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CLIMATE RESILIENT AND SUSTAINABLE INFRASTRUCTURES: GEOTECHNICAL CHALLENGES OF PROBLEMATIC SOILS IN NIGERIA

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Abstract

Climate change adaptation and sustainable infrastructure development are important in Nigeria due to different climate zones and poor soil types like expansive clays, laterite and peat grounds. The review highlights the necessity of incorporating climate change adaptation into infrastructure development processes to minimise the potential impacts of direct climate change phenomena, including extreme rainfall, flood, and temperature. It emphasises the importance of geotechnical engineering in tackling such challenges and advancing tools and frameworks required for constructing structures that successfully counter the undesirable soil responses caused by climate change. The review used literature search methods and data synthesis to identify empirical works that explore the geotechnical problems associated with Nigeria's problematic soils and their effects on infrastructures' durability. It organises results according to soil categories and introduces new geotechnical interventions, emphasizing chemical and mechanical stabilization methods to improve overall structural resilience. It also touches on some areas of policy and regulation that need reform in Nigeria to provide broader guidelines for geotechnical investigations and the adoption of new materials for construction. The manuscript concludes with policy implications and recommendations for implementing and developing solutions for climate-resilient infrastructure in Nigeria against climate change unpredictability concerning socio-economic activities and human life.

Keywords: geotechnical engineering, sustainable infrastructure, problematic soils, climate resilience

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1. 1INTRODUCTION

Climate change impacts have been on the rise recently making establishing sustainable infrastructure more vital, particularly for countries such as Nigeria [1]. Sustainable infrastructure is designed to be durable, and this is achieved by making minimal impacts on environmental systems while at the same time being capable of withstanding the climatic challenges that are being experienced today and, in the future [2]. In Nigeria, this relates to building structures capable of withstanding severe weather occurrences including rainfall, drought, and fluctuating temperatures [3]. The aim is to reduce vulnerability resulting from climate fluctuations and to foster higher levels of preparedness in regions where socio-economic activities depend on structures [4]. This double strategy protects investments and lives and promotes sustainable development in the face of climate change [5]. The climatic conditions in Nigeria encompass arid areas in the northeastern part of the country, making it relatively drier as one moves towards the southern parts of the country, where the climate is generally hot and more humid [6, 7]. Some of the natural conditions that affect infrastructure in Northern Nigeria include soil desiccation and cracking due to a generally dry weather condition [8]. On the other hand, the southern equivalents receive much rainfall and often experience floods which in turn cause soil erosion, landslides and dilapidation of roads and buildings especially in the flood-ravaged Niger Delta region [9]. These climatic impacts indicate the importance of considering climate resilience in infrastructure engineering to cater to drought and flood occurrences that are becoming more frequent and intense due to climate change [10]. These climatic conditions are of particular concern due to their significant impact on infrastructure construction and maintenance; geotechnical engineering offers methods and approaches to design structures for varying ground conditions [11, 12]. The nature of soils found in Nigeria such as expansive soils, lateritic soils, and peat soils present certain difficulties that should be controlled to enhance infrastructure stability [13]. The nation's development policies on infrastructure and climate change have been designed to preview the rising troubles of climate change, particularly those on sustainability. [14] also focused on developing the capacity to install effective structures that will withstand shocks of severe rainfall, floods and droughts as espoused in the National Adaptation Strategy and Plan of Action on Climate Change. Likewise, Vision 20:2020 and the Economic Recovery and Growth Plan (ERGP) agree with the development of infrastructure as paramount to the growth of a nation proposing the construction of roads, bridges and buildings that are resilient to climate change [15, 16]. However, these policies do not include clear recommendations and plans for dealing with the adverse geotechnical conditions in the country; especially the expansive clays, lateritic soils and peat soils on which some infrastructure developments are being established. Thus, it is necessary to develop new guideline documents that require detailed geotechnical characterization, state-of-the-art ground treatment solutions, and modern construction materials that would be effective for the future climate change of soils. Policymakers and engineers are encouraged to adopt several strategies for national infrastructure planning incorporating socio-economic and environmental factors. Transitioning from specification-based to performance-based design standards is necessary because it sets infrastructure resilience against current and future climate conditions and enables adaptability to uncertainties [17]. Whole-life cost approaches are included to incorporate long-term economic impact, sustaining development, and sustainable resource allocation [18]. Probabilistic Risk Assessments can help identify vulnerabilities so that disaster risk reduction policies can be formed to improve infrastructure resilience [17, 19]. Furthermore, incorporating socioeconomic metrics into project planning would help improve community value and equity while projects deliver broad societal benefits [20]. To achieve more resilient infrastructure systems [19], capacity building among stakeholders is essential for enabling collaboration and informed decision-making along the entire lifecycle of infrastructure systems. This review examines different engineering solutions and modifications required for sustainable infrastructure development in Nigeria; the stabilisations of expansive soils, mechanical or chemical methods for lateritic soils, and construction possibilities for sustainable development on peat soils [21, 22]. This manuscript also seeks to contribute to climate change adaptation by exploring these approaches to build more resilient infrastructures that will withstand climate change and its unpredictable effects [23].

2. METHODOLOGY OF THE REVIEW

2.1. Literature search strategy

In conducting the literature search for this review, the aim was to find works that discuss the tendencies of the geotechnical issues related to problematic soils in Nigeria and their effects on infrastructure under climate change conditions. The case studies were accessed from four databases; Google Scholar, Scopus, and Web of Science, and focused on the period from 2014 to 2024 since studies in the current period reflect the latest advancements in climate-resilient infrastructures. The search terms used were 'geotechnical engineering', 'problematic soils in Nigeria', 'climate resilience', 'infrastructure development', 'soil stabilization measures', and 'soil behaviour under climate change'. Other sources such as government documents, conference papers, and technical papers were also consulted to sample research from different regions of Nigeria.

2.2. Selection criteria

Studies were selected based on specific inclusion criteria:

- Relevance to geotechnical issues related to various types of problematic soils such as clayey soils, lateritic soils and peat soils in Nigeria.
- Considers the effect of climate change on the behaviour of soils and the structure of infrastructure.
- Empirical studies using methods such as field surveys, laboratory studies, geophysical and geotechnical investigations, and multivariate analysis
- Showcasing of sustainable and resilient infrastructure options, adaptation measures, and material alternatives.

Thus, exclusion criteria were as follows: Not published within the given period, unrelated to Nigerian soils, and not containing empirical data or practice application.

2.3. Research questions

- How do various problematic soil types in Nigeria, impact infrastructure stability under changing climate conditions?
- What climate-adaptive geotechnical methods are effective for stabilizing problematic soils to support resilient infrastructure?
- What regulatory and policy measures are necessary to support sustainable geotechnical practices for infrastructure resilience in Nigeria?
- How can geotechnical engineering innovations contribute to Nigeria's sustainable infrastructure goals in light of anticipated climate variability?

3. PROPERTIES OF PROBLEMATIC SOILS

Expansive soils such as clayey soils (table 1) especially the montmorillonite type are becoming prevalent in areas like central and northern Nigeria because they swell and shrink with changes in moisture content. Clay loam, concretionary clay, sandy clay, and silty clay (fig 1) are normally considered swell-shrink soils because of their high change in volume based on their moisture content as determined by microstructural and mechanical analysis [23]. They swell when wet and shrink when dry But, in the process, they exert relatively uneven pressure on the ground thus posing very high risks to the infrastructure [1, 21]. This cyclic behaviour leads to foundation uplift and cracking in roads, buildings, and pipelines and results in massive structural change [4, 22]. Expansion and contraction also undermine the stability of slopes, contributing to landslides and slope failures which is detrimental to slopes, embankments, retaining walls, and hillside roads [24]. Lateritic soils (table 1) common in southern Nigeria can be described as sandy-clay soil type (fig 1) and containing iron and aluminium oxide usually hardening into a cement-like mass when they are dry [25]. These soils are difficult to work with because of their cementation and the variation in the strength of the soils, such as their susceptibility to erode easily during the rainy season [11, 26]. Dispersed lateritic soils, when fully saturated, have a very low load-bearing capacity and this can result in the formation of structural failures or deformation of roadbeds, foundations, and even bridge abutments hence increasing construction costs [26]. The common soils in the coastal and deltaic regions of Nigeria such as the Niger Delta are highly organic peat soils with very low bearing capacity due to their high-water content and high compressibility (table 1). This leads to increased settlement and instability mainly in the foundation and road embankments [27, 28]. Due to the high compressibility and low shear strength of peat soils the chances of landslides and instabilities in infrastructure increase particularly when wet [29, 30]. Also, the decomposition of organic matter in peat soils changes the structure of the soil and acts negatively on the stability of the environment and structures [3, 31].

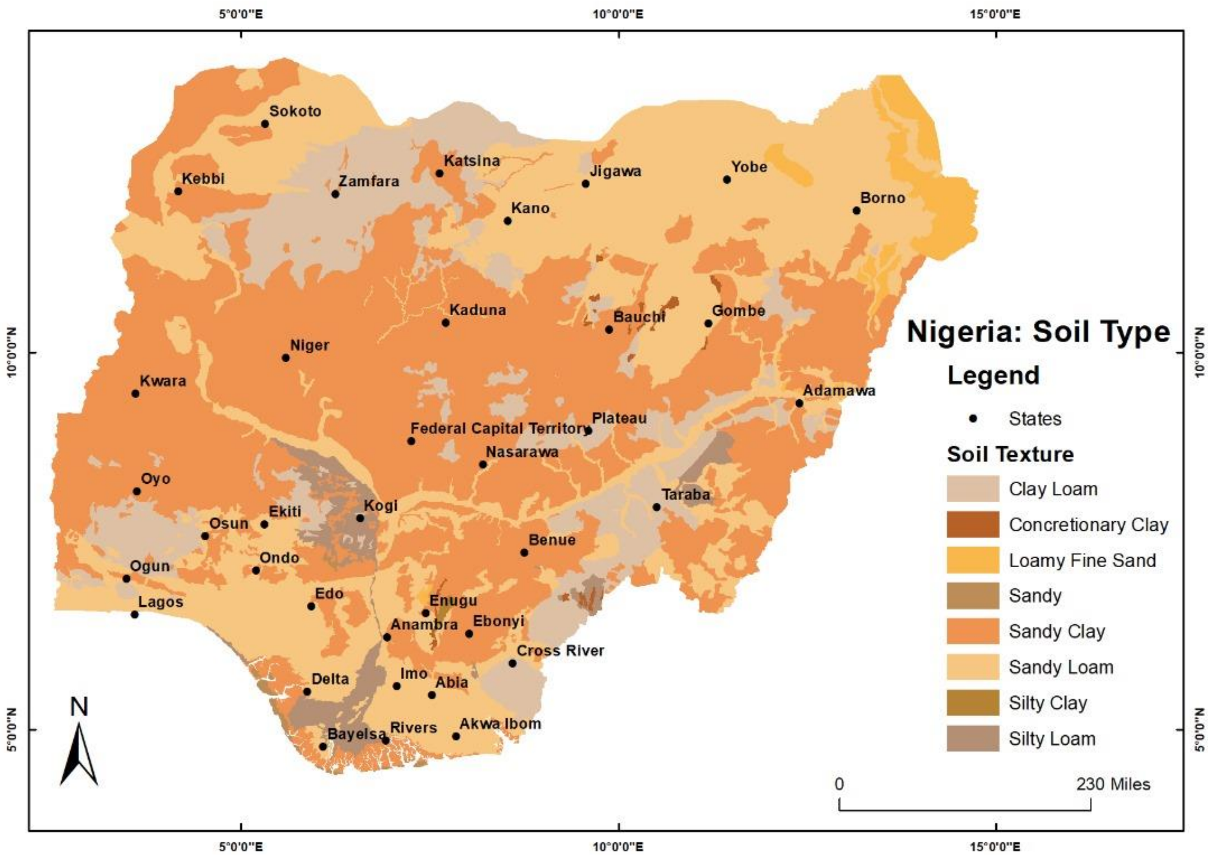

Fig. 1. Soil Map of Nigeria

Table 1. Common problems related to problematic soil movement

Problematic soil	Phenomenon	Soil reaction	Result	Geotechnical infrastructure affected
Expansive soils	Heaving/ Shrink & Swell	Soil undergoes significant volume changes due to moisture fluctuations.	Foundation uplift and damage to infrastructure such as roads and buildings, causing cracks and heaving.	Building foundations, pavements, road surfaces, and underground pipelines.
	Cracking	Soil contracts when dry and expands when wet, creating tensile stress.	Formation of large cracks on the ground surface and within structures, leading to structural instability.	Road pavements, walls, building foundations, and slabs.
	Slope instability	Repeated expansion and contraction weaken soil structure and slope cohesion.	Increased risk of landslides and slope failures, particularly during wet seasons.	Slopes, embankments, retaining walls, and hillside roads.
Lateritic soils	Cementation	Soil particles bind together due to high iron and aluminium oxide content.	Formation of hard, cemented layers that become difficult to work with during construction.	Road sub-bases, embankments, and dam construction.

	Erosion	Soil particles are easily detached and transported due to heavy rainfall.	Road surface degradation and loss of soil material, compromise road stability and require frequent maintenance.	Unpaved roads, slopes, embankments, and drainage channels
	Low load-bearing capacity	Soil strength diminishes under load due to its porous nature.	Structural failures or deformation of roadbeds and foundations lead to increased construction costs.	Roadbeds, building foundations, and bridge abutments.
Peaty soils	High compressibility	Soil compresses significantly under load due to high organic content and water retention.	Excessive settlement and sinking of structures, particularly for heavy buildings or roads.	Building foundations, road embankments, and bridge foundations.
	Low shear strength	Due to its fibrous and saturated nature, soil offers minimal resistance to shear forces.	Instability in foundation construction and higher risk of landslides, especially in wet conditions	Foundations, slopes, embankments, and retaining structures.
	Organic decay	Organic matter in the soil decomposes over time, altering soil structure.	Long-term settlement and potential release of greenhouse gases impact both structures and the environment.	Building foundations, roadways, and pipelines.

4. RESULTS AND DISCUSSION

4.1. Geotechnical challenges in developing climate-resilient and sustainable infrastructures

Foundation design issues

Planning and developing foundations on challenging ground conditions in Nigeria has some major barriers to attaining climate-adaptive and sustainable structures. Another problem is differential settlement where some parts of a building settle at different rates depending on the soil composition underneath and this leads to the formation of cracks and structural failure (fig 2). This is compounded by the situation where the soils are expansive, particularly the clayey and black cotton soils which are prevalent in states including Enugu and Plateau (table 2). They expand on contact with water and shrink when the water content in the soil decreases; this leads to a lot of ground movement negatively affecting the foundation [3, 32]. For instance, in States like Abia, dry seasons lead to the shrinkage of clayey soils and the formation of fissures that affect the stability of building foundations [5]. Water seeping via flood and increased precipitation aggravates the issues relating to foundations by decreasing the capacity of soils and soil stability. For example, in the Niger Delta, peat soils are compressible, low-shear strength soils which pose a lot of problems in the construction of foundations due to their high tendency to undergo settlement and stability when loaded [33]. Mitigation strategies in building foundations failure in problematic soils include increasing the use of geotextiles, installing sub-drainage systems to prevent groundwater, using filtration techniques to prevent the accumulation of soil particles and improve the stability of the structure and reduce the settlement risks [34]. Ground densification techniques also contribute to reducing net excess pore pressures and foundation settlements [35].

Fig. 2. Building foundation failures [3]

Road construction difficulties

The challenges associated with constructing roads on expansive and lateritic soils in Nigeria are immense especially as the issue of climate change is considered. Soil of expansive nature affects pavements significantly in central and northern Nigerian states like Niger and Kogi states where the development of cracks, ruts, and heave has been attributed to soil expansion and contraction as a result of increased moisture content [4]. These soils are sensitive to changes in weather conditions and they are most likely to be affected, meaning they require regular maintenance and they are therefore expensive. Another type of soil is the lateritic type of soil, which is found in the southern part of the country, including Oyo and Ekiti States, and has its own set of challenges. These kinds of soils deform and swell when they are wet particularly so during the periods of the heaviest rainfall [1, 2, 8] as illustrated by the pavement shown in Figure 3. This is because, apart from being prone to general wear and tear, erosion due to intense rainfall distorts the road surface requiring constant resurfacing and thus, such roads have a high cost-benefit of maintenance and are ruinous to the physical environment [1]. To increase the sustainability and longevity of road infrastructure, measures like the use of concrete pavement, polymer-modified asphalt and sound drainage systems have been adopted to make the roads more durable and withstand severe weather conditions as specified by [8, 36]. Similar challenges, in terms of road construction on lateritic soils, have been found in both Brazil and Southeast Asia, giving rise to innovative solutions designed to increase road resilience. Mechanical performance of reclaimed asphalt pavement and lateritic soil integration has been shown to have been improved particularly with a 25% reclaimed asphalt pavement mixture with reduced deformation and cracking [37]. In addition, the use of hydrated lime and liquid stabilisers has been shown to enhance the strength and the load-bearing capacity of lateritic soils and optimized combinations resulted in significant improvement in California Bearing Ratio (CBR) values [38]. Improving drainage systems and the use of soil stabilisers (e.g., lime and fly ash) in Southeast Asia has been shown to mitigate the problem of moisture sensitivity and extend road lifespan [39, 40].

Fig. 3. Road failure aided by intense rainfall [36]

Slope stability

Slope stability is an important factor in the climate adaptive design of infrastructure in problematic soil areas where slope failures such as landslides and erosion are more frequent and compounded by the effects of climate change. Soil shrinkage during dry time decreases the cohesive nature of the slopes in clayey and smectite-rich soils in Enugu State (table 2) and therefore leads to increased slope failure [5]. Likewise, in sandy and clayey soil types such as in the southwest part of Nigeria, probable high rainwater intensity causes soil saturation, decreasing its shear strength and thus exposing slopes to failure [41]. Due to steep slopes and poor soil compaction, those areas are more susceptible to landslides that greatly threaten roads, embankments, and other structures (fig 4). To overcome these challenges, and increase the stability of the infrastructures, slope reinforcement methods like retaining walls geotextiles, and drainages to countercheck cases of landslides and erodement [7, 42]. In Southern Africa, community-driven approaches have realised integration of the green infrastructure and nature-based solutions to improve slope stability and socio-economic benefits while addressing environmental hazards thereby enhancing community engagement and resilience towards climatic risks [43, 44]. In regions prone to landslides like Japan and Nepal, this challenge is made worse by climate-induced precipitation resulting in more sediment disasters and slope instability. Both countries employ multiple slope reinforcement techniques such as drainage systems and rock anchors that are used for landslide control [45, 46]. It has been shown that the development of underground drainage systems can significantly minimize the rise of groundwater level which leads to mitigating the slope instability caused by preferential shallow water flows during heavy rainfall [47]. Further, geosynthetics and other structural measures including retaining walls [46, 48] have been pointed out as important for the improvement of slope stability although the effectiveness of these might be dependent on local conditions and community perceptions.

Fig. 4. Failure of prevention works due to instability in slope material [41]

Table 2. Geotechnical challenges and climate-resilient solutions for problematic soils in Nigeria

Nr	References	Methodology	Type of Problematic soil/ geologic formation	Summary of research	Geotech. inf.	Impact of Climate Change	Sustainable and Resilient Infrastructure Solutions
1	[1]	Geotechnical study of pavement indices	Lateritic soils	Analyzed pavement indices influencing failures along Ado-Ajebandele-Ikere road in Southwestern Nigeria.	Road Pavement	**Drought and Soil Shrinkage:** Dry conditions lead to the contraction and cracking of lateritic soils, causing surface deformation and contributing to pavement failure.	**Case Studies:** Implementation of moisture control measures and the use of road surface sealants to protect against shrinkage and cracking during dry spells.
2	[2]	Road failure investigation	Sandy and clayey soils	Investigated causes of road failure along Sagamu-Papalanto highway in Southwestern Nigeria.	Road Pavement	**Flooding and Soil Saturation:** Increased rainfall and flooding lead to soil saturation, reducing soil shear strength and causing road surface failure and erosion.	**Adaptation Strategies:** Incorporating flexible pavement designs and implementing soil reinforcement techniques, such as the use of geotextiles, to improve road resilience against flooding.
3	[3]	Field investigations and integrity assessment	Clayey soils	Investigated the structural integrity of foundations in failed buildings in Ehamufu and	Building Foundation	**Flooding and Soil Saturation:** Increased rainfall leads to soil saturation,	**Adaptation Strategies:** Implementing proper drainage systems and using waterproofing materials can help

				Aguamede, South East Nigeria.		weakening clayey soils and compromising building foundations, causing settlement and structural failures.	manage increased soil moisture levels, improving foundation resilience against saturation.
4	[4]	Geophysical and geotechnical investigations	Clayey soils	Investigated failed road pavements in Northcentral Nigeria through geotechnical methods.	Road Pavement	**Drought and Soil Shrinkage:** Prolonged drought conditions cause clayey soils to contract, leading to cracks and weakening of the road subgrade, resulting in pavement failures.	**Case Studies:** Application of moisture-retaining agents and polymer-based stabilizers to maintain subgrade integrity during dry periods, ensuring road longevity.
5	[5]	Geotechnical and geophysical techniques	Smectite-rich clayey soils	Assessed frequent building collapses in Akpugo, Enugu, South-East Nigeria using geotechnical and geophysical methods.	Slope Stability	**Drought and Soil Shrinkage:** Dry conditions cause smectite-rich clayey soils to shrink, reducing slope stability and increasing the likelihood of slope failure.	**Adaptation Strategies:** Implementing slope reinforcement techniques such as retaining walls and geotextile reinforcements to enhance slope stability under dry conditions.
6	[6]	Chemical and geotechnical assessment	Low organic clayey soils	Evaluated the chemical and geotechnical properties of low organic foundation soils in Southwestern Nigeria.	Embankment	**Climate Variability and Soil Behavior:** Changes in soil chemistry and moisture levels due to climate variability affect the structural integrity of low organic clayey soils, leading to embankment failure.	**Case Studies:** Incorporating chemical additives to improve soil properties and resilience to changing climatic conditions, enhancing embankment stability.
7	[8]	Satellite imagery and geophysical investigation	Lateritic soils	Used satellite imagery and geophysical methods to investigate highway pavement instability in Southwestern Nigeria.	Road Pavement	**Flooding and Soil Saturation:** Heavy rainfall leads to saturation of lateritic soils, reducing soil cohesion and causing instability and deformation of highway pavements.	**Adaptation Strategies:** Designing elevated road embankments and implementing proper drainage systems to reduce the impact of flooding on road stability.
8	[10]	Geotechnical investigation	Sandy-clay subsoils	Investigated the geotechnical properties of sub-soils in Daki Biyu District, Abuja, Central Nigeria for infrastructural development.	Road Pavement	**Climate Variability and Soil Behavior:** Variable precipitation and temperature fluctuations affect soil cohesion and stability, posing risks to road infrastructure.	**Case Studies:** Utilizing advanced soil compaction techniques and moisture control measures to improve soil resilience and infrastructure durability.
9	[30]	Geotechnical and environmental testing	Sandy soils with tar contamination	Investigated the engineering properties of soils in tar sand areas of	Bridge Foundation	**Climate Variability and Soil Behavior:** Variations in temperature and moisture levels due	**Case Studies:** Implementing enhanced compaction techniques and using soil stabilization methods to

				Southwestern Nigeria.		to climate change impact the compaction and stability of sandy soils, leading to potential issues in bridge foundations.	improve the load-bearing capacity and reduce settlement risks in sandy soils.
10	[32]	Structural and geotechnical analysis	Black cotton soils	Characterized structural failures founded on soils in Panyam and Mangu, Central Nigeria.	Building Foundation	**Drought and Soil Shrinkage:** Extended periods of drought lead to severe shrinkage in black cotton soils, causing foundation movement and structural damage.	**Innovative Materials and Technologies:** Developing flexible foundation designs that can accommodate soil movement and using chemical soil stabilizers to minimize shrinkage.
11	[33]	Geotechnical and geophysical investigation	Peaty and clayey soils	Created profiles and spatial distribution maps of problematic soils in Kosofe, Lagos, Southwestern Nigeria.	Building foundation	**Flooding and Soil Saturation:** High rainfall events increase soil moisture levels, reducing soil strength and causing settlement and foundation instability.	**Adaptation Strategies:** Elevating building foundations and using pile foundations to avoid settlement in areas with high water table and peat presence.
12	[36]	Pavement deterioration analysis	Lateritic soils	Analyzed the rates of deterioration in flexible road pavements in Benin City, Nigeria.	Road Pavement	**Climate Variability and Soil Behavior:** Temperature fluctuations and increased rainfall cause swelling and softening of lateritic soils, leading to accelerated pavement deterioration	**Case Studies:** Using concrete pavements and polymer-modified asphalt to improve the durability and lifespan of roads in regions with problematic lateritic soils.
13	[41]	Geotechnical testing and slope stability analysis	Water-saturated slopes	Examined the effects of water saturation on slope stability in the Iva Valley area, focusing on slope failures due to soil saturation.	Slope Stability	Flooding and Soil Saturation: Heavy rainfall and increased water saturation reduce soil stability, increasing landslide risks.	Adaptation Strategies: Implement proper drainage systems and use slope reinforcement techniques such as retaining walls to enhance stability against water saturation.
14	[49]	Multidimensional soil characterization	Lateritic and clayey soils	Characterized problematic soils linked to foundation and building failures in Southeast Nigeria.	Building Foundation	**Drought and Soil Shrinkage:** Prolonged dry periods cause shrinkage in clayey soils, resulting in cracks and damage to building foundations, increasing the risk of structural failure.	**Innovative Materials and Technologies:** Utilizing soil stabilization techniques, such as lime stabilization and geosynthetics, to enhance soil strength and reduce shrinkage.
15	[50]	Geotechnical appraisal	Sandy and clayey soils	Appraised geotechnical failures in highway pavements in Northcentral Nigeria.	Road Pavement	**Climate Variability and Soil Behavior:** Temperature changes and variability in precipitation affect soil strength and stability, leading to	**Innovative Materials and Technologies:** Using advanced materials like geosynthetics and nanomaterials in pavement construction to enhance soil stability and

						differential settlement and cracks in pavements.	reduce susceptibility to temperature and moisture changes.
16	[51]	Laboratory geotechnical tests	Lateritic soils	Investigated the geotechnical properties of lateritic soils in Ogua, Niger Delta, Nigeria.	Road Pavement	**Climate Variability and Soil Behavior:** Fluctuating moisture levels due to climate change impact soil behavior, causing differential settlement and cracking in road pavements.	**Innovative Materials and Technologies:** Using soil stabilizers and reinforcement materials to enhance the durability and performance of road pavements under variable climatic conditions.
17	[52]	Geotechnical analysis	Lateritic soils	Evaluated the geotechnical properties of lateritic soils in Minna, North Central Nigeria for road design and construction.	Bridge Foundation	**Flooding and Soil Saturation:** Increased rainfall and flooding events lead to soil saturation, reducing the strength and load-bearing capacity of lateritic soils, compromising bridge foundations.	**Case Studies:** Utilizing deep foundation techniques such as pile foundations to transfer loads to stable strata and avoid settlement in saturated soil conditions.
18	[53]	Multivariate analysis and geotechnical testing	Lateritic soils	Assessed the quality of lateritic soils in Northeastern Nigeria for use in embankment construction.	Embankment	**Drought and Soil Shrinkage:** Dry conditions lead to the hardening and cracking of lateritic soils, compromising embankment integrity and increasing maintenance needs.	**Innovative Materials and Technologies:** Applying soil conditioning agents and geotextiles to enhance soil properties and reduce susceptibility to drying and cracking.

4.2. Ground improvement techniques

Chemical stabilisation

Soil chemical stabilization is an essential technique that enhances the characteristics of soil which can enhance climate change resilience and sustainable construction. It was also found that the property of making the expansive and lateritic soil more stable can be improved through chemical stabilizers including lime, cement, or fly ash which proved to increase the load-bearing ratio while reducing swelling potential [51]. For example, lime stabilisation has been adopted in south-eastern Nigeria especially in Abia and Edo States (table 2) to increase the stability of clayey subsoil due to its plastic nature [49]. Cement stabilization is most appropriate in lateritic soils because it strengthens the bonding of the soil and also reduces the ability of the soil to be eroded when exposed to very high rainfall and flooding [52]. The use of stabilisers which include waste materials and industrial byproducts enhances the properties of the soil besides helping in environmental conservation by recycling wastes and reducing carbon dioxide emission [21]. Such chemical treatments assist in the control of moisture content in the soil as this will affect the stability of any infrastructural development during instances of floods or storms [50]. In India, the use of geosynthetics and deep soil mixing to strengthen soil and mitigate expansion problem is a common practice [54]. Similarly, the problems of shrinkage and swelling in expansive soils [55] in the arid regions of Australia are addressed by means of chemical stabilization techniques, such as lime stabilization, which further demonstrate the versatility of such techniques.

Mechanical methods

Compaction and dynamic compaction procedures are effectively used as mechanical methods to increase the density and stability of problematic soils, thereby causing an increase in the durability of infrastructure. There are compaction techniques for increasing soil density by reducing the void spaces they are more effective for sand and clayey soil in southwestern Nigeria where it improves the strength and bearing capacity of the soil [2]. Dynamic compaction, which involves dropping heavy weights to densify the soil is suitable for treating lightly consolidated, compressible and mobile soils as noticed in Ondo state which has sandy soils [30]. They are important tools in settlement reduction and enhancing the bearing capacity of the soils under different climate changes [4]. Furthermore, the application of other geosynthetics products, including geotextiles and geomembranes, has been found to work well in the stabilisation of soils and improvements in road pavements and slopes where there are problems with rainfall or fluctuating temperatures [50]. However, when these mechanical techniques are incorporated and interwoven with timely and adequate measures for drainage and aeration of the soil used in the construction of such linear infrastructure, then it is possible to have a construction that would be able to withstand the effects of climate change. Moreover, enhanced mechanical properties were obtained in clayey soils by adding sustainable materials such as rice fibers and nano clay, thus becoming a low cost and ecofriendly alternative to conventional stabilizers [56]. Additionally, the mixed use of rice husk ash and cement kiln dust as stabilizers was found to improve the durability and strength of clayey soils and support sustainable construction [57]. Innovative approaches, including the incorporation of industrial solid waste and polypropylene fibres, have shown the possibility of improving the mechanical properties of expansive soils to improve their durability and eliminate volume changes [58, 59] whereas incorporation of geosynthetics, such as nonwoven geotextiles, have been proven to remedy adverse mechanical behaviour in weak soils and improve pavement performance over loose subgrades [60].

5. LIMITATIONS OF THE STUDY

Several limitations in this review may preclude the broader applicability of its findings. The attention is more restrained over Nigeria's geotechnical problems particularly problematic soils that would limit the generalizability of the conclusion for other climatic and soil conditions. However, variations in soil response under various environmental settings may render the suggested climate adaptation strategies inapplicable outside Nigeria. The review also focuses on expansive clays, lateritic soils and peat while neglecting other soil types that might pose problems in Nigeria and similar regions. This then can lead to valuable insights on climate resilience for a variety of soil contexts going unmentioned, leaving its proposed solutions less comprehensive.

Additionally, this review only briefly examines socio-economics implications, not attempting to delve into practical constraints like economic factors, policy gaps and local community dynamics which might contribute to the feasibility and efficacy of these geotechnical solutions in Nigeria. The applicability of these recommendations could be strengthened with the inclusion of a more detailed socio-economic assessment, which takes into account real-world implementation challenges. Both the reliance on secondary data and the lack of primary field data limit the ability to fully capture some nuanced aspects of how soil behaviour responds to climate stress, and therefore the accuracy of the insights.

Finally, the recommendations that arise from the review are relatively general, with no specified specific steps for incorporating climate resilience in Nigeria’s infrastructure development policies. The practical value of these recommendations would be increased by more specific policy guidelines targeted to Nigeria’s unique regulatory environment. Future research, however, could take on addressing these limitations by way of field-based studies, expanded soil types, and all-encompassing socio-economic analysis, to a great extent to help climate-resilient infrastructure planning in Nigeria.

6. CONCLUSION AND RECOMMENDATION

The review focuses on the need for sustainable infrastructure in Nigeria and the importance of geotechnical engineering in managing climate change effects on structures constructed on adverse soils. This paper identifies Nigeria's climatic and soil types, expansive clays, lateritic soils and peat as major factors affecting the structural stability of infrastructure. These problems are further worsened by climate change, for instance, with an increase in rainfall and flooding and fluctuations in temperatures, infrastructure becomes more vulnerable to failure and damage as well as high incidences of maintenance. To improve the performance of soil under climate stressors, this review proposes chemical (e.g., lime and cement treatments) and mechanical (e.g., compaction and use of geosynthetics) stabilisation methods and drainage systems as viable solutions to improve infrastructure durability. Sustainable infrastructure development also requires policy reforms, because guidelines at present do not have specific requirements for dealing with climate-driven soil behaviours. Predicting soil response to climate variations can be facilitated by the adoption of performance-based standards and systematic geoenvironmental assessments, preferably, leading to proactive infrastructure design. Furthermore, adopting whole-life cost approaches into infrastructure planning would aid long-term resilience by incorporating maintenance costs associated with climate impact.

Finally, this review concludes by emphasising the socio-economic benefits of the use of resilient geotechnical solutions, which could lower maintenance costs, minimize infrastructure failures as well as enhance community safety. Nigeria's strategic incorporation of climate adaptation measures into infrastructure planning can allow for increasingly sustainable, resilient infrastructure that can withstand unpredictable effects of climate change, whilst simultaneously promoting socio-economic growth and environmental protection. This approach emphasises the need for collaboration amongst policymakers, engineers and researchers in solving the isolated problems associated with the country's different soils and climatic conditions, while creating infrastructure that can sustain human and economic development.

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