the liquid limit suitability classes map.

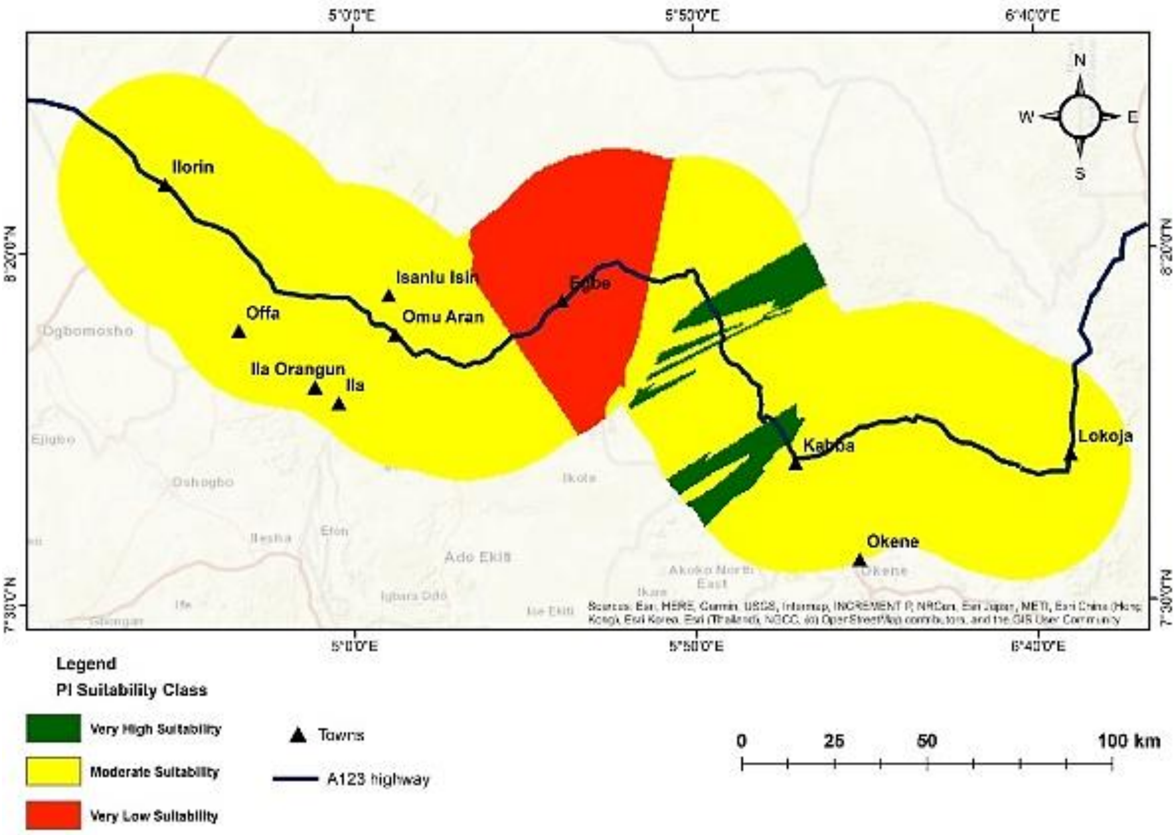

Figure 8. Map of the plasticity index suitability classes.

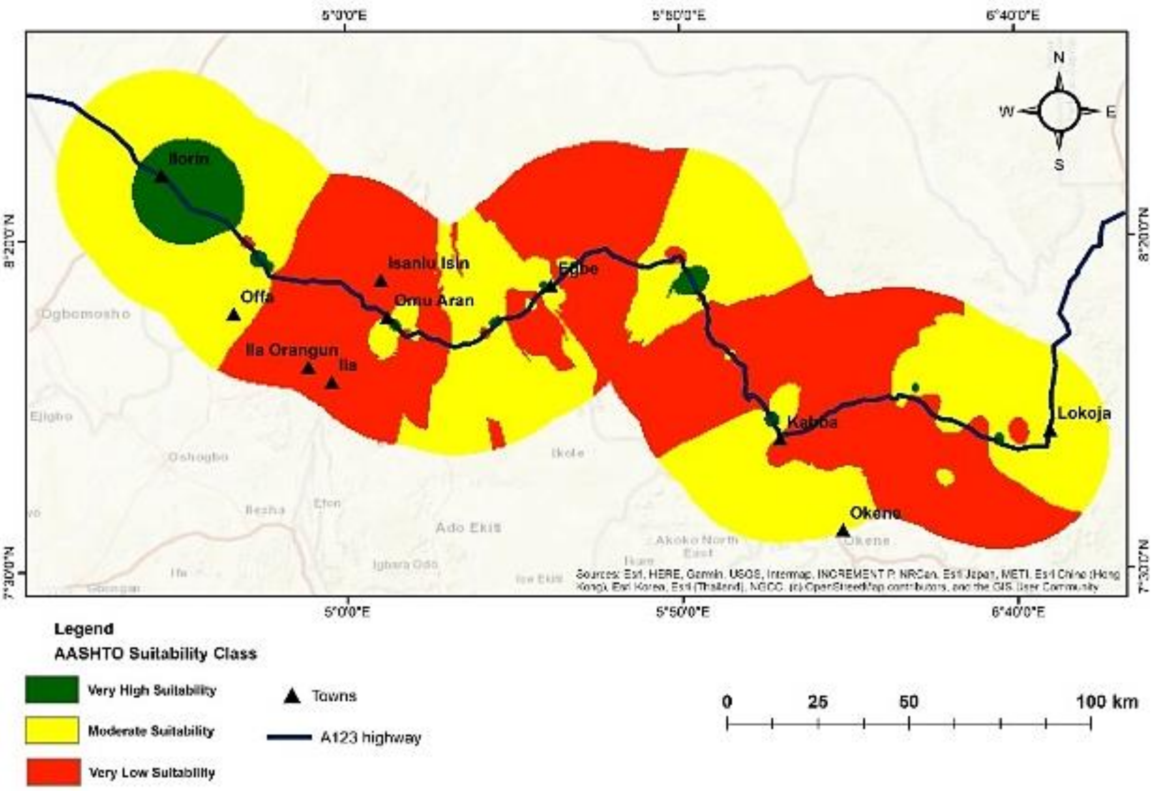

Figure 9. Map of the AASHTO classification suitability classes.

Engineering Geological and Geotechnical Influence Factors

Based on the AASHTO classification system, subgrades falling into the A1 and A3 classes (silty or clayey gravel) are of excellent quality as pavement foundation materials. A2 subgrades, which consist of silty or clayey gravels and sands, are considered to have fair to poor subgrade quality. Silty clays and clays, where 35% of the material is finer than the 75-micron sieve, fall into the A4, A5, A6, and A7 classes, indicating fair to poor subgrade materials. In consideration of the classification and prevailing subgrade types, three influence factor classes were adopted for the analytic hierarchy process (AHP) analysis:

- A-2 (suitable, very high for fair to poor quality),
- A-4 (silts, moderate, low suitability),
- A6/7 (clayey soils, very low suitability or unsuitable).

Ground topography and slope are crucial for drainage and slope stability. The slope's angle, rock and soil formations, evidence of past slope movement, and drainage features are all important factors. Ground topographic depressions increase the risk of flooding, runoff collection, detention time, ponding, and potential for piping failure. The grade of the roadbed affects the choice of locations for hydraulic structures and drainage systems, especially in flat topography areas. Slope refers to the rate of change in elevation and influences the flow of water, site selection, and structural integrity.

The slope map was generated from the Shuttle Radar Topographic Mission (SRTM) digital elevation model dataset, and slope classes were used in the pairwise comparison. These classes relate directly to the tendency of ponding and the degree of water infiltration, which affects subgrade strength. Given the lack of prior records of slope instability or landslides, these risk factors were not considered in the AHP. The suitability classes, excluding the effects of slope instability or failures, include:

- 0–30 (very low),
- 4–60 (low),
- 7–100 (moderate),
- 11–150 (high),
- 150 (very high).

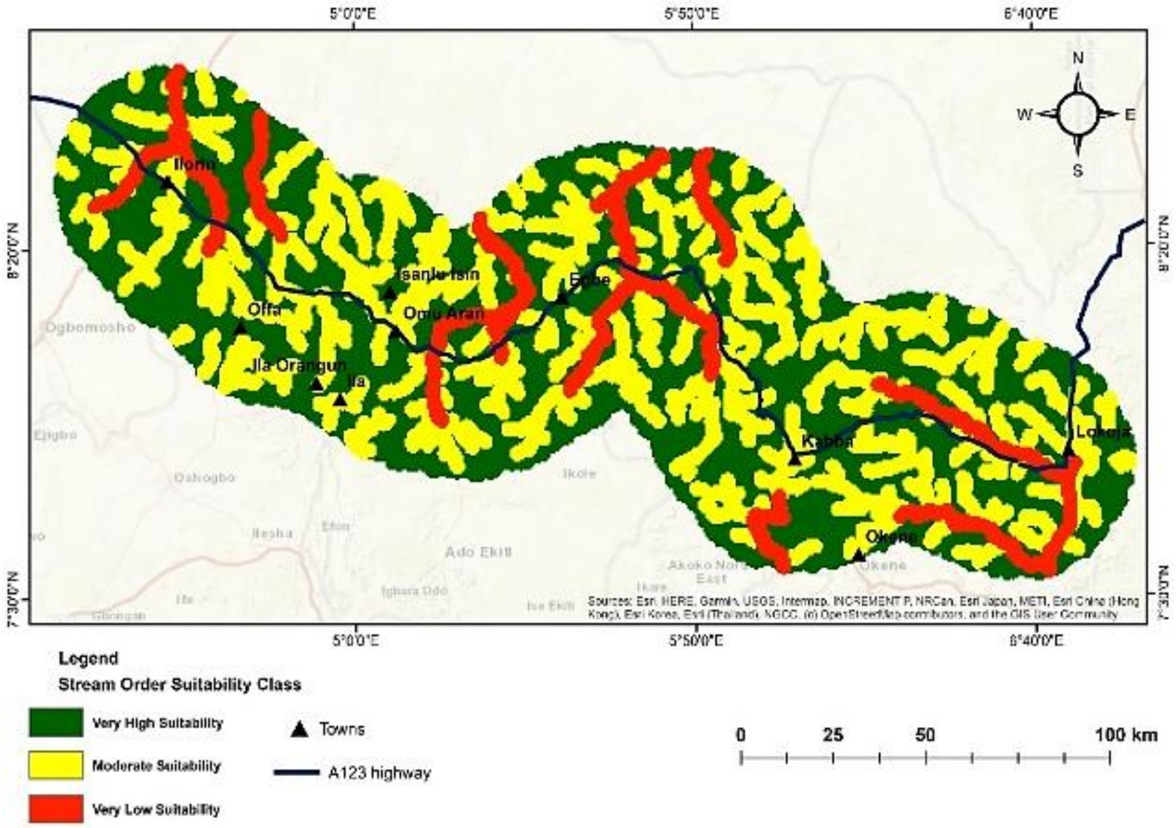

Figure 10. Map of the stream order suitability classes.

Surface streams and channels often constitute depositional zones, where fines such as clays, silts, and organic debris accumulate, leading to low-quality geomaterials in terms of strength and compressibility. Higher stream order equates to a higher rate of groundwater recharge and increased infiltration, which can reduce material strength and increase pore water pressure, necessitating subsurface drainage systems. Pavement proximity to drainage channels influences its deterioration. The classes of stream order adopted in the multi-criteria analysis for suitability and pavement sustainability were:

- Stream Order 1–2 (very high suitability),
- Stream Order 3–4 (moderate suitability),
- Stream Order 5–6 (very low suitability or unsuitable).

Mechanical compaction and densification are critical components of earthworks quality, stability, and durability for roads, airfields, embankments, and foundations Figure 11.

The densification of in situ subgrades, subbase layers and base course with expulsion of air rely on the moisture – density relationship of the materials. A maximum dry density develops at an optimum moisture content at which each material layer becomes sufficiently workable under a given compactive effort to cause the particles to be closely packed that most of the air in the voids is expelled. A high maximum dry density also implies greater strength that may require a lesser pavement thickness. Based on laboratory compaction test, data have been assigned three classes for purpose of pairwise analytical hierarchy process to derive zones of very low, high and very high suitability for the preferred highway rout and design of the pavement crust. The range of results for the maximum dry density (MDD) and their classes are 1 – 10kg/m^3 for very low, 10 – 20 kg/m^3 for the high and >20 kg/m^3 for the very high suitability (Figure 11) while the corresponding optimum moisture content (OMC) suitability classes are 1 – 10% (very low), 10 – 20% (moderate suitability) and >20 % (very high suitability) as the higher the moisture content, the greater density for the optimum moisture content (Figure 12). At low moisture content, the soil is dry and difficult to compress Figure 13 and 14.

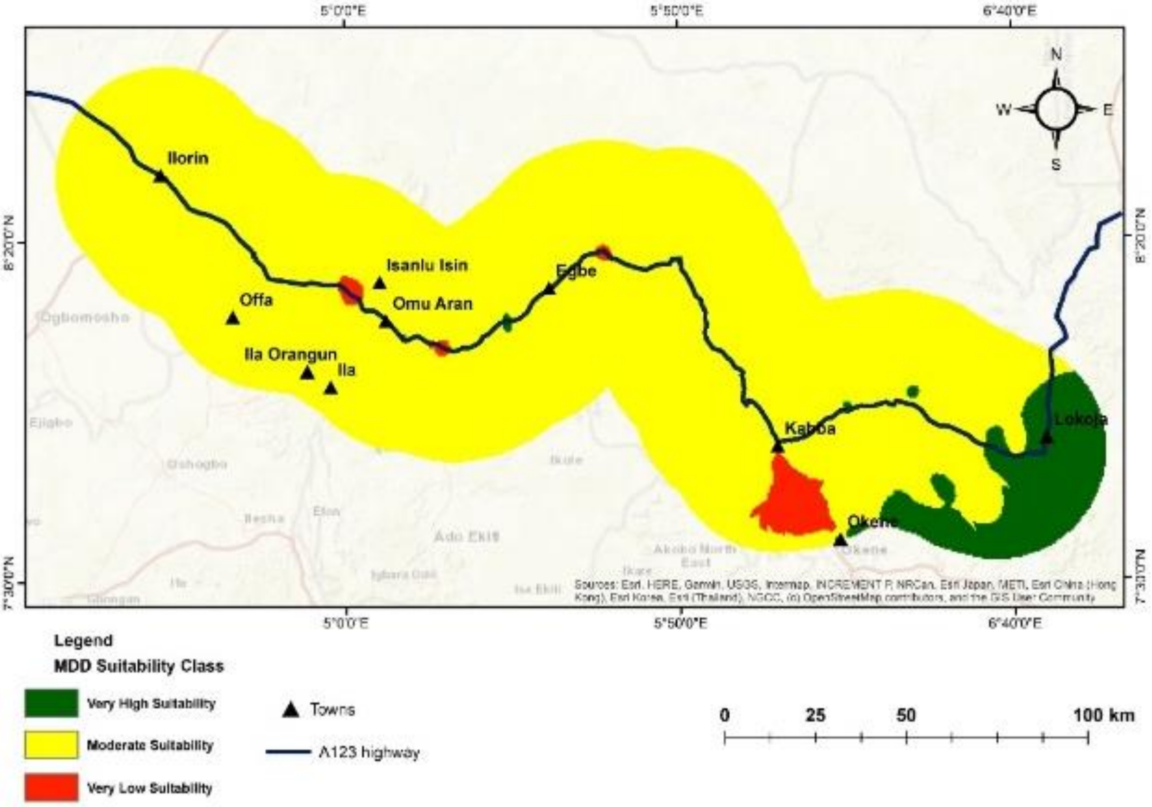

Figure 11. Map of the maximum dry density suitability classes.

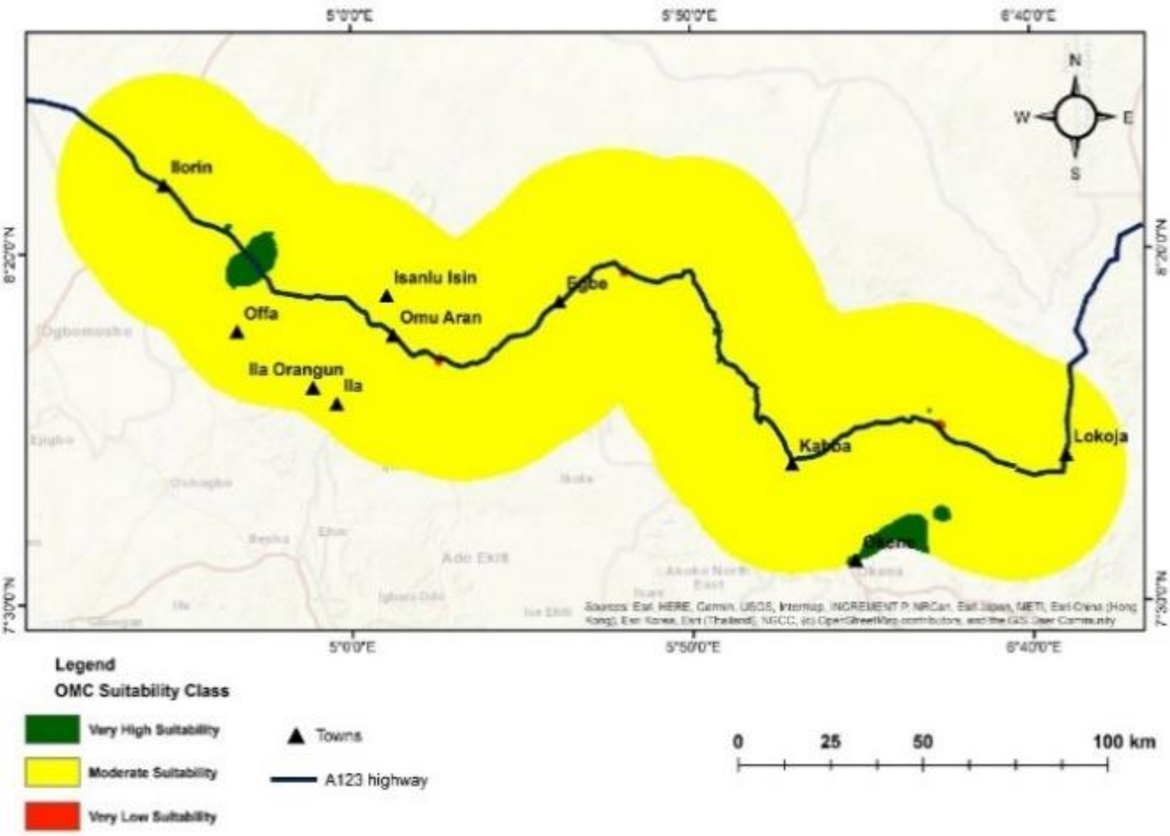

Figure 12. Map of the optimum moisture content suitability classes.

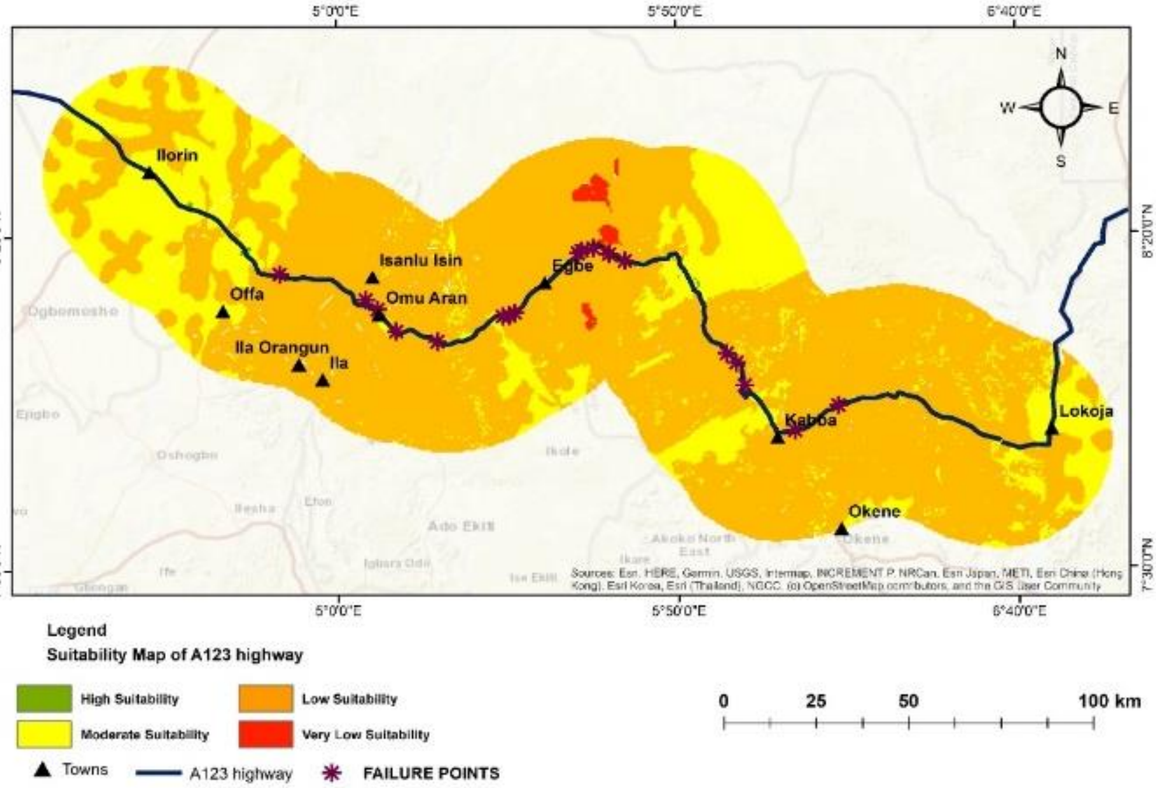

Figure 13. Suitability zones map and superimposed failed sections along the A123 highway.

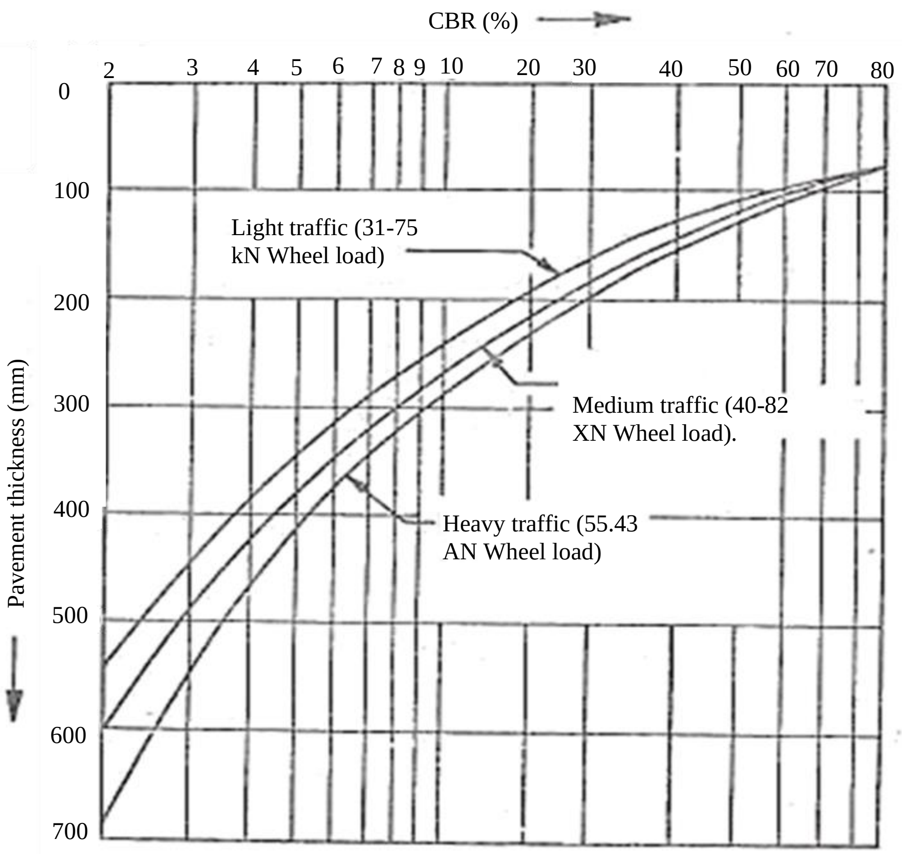

Figure 14. Empirical pavement design curves (CBR design curves, 1970).

Geotechnical Influence Factor-Based Design and Construction

The primary goal of pavement design is to achieve maximum performance efficiency while minimizing costs. In line with influence factor-based suitability criteria, the Ilorin-Kabba section of the A123 Ilorin-Lokoja highway has been divided into four design sections for cost-effectiveness and optimal performance:

1. Design Section 1 for areas with very low suitability materials,
2. Design Section 2 for low suitability areas,
3. Design Section 3 for moderate suitability areas, and
4. Design Section 4 for high suitability areas.

Design Section 1 represents areas with unsuitable materials, where mineralogical X-ray diffraction intensity exceeds 11cts. These sections are characterized by the lowest subgrade quality, with California Bearing Ratio (CBR) values between 0-3%, and they classify as A6/7 (clayey soils). The maximum dry density (MDD) in these sections varies from 1 to 10 kg/m³, and the optimum moisture content is between 1-10%. Due to these poor conditions, a total minimum compacted highway thickness of 700mm is recommended, which may be adjusted depending on ground levels after excavation and removal of unsuitable materials.

Design Section 2 includes areas with low suitability materials, with XRD mineralogical intensity between 10-11cts. These sections have fines content varying from 21-35% and an MDD class range of 10-20 kg/m³. The optimum moisture content ranges from 10-20%, and the CBR strength varies from 4-10%. A minimum compacted thickness of 480mm is required based on a representative minimum CBR of 4%.

Design Section 3 is designated for areas with moderate suitability. These sections consist of A-4 (silts) with a CBR range of 10-15%, an MDD between 10-20 kg/m³, and optimum moisture content between 10-20%. The recommended minimum compacted highway thickness for these sections is 300mm.

Design Section 4 covers areas with high suitability materials. These sections consist of A-2 materials, with CBR values above 15%, indicating strong and highly suitable subgrades. The MDD exceeds 20 kg/m³, and the optimum moisture content is above 20%. The minimum compacted thickness for this section is 250mm after compaction.

For the entire highway section, it is critical to validate the thicknesses of roadbed courses with site-specific surveys. Earthworks construction should ensure subgrade compaction to at least 90% of B.S. compaction using high compactive effort. The top 150mm of the subgrade should be watered below the optimum moisture content to increase in-situ density and shear resistance. The cohesionless granular fill materials in the subbase and base courses should attain 100% optimum moisture content, with a sheepsfoot compactor followed by vibratory roller compaction to achieve field density.

RECOMMENDATIONS

Nigeria's pavement systems, typically flexible pavements, have shown failures in sections of the A123 highway. Given climate-induced extreme rainfall and temperature variations, the adoption of composite pavement designs is recommended for enhanced climate resilience. Composite pavements, which mitigate issues such as asphalt fatigue cracking, subgrade rutting, and loss of friction, offer a cost-effective and high-performance alternative to traditional designs.

Composite pavement systems should include adequate drainage provisions, including subsurface and cross-drainage systems, to manage runoff and keep the roadbed dry Figure 15.

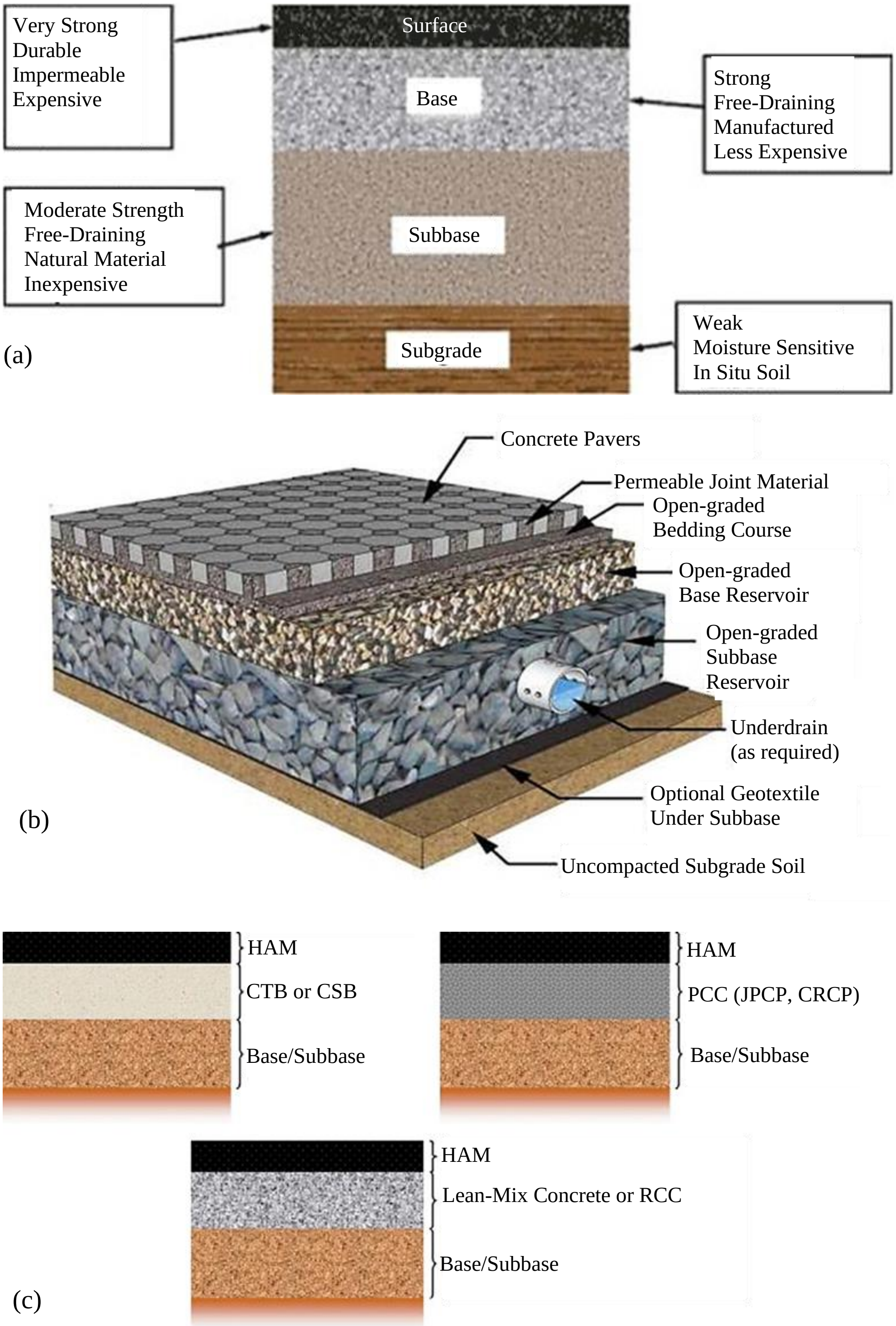

Figure 15. (a). Deep strength composite pavement. (b) Subsurface draining permeable pavement (c) Typical cross sections of composite pavement systems.

CONCLUSION

Multi-criteria decision analysis using ground design influence factors and their derived geotechnical maps as exemplified by its application in the A123 high can be hands-on aid in geolocation, zonation of the highway into material quality, route selection and hence a practical design tool. The overall suitability map can also serve as a field tool for surveying, highway chaining, design detailing and setting out during construction. For cost effective material control, highway sections can easily be divided into sections for implementation of the design and construction of resilient pavement crust. Zonation of the design study area into subgrade material quality zones and the corresponding design sections provides a straight forward application of lower limit of material's design parameters for choosing the thickness of the pavement.

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