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Analysis of Soil and Environmental Conditions for Resilient Pavements in the Niger Delta

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Abstract

The short service life of pavements in the Niger Delta has resulted in high recurrent maintenance cost of roads. Pavement failures have been attributed to widespread weak, expansive clays and silty soils, which lead to high water table issues and poor drainage without an understanding of the mechanisms involved and an appreciation of the adequacy of the codes used in their design. This paper explores the concepts of pavement design, assessing the necessity and functions of individual layers as well as the geological materials they are made of. The paper then identifies the weaknesses in the pavement design culture practiced in Nigeria to include poorly prepared subgrades, use of unsuitable aggregates, insensitivity to the environmental conditions among others. It further investigates the relationship between the distribution of axial load and the thicknesses of pavement layers to identify vulnerabilities particularly in the Niger Delta that can promote pavement failure. It examines the influence of moisture on the attainment of adequate compaction as well as on the resilience of pavements. The paper argues that the extensive weak subgrades and rapid variability of superficial geology such as exist in the Niger Delta demands a review of the national design code to accommodate the peculiarities of the region. To ensure resilient pavements, understanding soil and environmental conditions is paramount. This involves integrating soil-structure interaction principles, ground improvement and stabilization techniques, as well as risk assessment methodologies to enhance structural integrity and sustainability of pavements.

***Keywords**: Pavement, soil, water, environment, sustainability, design code*

Introduction

There are essentially two main types of pavements - rigid and flexible (Fig. 1). These two types use different materials and road construction methods and respond differently to the same soil and environmental conditions. The rigid pavement experiences brittle failure when subjected to significant loads, whereas flexible pavement experiences ductile behaviour in failure (Fig. 2). Ductile failure involves large deformations and energy dissipation before fracture, while brittle failure involves sudden and catastrophic cracking with little warning. The functions and requirements of a pavement include provision of a strong and smooth surface to resist traffic loads, distribution of the loads safely onto a larger area of the foundation soil through the intermediate layers/courses and carrying traffic loads under repeated application during the design life without developing excessive or harmful deformations/strains (Rossow, 2008). These functions inform the basic design of pavements into different layers (Fig. 3) with a combined minimum and maximum thickness of 425 mm and 1,050 mm, respectively. Understanding the functions of each pavement layer is crucial for the selection of suitable construction materials. The subgrade is the foundation of the road, thus it's the lowest and most important component of road structure. It is constructed at least 60 cm (2ft) high from highest flood level of the area. This layer bears all the load which it transfers through grain-to-grain contact, thus acting as a foundation of the road. In this role, and to enhance intergranular contact stress, it must minimize interaction with water which will cause a reduction in the soil's frictional resistance. It is for this reason that it should be elevated above the maximum expected flood level. At the same time, the material used for its construction should be better than the material of subgrade (AASHTO, 2015).

The subbase is the layer constructed over and above the subgrade and usually, its thickness varies from 7.5cm (3 in.) to 15cm (6in.). The principal functions of the subbase layer is to provide additional help to the courses above it in distributing the loads. The subbase also helps in preventing soil grains of the subgrade from intruding into the base course and rise of water or capillary action. For this reason, the effective particle size (D_{10}) has to be larger than that of the subgrade and may consist of stabilized soil or soil aggregate mixes, which facilitates

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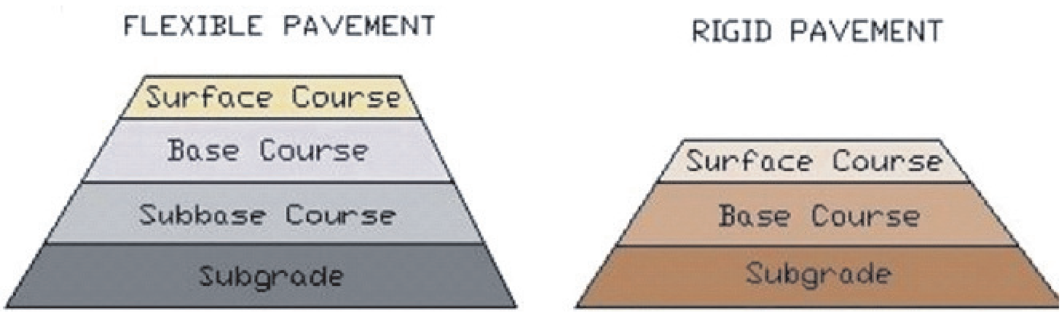

Fig. 1: Types of pavements

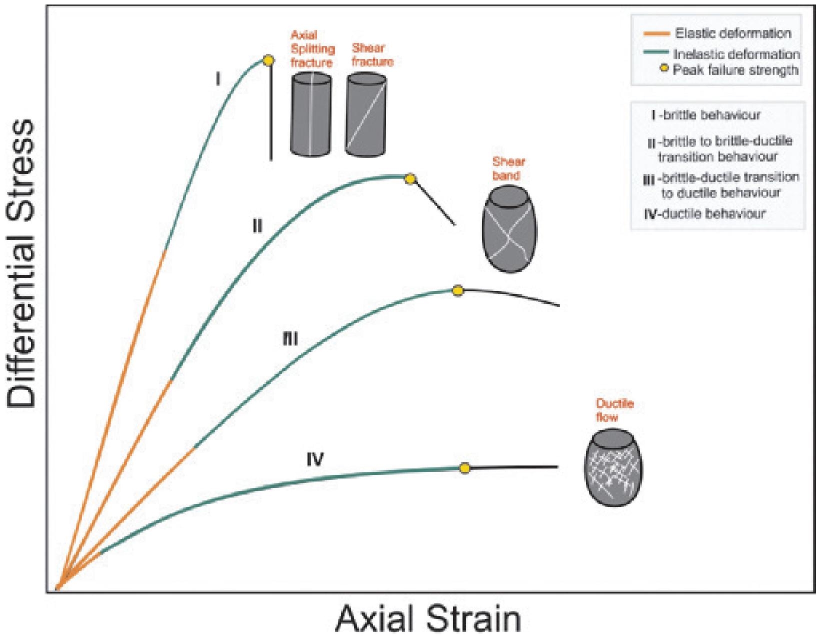

Fig. 2: Stress – Strain diagrams illustrating Brittle and Ductile failure

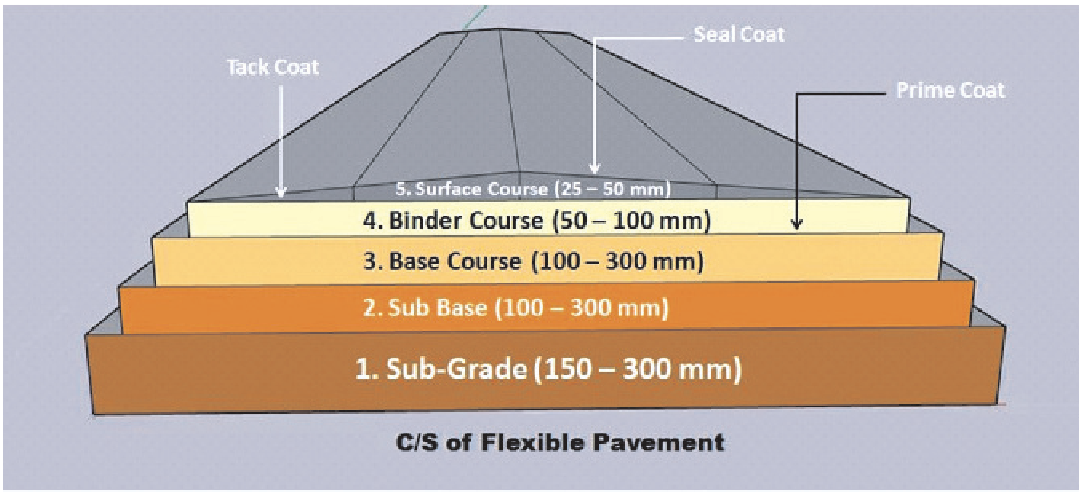

Fig. 3: Typical road pavement layers and associated thickness

drainage of free water from the pavement (Kadyali and Lal, 2008). The functions of the base course include distributing the stresses transmitted through the surface course evenly onto the layers below and acts as a structural part of the pavement assisted by the binder course. This layer also helps to avoid the distortion of wearing course due to its sufficient density and stiffness as well as support the wearing course. The base course is usually strong enough structurally to withstand the stresses imposed by the traffic. Its thickness should be adequate to transmit the applied loads and distribute them on to a larger area of the soil below so that the pressure transmitted is small. It should provide a hard-wearing surface so as to resist the abrasion caused by vehicle tyres. It should be smooth enough to provide riding comfort, yet provide enough friction for tractive effort and to prevent skidding. It should be impervious to water so as to prevent its deteriorating effect on the layers below. It should also have adequate durability to serve through its design period.

Surfacing or surface course is the uppermost layer of the road cross section. It can be provided in one or two layers namely; binder course and wearing course. It is the layer that is in direct contact with the tyres of the vehicle. The reasons for surfacing of roads include abrasion-resistant and reasonably impervious course, prevent penetration of water in to the pavement and protects the lower layers from abrasion and weathering effects of the moving vehicles. The minimum degrees of compaction to be attained and the recommended California Bearing Ratios for each of this road layers are summarized in Fig. 4. Reddi and Inyang (2000) noted that soil mineral type imparts a signature characteristics and engineering behaviour of the clay fractions, thus there is the frequent need to evaluate and examine clay materials in soils for civil engineering projects, as suggested by Reeves *et al.* (2006) and Murthy (2014). Gaspard *et al.* (2020) reiterated the important and significant role environmental conditions play on the performance of both flexible and rigid pavements as recognized by the pavement engineering community.

Climatic zones

Climatic environmental factors such as precipitation, temperature, wind speed, solar radiation, relative humidity, and depth to water table are important parameters that impact pavement performance ((Lekarp *et al.*, 2000, Dempsey *et al.*, 1985, Lytton *et al.*, 1990). Drainage of paving layers, and infiltration potential of the pavement, define the extent to which the pavement will react to the applied external environmental conditions (Dempsey *et al.*, 1985, Lytton *et al.*, 1990). Moisture and temperature are two environmentally driven variables that can significantly affect the pavement layer and subgrade properties in any pavement structure, hence, its load carrying capacity and stiffness (Lytton *et al.*, 1990).

Nigeria is characterized by diverse and widely varying climatic and ecological zones (Figs. 5 to 8) differentiated by wide temperature and moisture regimes. Pavements that traverse these ecological zones will inevitably respond differently to the environmental stressors, thereby justifying the case for integration of regional environmental peculiarities affecting pavement performance into design code.

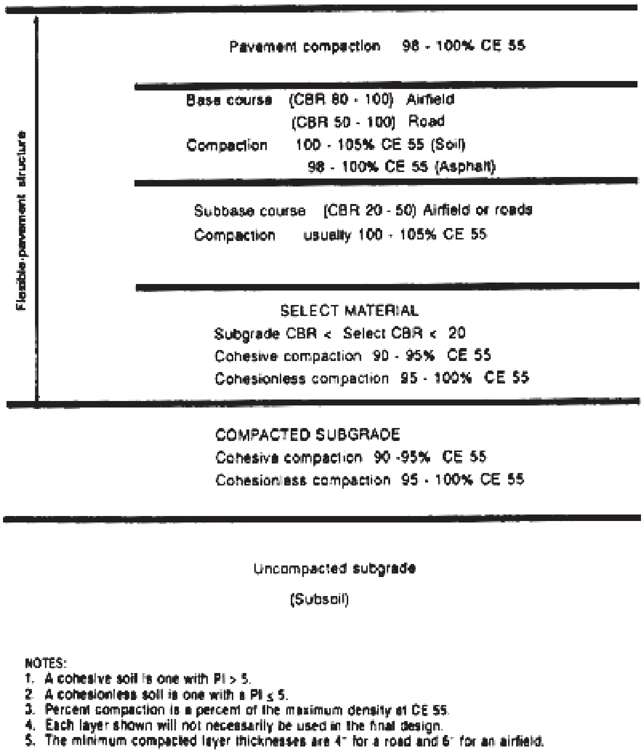

Fig. 4: Recommended compaction requirements for road layers Crop out 'Figure 5-4' above!

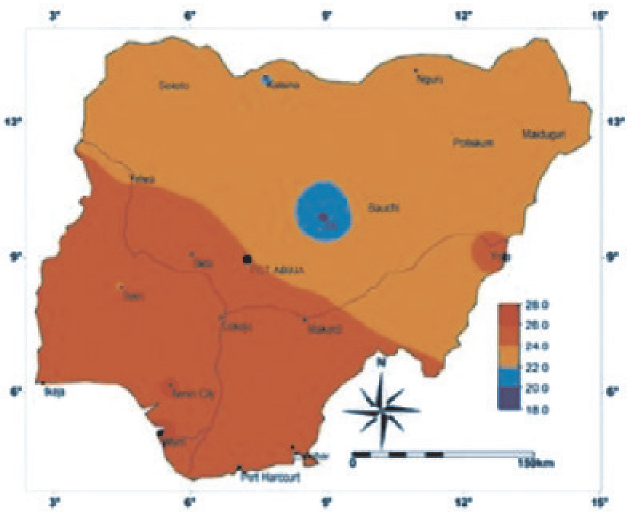

Fig. 5: Annual mean Evapotranspiration

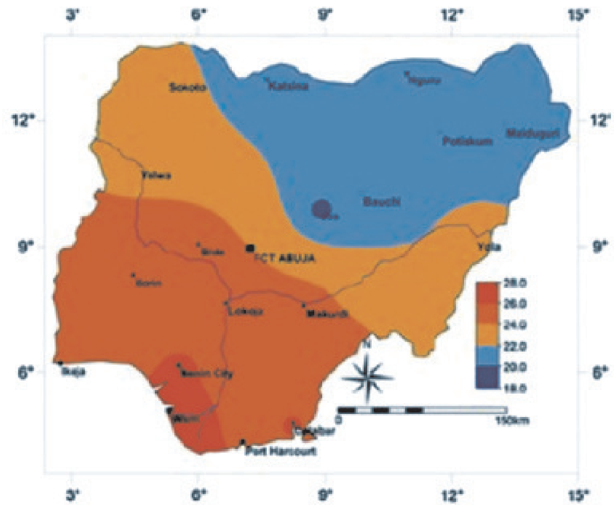

Fig. 6: Annual mean Temperature

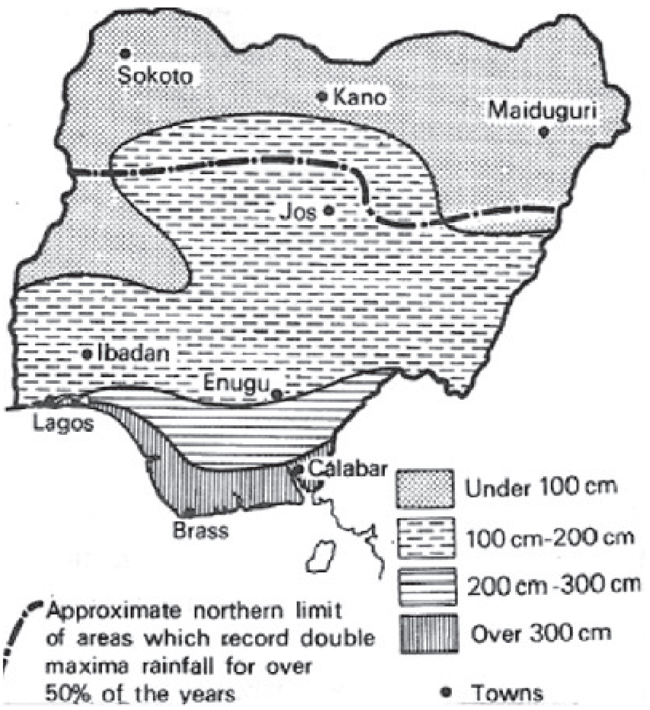

Fig. 7: Rainfall Distribution

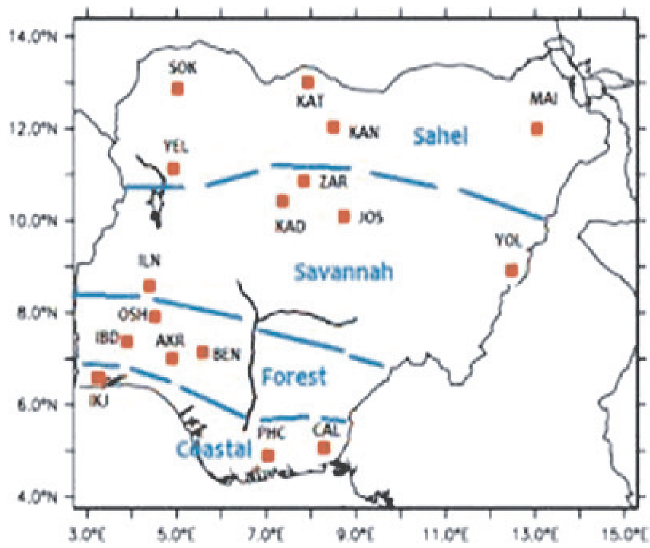

Fig. 8: Ecological zones of Nigeria

The Nigerian design code, developed by the Federal Ministry of Works and Housing (FMWH, 2013), was essentially based on the British equivalent, which is derived from prevailing metocean conditions in the United Kingdom (UK) that are at variance with the Niger delta. For example, records from the Climate and Weather Office of the UK (Salas, 2024) puts the average annual rainfall between 1910 and 2023 at 1,100 mm, distributed monthly, as presented in Fig. 9, against that of the Niger delta, with a total of about 2,600 mm; a typical monthly distribution as shown in Fig. 10 (Abam, 2016). In effect, the rainfall in the Niger delta is more than twice the rainfall in the UK and therefore there is no basis for adoption of the pavement design code of the UK due to glaring disparities in significant factors of environmental influence. Please, recast the rhetorical question into a direct statement of fact! Environmental conditions also play an important role in the pavement alignment and construction process because of the effect of surface water management and soil moisture control on workability, achieving target compaction level and in post construction performance of pavement. The case of surface water management is exemplified by the East-West Road linking Port Harcourt to Warri, which although trending east-west in orientation, has over 95% of all the drainage rivers flowing perpendicular to the road alignment. To save cost, the design reduced the span of the 23 bridges and culverts and in the process impeded flow, causing an upstream buildup of surface water? that eventually causes flooding.

Fig. 11 depicts the compaction profile for the major construction materials in the region, namely; lateritic soil and for crushed stones and indicates the ranges of moisture for attaining 95 % of the target maximum dry density for both materials. The acceptance criteria which determine the actual values of the maximum dry density are specified in table 11. It follows that where the moisture content is greater than 19.8 %, the target compaction level cannot be achieved no matter the number of passes unless the compactive effort is increased.

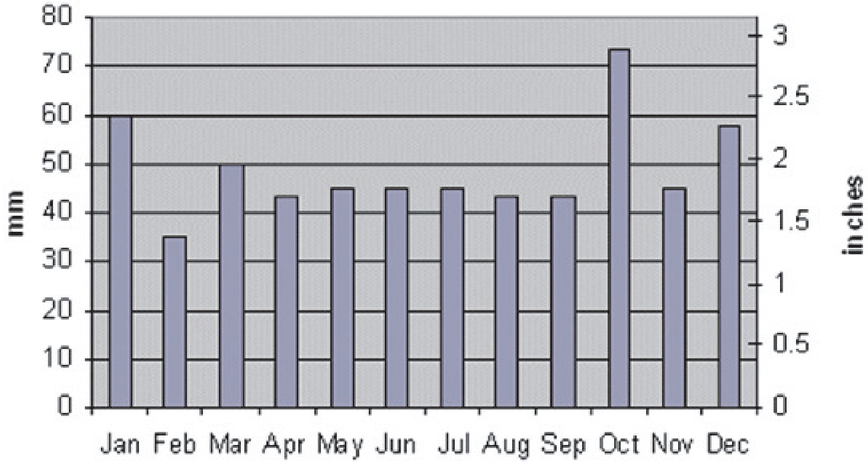

Fig. 9: Rainfall distribution in United Kingdom

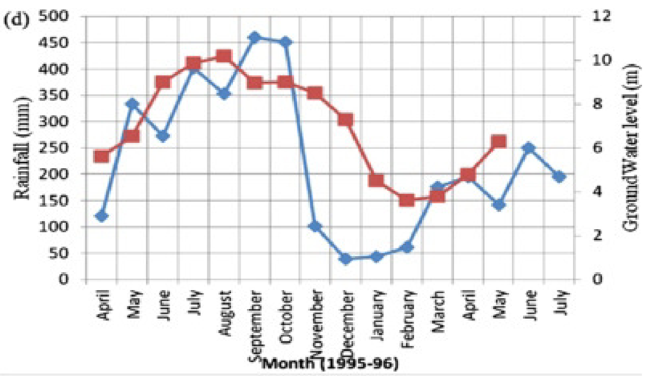

Fig. 10: Rainfall distribution in the Niger Delta

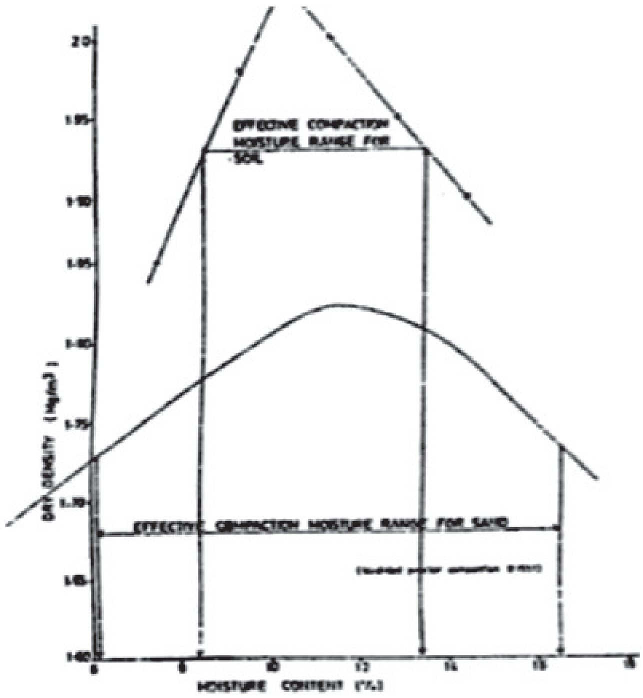

Fig. 11: Comparison of effective compaction moisture ranges for lateritic soil and sand

Table 1: Acceptance criteria for compaction

S/NO	Maximum dry density (Mg/m^2)	Optimum moisture content OMC (%)
1		
2		
3		
4		
Averages	1.92	16.8
Acceptance criteria	Not less than 95% of laboratory maximum (i.e. greater than 1.73 Mg/m^3)	Operating moisture content window 15.8-19.8%

The combination of widespread poor soil condition and the use of a design code that has little regard for our regional peculiarities has created a situation of pavements with very short service life often lasting not more than 2 years. Some of resultant road failures are depicted in Fig. 12.

Several questions are usually asked following the premature failure of these pavements. Such questions range widely from foundation, subgrade conditions, aggregates, compaction states, QA/QC, responsible officers and may include:

- Were the provisions of the code adequate and were they followed diligently – Does the code recognize the peculiarities of the region?
- Could the problem be the choice of construction materials; laterites, sand and crushed stones?
- Were the personnel involved in the material selection and testing Certified Engineering Geologists?
- Was a sub-soil investigation performed by a competent and duly certified engineering geologist or geotechnical engineer?

In responding to these questions, it is important to understand that the key requirements for pavement

Fig.12: Pavement conditions in sections of the Niger Delta.

design is the duty of the engineer. Usually, careful consideration includes various factors to ensure durability, safety, and efficiency.

Traffic and Load Considerations: Pavements must be designed to withstand specific traffic loads and climatic conditions, ensuring that stresses and strains do not exceed acceptable limits.

Material Selection: The choice of materials for pavement component layers exclusive of the subgrade, which must be fit to purpose, is crucial. This ensures use of environmentally friendly materials and construction processes

Sustainability and Efficiency: Lastly, the integration of sustainable practices and advanced methodologies such as the use of geosynthetics. Understanding soil behavior is the duty of the Engineering Geologist. The considerations for choice of material and preparation of each layer considers Strength, Stiffness, Permeability, Groundwater Condition and Compressibility.

Construction and Earthworks Quality Control

It is important to keep water away from the road throughout the service life. This is because water in road bed leads to increased unit weight under saturated conditions, reduced shear strength, excess pore water pressures, increased seepage pressure and reduced effective stress constituting the major culprit in road failures (Abija *et al.* 2019). Good construction practice therefore ensures the road surface is cambered and there is adequate provision of cross drainages at appropriate location chosen on the basis of geohydrological and geomorphological setting along the route. Adequate compaction of each pavement material layer to field density conditions is a step to ensuring maximum performance of the pavement structure.

Geotechnical setting of the Niger Delta Region and

There are six major geomorphic units that comprise the Niger delta as evidenced in Fig. 13. Their geospatial locations, compositional make-up and basic hydrologic conditions have been associated with observed peculiarities in geotechnical behaviours, particularly strength, compressibility and permeability as summarized in Table 2 (Abam, 2020).

With such wide variations in geotechnical properties, it is difficult to understand how the same road design code could be applied across the Niger delta. The argument for an urgent review of the Federal Road Design Code to

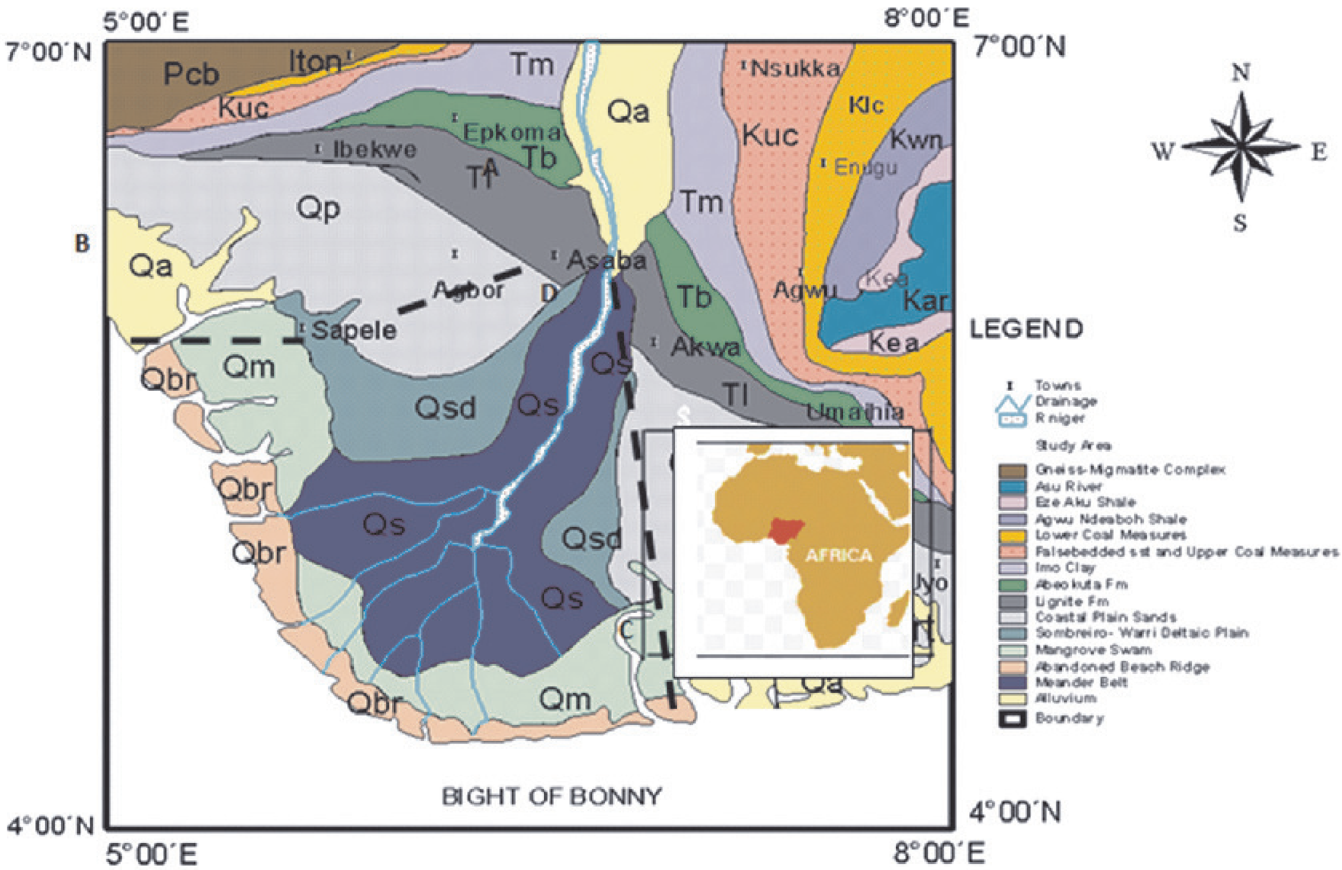

Fig. 13: Geological map of the Niger Delta.

Table 2: Summary of Geotechnical properties for geomorphic units

Geomorphic Units	Depth (m)	Bearing Capacity kN/m²	California Bearing Ratio (CBR) %	Undrained Strength UU (kPa)	Unit Weight (kN/m³)	LL (%)	PL (%)	PI (%)	Moisture Content (%)
Mangrove Swamp	0-3 0-10	5-30 30-100	1-2 1.5-6	12 55	14-16	55-300	20-80	50-220	50-90
Coastal Plain sands	0-3 0-10	10-150 150-250	3-5 10-20	50 120	17-20	35-50	10-25	17-25	12-27
Lower Niger Flood Plain	0-3 0-10	60-110 120-230	3-5 8-15	35 110	16.8-20	35-49	9-20	10-23	18-25
Barrier Island	0.3 0-10	100-180 125-280	6-16 8-30		17-21 18-22				11-18
Niger flood zone (Meander Belt)	0-3 0-16	20-80 40-150	1-6 2-8	8-63	12-18.4	35-174	11.5-45	11.7-113	38-430

allow or accommodate the peculiarities of the region is therefore not only appropriate but imperative. Depth to water table as well as the antecedent moisture content also varies across the region (Fig.16) from less than 0.5 m in the coastal area and up to 30 m in the northern section of the delta. The depth to water table is significant because it defines the available sub-soil storage capacity at periods of prolonged rainfall or other surface runoff generating events that can potentially result in submergence of pavement. It also helps in assessing the risks posed by capillary rise in the effective performance of the pavement.

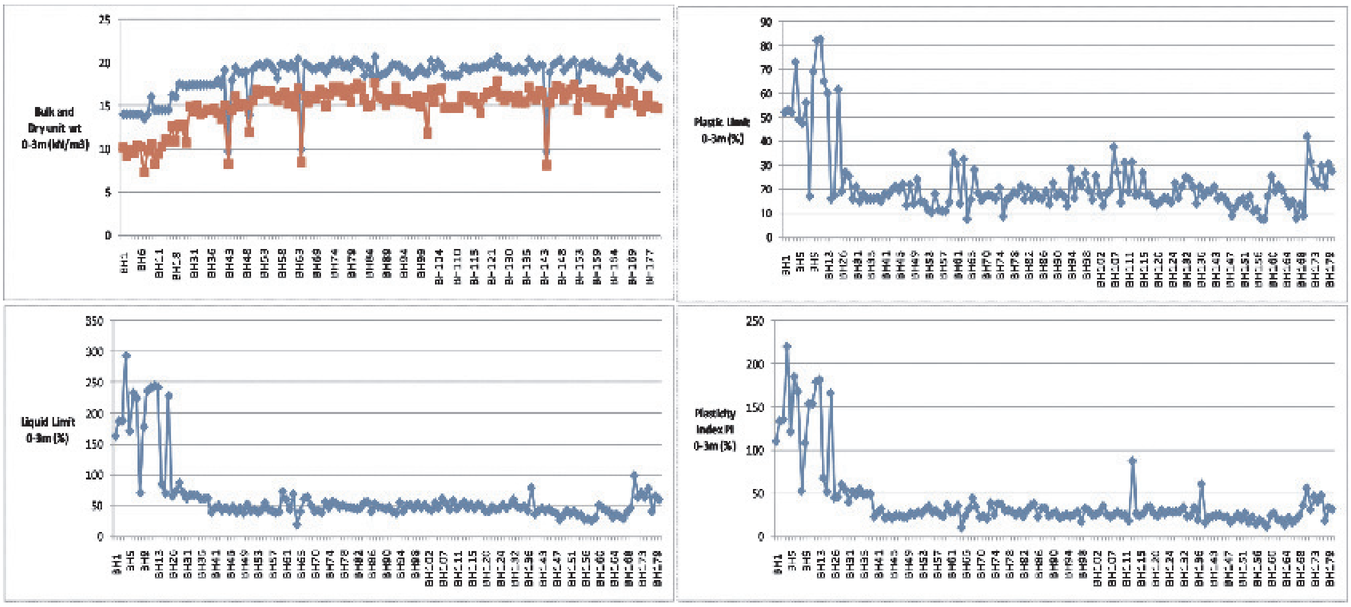

Fig. 14: Spatial variations in geotechnical properties

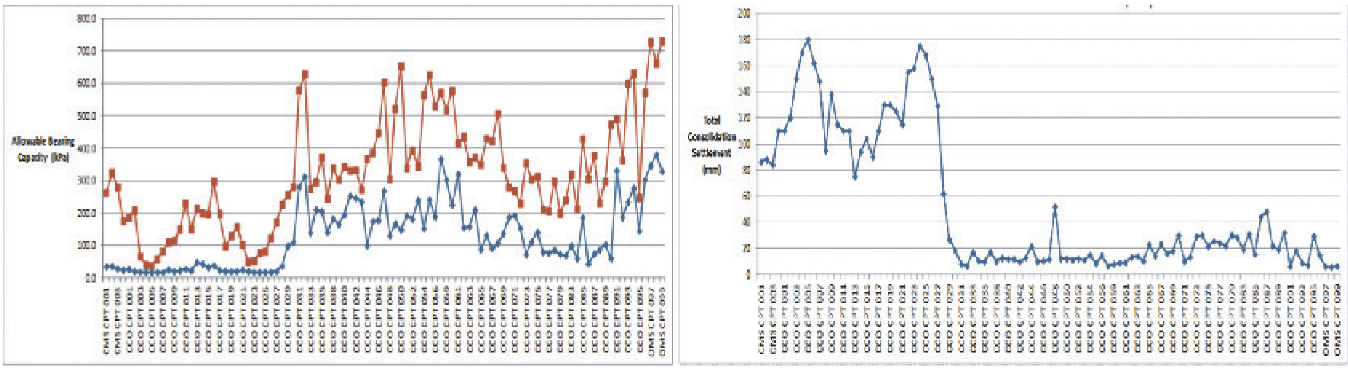

Fig.15: Variation in allowable bearing capacity and consolidation settlement across the Niger delta

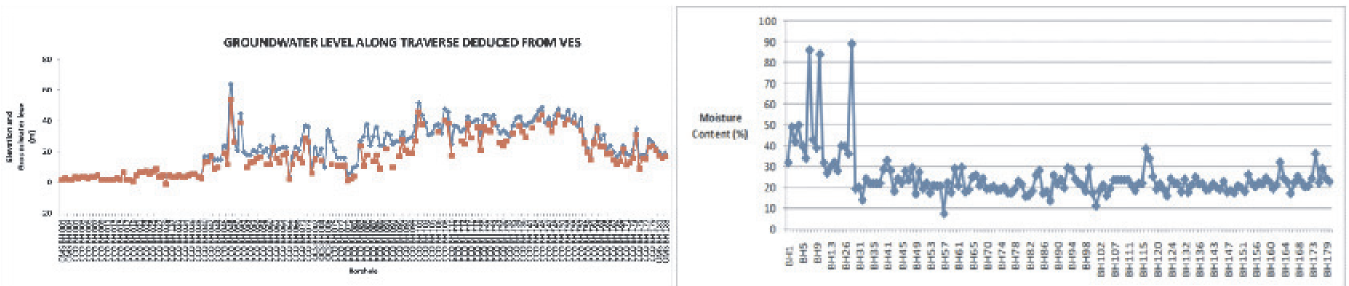

Fig. 16: Variation in depth to water table and moisture content across the Niger delta

Assessment of Feasibility of Deep Failures

Pavement failures are not always due to poor design or construction. They could be due to deeper poor soil conditions which are prevalent in the Niger delta, as illustrated in Fig. 17. In normally consolidated soil typified by Fig. 17, where the bearing capacity of the top soil is less than the axially induced stress, the top 0.5 m of the subgrade would be excavated and replaced or stabilized prior to construction of the pavement. However, there may be cases of weak layers at depth where such excavations may not be possible. In such cases, failures would be expected where the stress induced by the axial load exceeds the bearing resistance of the soil at a given depth. Fig. 17 shows several horizons where the axially induced stress increment is equal or in excess of the bearing capacity of the soil creating conditions for potential shear failure beneath and endangering the overlying pavement.

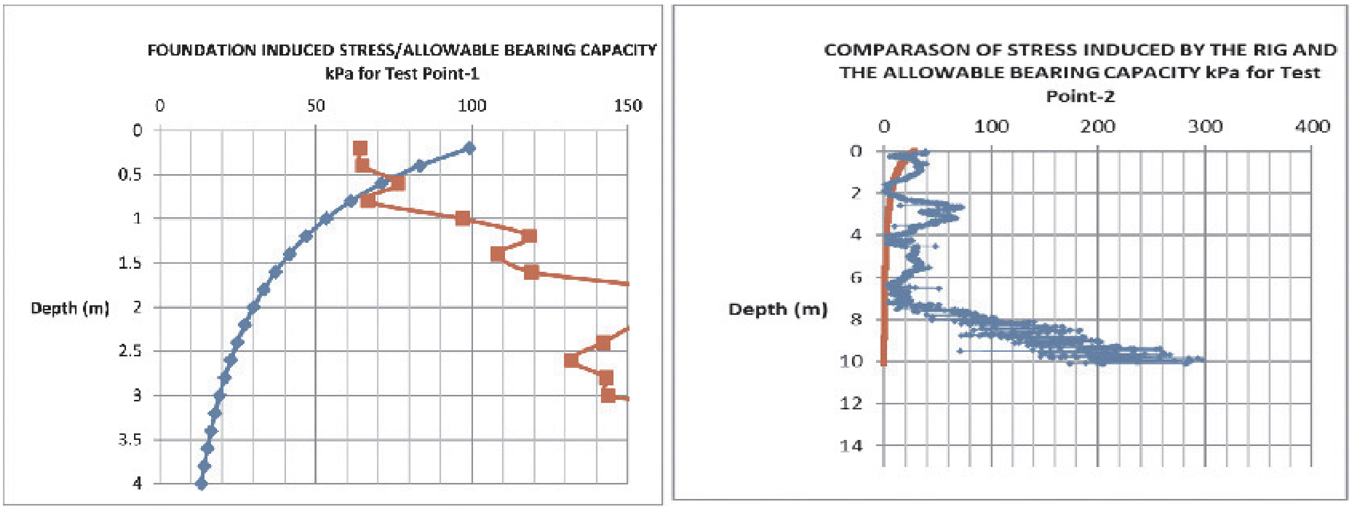

Fig. 17: Comparison of bearing resistance profile produced from CPT with traffic induced stress revealing potentially vulnerable zones of deep shear failure.

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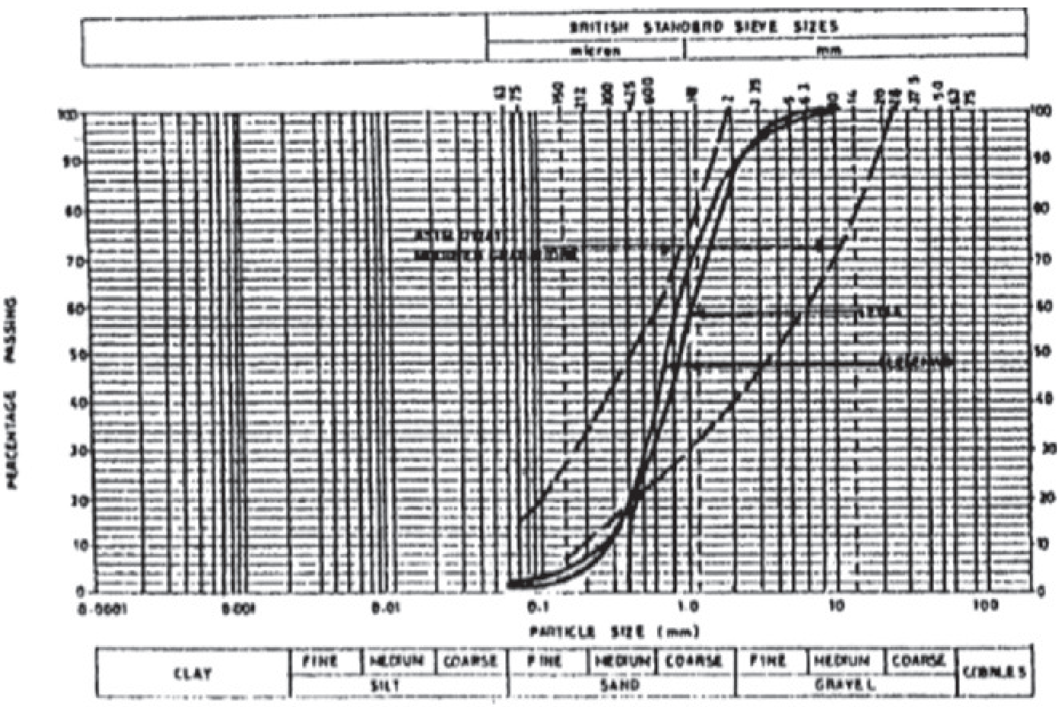

Fig. 18: Particle size distribution and specification for sand backfill aggregates

The idea of increasing intergranular contact to maintain strength, stiffness and durability while allowing the flow of water leads us only to the concept of granular filters exemplified in Fig. 18.

Resilience – Considerations and Role of an Engineering Geologist

To ensure resilient civil structures, understanding soil and environmental conditions is paramount. This involves integrating soil-structure interaction principles, stabilization techniques, and risk assessment methodologies to enhance structural integrity and sustainability. Soil-structure interaction (SSI) plays a crucial role in structural reliability, particularly under varying load scenarios. Effective integration of SSI principles can lead to sustainable construction practices that withstand environmental changes.

Soil Stabilization Techniques

Chemical and physical techniques, improve soil properties, increasing bearing capacity and reducing environmental impacts. Utilizing waste materials (for example, quarry dust) as stabilizers not only enhances soil performance but also promotes eco-friendly construction practices. While these strategies enhance resilience, challenges remain in balancing immediate construction needs with long-term environmental sustainability, necessitating ongoing research and innovation in civil engineering practices.

Geological Assessment and Material Selection

Engineering geologists conduct thorough geological investigations to identify material properties and site conditions, which are essential for sustainable pavement design (Paige-Green, 2011). They advocate for the use of alternative materials, such as geosynthetics, which have been shown to significantly reduce rutting and improve pavement longevity (Harish *et al.*, 2019).

Innovative Solutions for Ground Conditions

Addressing problematic ground conditions, the engineering geologists develop innovative solutions like lightweight fill technologies and composite mat structures, which enhance stability and reduce maintenance costs (Ratha *et al.*, 2018). Their involvement in rural infrastructure projects emphasizes the importance of sustainable practices in low-resource settings, contributing to poverty alleviation (Lagesse *et al.*, 2022).

Environmental Considerations

Engineering geologists also focus on minimizing environmental impacts by optimizing resource use and implementing technologies that promote sustainability in construction practices (Bellezza *et al.*, 2019). While the engineering geologists play a pivotal role in advancing sustainable pavement design, challenges remain, such as balancing cost-effectiveness with environmental sustainability, particularly in resource-limited contexts.

Risk Assessment and Site Suitability

Engineering geologists employ various techniques to mitigate geological hazards in pavements, focusing on risk assessment, monitoring, and structural reinforcement. These methods are crucial for ensuring the safety and longevity of transportation infrastructure.Engineering geological assessments are essential for identifying potential hazards before construction.In regions prone to landslides, such as Ethiopia, timely assessments can prevent road blockages and economic losses by analyzing causes and mechanisms of failures (Hearn and Massey, 2009).

Structural Reinforcement

The use of geogrids has been shown to significantly reduce pavement defects caused by expansive soils, demonstrating a reduction in deformation by those factors. This method addresses the shrink/swell effects that can compromise pavement integrity. While these techniques are effective, challenges remain, particularly in developing regions where geological data may be limited. Continued innovation and adaptation of these methods are necessary to enhance resilience against geological hazards.

Sustainable Pavements Through Stabilization and Use of Geosynthetics

In road construction, encountering weak or variable ground can prompt the adoption of road stabilization – an alternative to excavating and replacing the subgrade. This method involves modifying subgrade soil properties by adding a stabilizing lime cement, or other chemical agent, mixed in-situ. Chemical stabilization methods, such as the use of slaked lime and cement, have been shown to significantly reduce swelling potential and enhance the strength of active soils, making them more suitable for road construction (Omotosho and Ogboin, 2009). A combination of well-compacted subgrade, cement-stabilized base courses, and effective drainage systems is recommended to improve pavement performance and longevity (Arumala and Akpokodje, 1987).

Geosynthetics have been used in sustainable pavement design to enhance the soil's bearing resistance, drainage efficiency and to facilitate consolidation settlement. Incorporating geogrids (Fig.19) for road and pavement stabilization further reinforces the efficiency of the road, offering a versatile solution for challenging ground conditions. This approach reinforces road efficiency whilst minimizing the need for extensive excavation, offering a versatile solution for challenging ground conditions.

Fig. 19: Geogrid in subgrade reinforcement

The geosynthetic performs drainage functions (Fig. 20) by permitting adequate fluid flow with little soil particle movement within its plane from the surrounding soil mass to different outlets. This figure demonstrates how water is captured from the pavement surface and safely conducted to the embankment drainage.

A more sustainable and cost-effective approach can be to place a stronger soil layer, typically compacted aggregate material, over the weak soil to distribute load (Fig. 21). This enhances bearing capacity, often incorporating a geosynthetic at the subgrade level and sometimes in combination with piles.

Where pavements are to be constructed in thick and very weak and saturated soils, prefabricated vertical drains (PVD), as depicted in (Fig. 22), can be used to facilitated drainage and by extension accelerate consolidation settlement. Consolidation enhances the undrained strength and the bearing resistance of the subgrade enabling it to support embankment and pavement construction.

Conclusions

Based on this study, the following conclusions are made:
The analysis of soil and environmental conditions for resilient pavements in the Niger delta reveals significant challenges due to the region's unique geotechnical properties and environmental factors. Understanding these conditions is crucial for developing effective pavement solutions. The role of the engineering

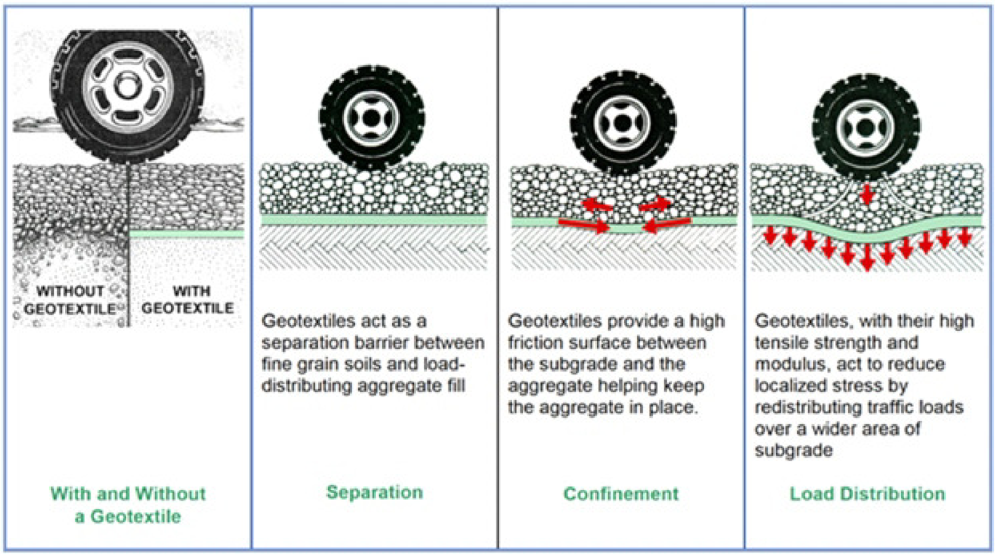

Fig. 20: Geosynthetics in facilitating pavement drainage

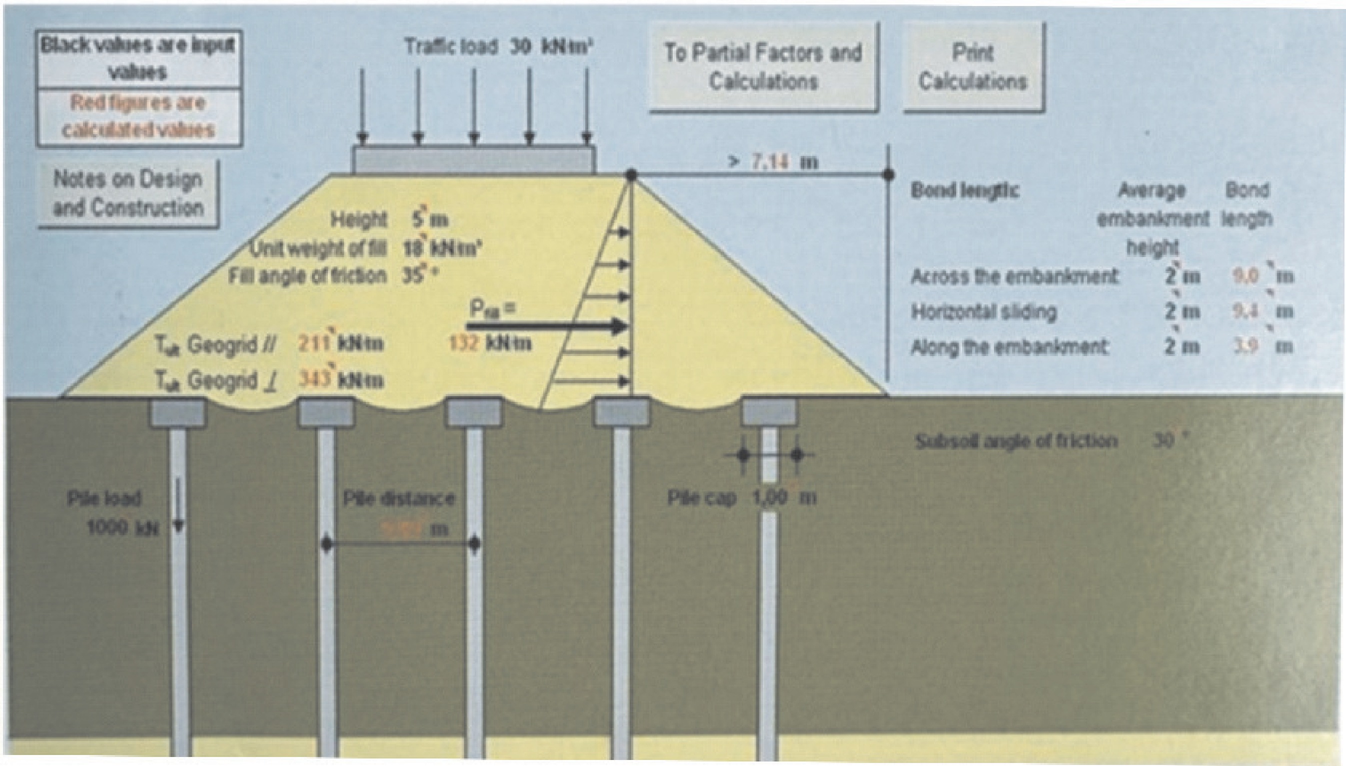

Fig. 21: Geosynthetics used in combination with piles

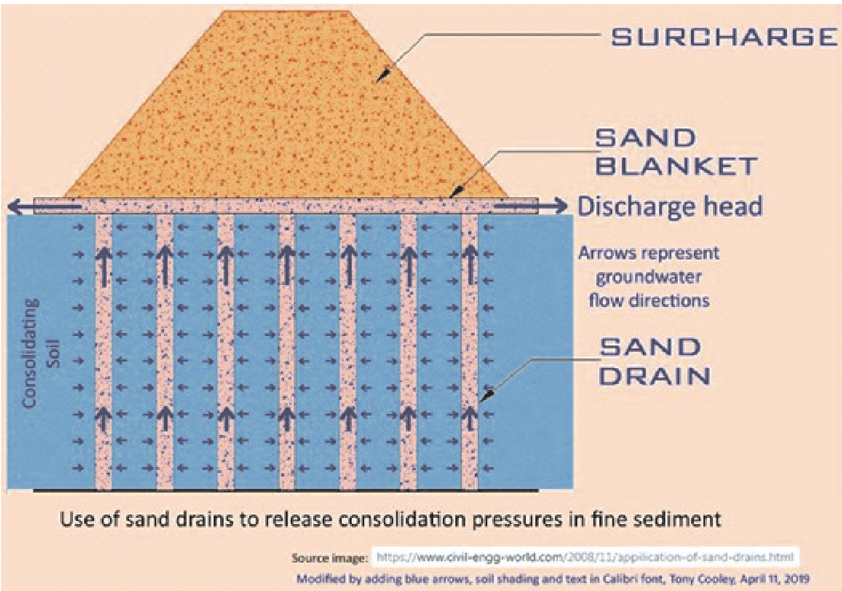

Fig. 22: Use of prefabricated vertical drainage for acceleration consolidation settlement

geologists in sustainable pavement design is crucial, as they address geological challenges and promote the use of sustainable materials and practices.

The expertise of the engineering geologists ensures that pavement systems are resilient, environmentally friendly, and economically viable. The case for domesticating the design codes for roads based on regional geological and environmental peculiarities such as exist in Lagos and Niger delta is justifiable. The choice of materials is to reflect both availability, function of structural components, flexibility of use during both seasons (wet/rainy and dry). In summary, while the Niger delta presents significant challenges for pavement construction due to its soil and environmental conditions, effective stabilization techniques and proper design can enhance resilience. However, ongoing environmental issues must also be addressed to ensure long-term pavement integrity.

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