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Research Article

Durability Performance of Onna Expansive Subgrade Soil Stabilized with Rice Husk Ash Geopolymer for Road Pavement Construction

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Abstract

The use of expansive soils as subgrades in road pavement construction poses significant challenges due to their high swell-shrink potential, leading to structural damage resulting to increased maintenance costs. This study investigates the durability performance of Onna Expansive Soil (OES) stabilized with rice husk ash (RHA)-based geopolymer, an eco-friendly alternative for enhancing soil properties. Geopolymer mixtures with varying RHA contents (10%, 20%, and 30% by dry weight) were prepared and subjected to cyclic wetting-drying conditions to simulate natural climatic changes. Key parameters, including California Bearing Ratio (CBR) and Unconfined Compressive Strength (UCS), were evaluated after 7 and 28 days of curing. The results reveal that mixtures with 10% RHA content showed significant weight loss, disintegrating by the 7th cycle, whereas 20% RHA stabilized samples survived up to intermediate cycles. The mixture containing 30% RHA exhibited optimal performance, retaining over 90% of its mass after 12 cycles, with a CBR value of 14.97% at 7 days and a residual UCS of 714 kN/m² after 28 days. These findings indicate that a higher RHA-geopolymer content significantly improves the long-term durability and strength of OES, making it a viable option for sustainable road construction. This study contributes to addressing both the disposal issues of agricultural waste and the enhancement of problematic soils, offering a pathway to cost-effective and durable road infrastructure in regions with similar soil conditions.

Keywords

Onna Expansive Soil, Subgrade, Rice Husk Ash, Geopolymer, Wetting-drying Cycles, Stabilization

1. Introduction

Sustainable road infrastructure development occasionally demands significant financial investment, making cost efficiency a critical factor in pavement engineering [1]. The stability and durability of pavement structures largely depend on the strength of the underlying native soil otherwise known as "subgrade soil" [2]. While some soils are inherently suitable for supporting pavement foundations, others—such as expansive soils—pose challenges due to their poor engineering properties. These soils can cause severe damage to pavements if not properly managed, leading to costly repairs and frequent maintenance.

Expansive soils are known for their high swell-shrink be-

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havior, which results from seasonal variation in moisture content [3]. These soils swell significantly when they absorb water and shrink when they dry, causing considerable movement that can damage overlying structures such as pavements, buildings, and retaining walls [4]. The collective annual loss attributed to damage caused by expansive soil in several developed nations like the UK, China, France, and the USA is estimated to exceed $23 billion [5].

Given the challenges posed by expansive soils, effective soil stabilization remains the key focus to enhance the geotechnical properties of weak soils, enabling them to withstand loads from traffic and resist environmental degradation. Stabilization methods can be broadly categorized into mechanical and chemical techniques [6]. Mechanical stabilization involves physical processes like compaction and reinforcement to improve soil properties without altering its chemical composition. On the other hand, chemical stabilization involves the addition of stabilizing agents, such as lime, cement, fly ash, and other industrial by-products, to react with the soil matrix, thereby enhancing its load-bearing capacity and reducing its swell-shrink potential [7, 8].

In recent years, there has been growing interest in sustainable and cost-effective alternatives for soil stabilization. One promising approach is the use of geopolymers derived from agricultural waste materials. Geopolymers, which are inorganic polymers formed through the chemical reaction of aluminosilicate materials, have shown significant potential as eco-friendly stabilizers due to their low carbon footprint, durability, and ability to utilize industrial and agricultural by-products [9]. These by-products act as precursors, which, upon activation with an alkaline solution, undergo a reaction known as "geopolymerization". This process results in the formation of polymeric Si-O-Al bonds, where silicon and aluminum atoms are coordinated tetrahedrally with oxygen and can be represented by the molecular formula $\{M_n\text{-}(SiO_2)_z\text{-}AlO_2\text{-}\}_n$, where M stands for alkali cations such as Na^+ or K^+, n represents the degree of polymerization, and z is the Si/Al molar ratio [10]. When the Si/Al ratio (z) is below 3, the resulting geopolymer forms a rigid three-dimensional network, whereas ratios exceeding 3 produce more linear structures with adhesive properties, making them suitable for soil stabilization [11].

Higher-temperature curing enhances early-stage strength in geopolymers, but excessive heat can cause weaker polymeric chains to form, which may compromise long-term durability. Furthermore, a low concentration of Ca^{2+} ions reduce the risk of ettringite formation, which is particularly beneficial in sulfate-rich soils [12]. Geopolymer-treated soils with optimal geopolymer content exhibit a marked increase in synthetic bond formation, enhancing the dynamic shear modulus and reducing shear modulus degradation [13]. This makes geopolymer-stabilized soils highly effective for supporting dynamic loading systems such as highway pavements.

RHA, a by-product of rice milling, has gained attention as a promising precursor for geopolymer synthesis. As an agricultural waste, RHA is derived from the burning of rice husks, which are generated during rice processing. In 2021, global rice production reached 787.3 million metric tonnes, with Nigeria producing approximately 8.34 million tonnes [14]. This yielded around 1.67 million tonnes of rice husk, which, when incinerated, produced roughly 333,680 tonnes of RHA [15]. Typically discarded in landfills, RHA contributes to environmental pollution. However, due to its high biogenic silica content, it exhibits excellent pozzolanic properties, making it a valuable material for sustainable construction [16, 17].

In recent years, extensive research has explored the use of RHA as a precursor for geopolymer production. Geopolymers derived from RHA have shown significant potential for stabilizing expansive soils. This sustainable approach not only addresses the disposal issue of rice husk ash but also offers an innovative method for improving soil stability in construction. For instance, Emmanuel et al. [18] explores the use of two wastes RHA and cement kiln dust (CKD) for improving the mechanical strength of a subgrade soil. The results showed improved mechanical properties with both stabilizers.

Similarly, Ayodele et al [19] investigated the use of RHA-based geopolymer for enhancing the properties of two tropical soils. Soils were stabilized with alkali-activated RHA (3–15% by weight), and the effects on Atterberg limits, compaction properties, CBR, and UCS were evaluated. The results showed a reduction in liquid and plastic limits by up to 30% and 40%, respectively, while CBR and UCS increased by up to 300% and 1500%.

Further studies, such as Khanday et al [20], also explored the potential of RHA-based geopolymer enhanced with aluminum oxide (Al_2O_3) to stabilize Indian peat. Specimens were treated with 10- 30% binder and activated by sodium hydroxide (NaOH) at different molarities (3, 6, and 9). The optimal conditions of 20% binder with 6 M of NaOH resulted in an increase in UCS up to 136 times that of untreated peat. The study also showed that UCS decreases with higher organic content but improves with longer curing periods. Swamy et al. [21] investigated the effectiveness of using RHA-based geopolymer as an additive to stabilize laterite soil. Unconfined compressive strength tests revealed that the treated soil exhibited a 2, 3, and 5-fold increase in strength after a 7-day curing period. RHA-based geopolymer proved effective for eco-friendly subgrade stabilization. Similarly, He et al. [22] explored the use of rice husk ash in combination with geopolymer as a cementitious material to stabilize red mud, a by-product of the aluminum refining process via the Bayer method, with the goal of developing a viable construction material. Their findings indicate that incorporating red mud for subgrade soil stabilization yielded promising and effective results.

Although these studies have established the benefits of RHA-based geopolymer in improving the strength of expansive soils, they primarily focus on short-term performance. Limited attention has been given to the effects of long-term environmental conditions, particularly the durability of stabilized soils under varying climatic conditions. This is a significant gap, given that road pavement structures are often exposed to cycles of wetting and drying, which can significantly affect the long-term performance of soil stabilizers. Wetting-drying cycles are crucial in assessing the durability and strength of stabilized soils, as they mimic natural climatic conditions where soil repeatedly absorbs and loses moisture [23]. Expansive soils, such as OES, are particularly susceptible to moisture-induced volume changes, leading to swelling when wet and shrinking when dry. Without proper stabilization, these moisture fluctuations can weaken the soil and compromise the stability of overlying pavement structures.

The influence of wetting-drying cycles on soil-stabilizer performance is critical because the repeated expansion and contraction of expansive soils can degrade the bonds formed between the stabilizer and soil particles [24]. The ability of a stabilized soil to withstand multiple cycles of wetting and drying without significant strength loss is an indicator of its durability and long-term performance, which are critical for road construction applications. To address this research gap, the present study aims to investigate, for the first time, the effects of cyclic wetting and drying on the durability and strength of OES stabilized with RHA-based geopolymer in the Onna area of Akwa Ibom State, Nigeria. The study seeks to provide valuable insights into the durability performance of expansive soils in the region, thereby contributing to increased pavement lifespan and reduced maintenance costs. Specifically, the research evaluates the impact of wetting-drying cycles on the CBR and UCS of the stabilized soil through laboratory simulations.

2. Description of Study Area

The study area is the Etinan-Onna Road which spans 29 km, connecting some towns and communities in Akwa Ibom State, Nigeria. Figure 1 shows the location of the study area on a map. The proposed dual carriageway consists of a flexible pavement structure, starting with a surface layer of asphalt concrete (AC), comprising a 50 mm thick binder course and a 100 mm thick wearing course. Beneath the surface layer is a 200 mm thick base layer of crushed stone aggregate, with some sections reinforced by a 150 mm thick cement-treated base. This is followed by a 250 mm thick sub-base layer of granular material. The subgrade, composed of compacted natural soil, lies beneath the sub-base and provides essential support to the entire pavement structure. Figure 2 shows the sketch of the section of the road layers. The road passes through a flat, sandy coastal area with low relief. This region includes mangrove swamps, floodplains, recent alluvial deposits, and beach ridges [24]. The climate is marked by two distinct seasons: a prolonged wet season lasting approximately 9 to 10 months and a brief dry season. The area experiences heavy rainfall exceeding 3000 mm annually and temperatures ranging from 26°C to 28°C [25].

The Etinan- Onna Road provides a critical transportation link, facilitating the movement of goods and services between urban and rural areas. Its strategic importance makes it a focal point for research into sustainable road construction practices, particularly those that can address the challenges posed by the region's soil and environmental conditions. The surrounding areas are primarily agricultural, with cassava, palm oil, and other crops serving as major sources of livelihood for local communities. In addition to agricultural activities, a commercial sand dredging site located along the road contributes to the presence of heavy axle loads on the pavement, further impacting its durability. This combination of factors makes the study area particularly significant for infrastructural research. From a hydrological perspective, the region is interspersed with rivers and streams, which influence drainage patterns and soil moisture levels. These geographical and climatic characteristics cause substantial volume changes in the lateritic soils due to moisture variations which present difficulties for road construction. Insights from this study will guide the design of durable and cost-effective pavement structures, improving infrastructure resilience in similar regions globally.

Figure 1. Location of the study area.

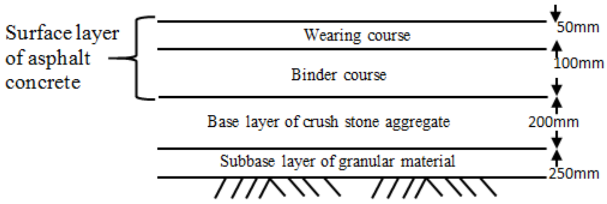

Figure 2. Section of the Road layers.

3. Materials and Methods

3.1. Materials

3.1.1. Onna Expansive Soil

The soil sample was collected from the study area at Km 17, at a depth of 0.8 m below the surface, using a hand auger. Once collected, the sample was immediately sealed in an air-tight container and transported to the soil mechanics laboratory. The soil was pulverized with a mallet to avoid damaging the soil particles. This area experiences high annual rainfall and significant seasonal moisture variation, making it an ideal case study for cyclic wetting-drying effects on subgrade materials. To characterize the soil, geotechnical tests were conducted in accordance with BS 1377 standards. The tests included Atterberg limits, specific gravity, moisture content, CBR, UCS, and differential free swell. These parameters were chosen as they critically affect the soil's engineering behavior under environmental stressors. The results, presented in Table 1, indicate that the soil is classified as highly plastic clay (CH) under the unified soil classification system (USCS), making it unsuitable for direct use as a subgrade material without stabilization.

Table 1. Geotechnical properties of Onna expansive subgrade.

S/N	Properties		OES
1	Sand		7.61%
2	Natural Water Content		62,4%
3	Fines		92.8%
4	Specific gravity		2.59
5	Atterberg's limits	Liquid limit	60.84%
		Plastic limit	28.78%
		Plasticity index	32.06%
6	Compaction Characteristics	Maximum dry density	1.47 g/cm^3
		Optimum moisture content	25.20%
7	Differential free swell		77%
8	Classification	USCS	CH
		AASHTO	A-7-6

3.1.2. Rice Husk Ash

In this study, RHA was obtained through open burning of Rice husk collected from Itumbonuso in Akwa Ibom State, Nigeria. The physical and chemical properties of the RHA as obtained through laboratory analysis conducted at the Civil Engineering Materials Laboratory are presented in Table 2. The analysis revealed that it contains approximately 86.4% amorphous silica, making it highly suitable as a pozzolanic material, according to ASTM C618 [26] standards, which require more than 70% amorphous silica content for classification as a pozzolan. However, the RHA was found to have a very low aluminum oxide (Al_2O_3) content, around 1.59%, requiring the addition of commercial alumina to achieve the optimum silica-to-alumina (Si:Al) ratio for geopolymerization. The variability of RHA's properties due to open burning was noted as a potential limitation. To mitigate this, samples were prepared in controlled batches, and their composition was verified before use.

Table 2. Chemical composition of RHA.

Chemical Composition	Content (%)
Silicon oxide (SiO_2)	86.4
Aluminum oxide (Al_2O_3)	1.59
Iron oxide (Fe_2O_3)	2.23
Calcium oxide (CaO)	0.46
Magnesium oxide (MgO)	2.13
Potassium (K_2O)	2.01
Sodium (Na_2O)	0.22
Titanium oxide (TiO_2)	-
Sulfur trioxide (SO_3)	-

3.1.3. Commercial Alumina

Aluminum oxide powder, commonly referred to as commercial alumina, was procured from a chemical supplier in Uyo, Akwa Ibom State. The purpose of incorporating this material was to achieve the desired silica (Si) to alumina (Al) ratio, which is crucial for optimizing the strength of the precursor in the geopolymer mix. The mean particle size of the commercial alumina was determined to be 13.1 µm.

3.1.4. Alkaline Activator

The alkaline activator (AA) utilized in this study was sodium hydroxide (NaOH) which was obtained commercially from a chemical store in Uyo, Akwa Ibom State, Nigeria. The NaOH had a purity of 98% and a specific gravity of 2.13. This alkali activator was selected due to its strong ability to leach Si and Al from the precursor [27], which is essential for the geopolymerization process. To prepare the activator solution, NaOH was dissolved in distilled water to achieve the desired molarity.

3.2. Method

To comprehensively evaluate the properties of the OES and its response to stabilization with RHA-based geopolymer under wetting-drying cycle, a comprehensive series of geotechnical tests was conducted in accordance with established standards to evaluate the engineering behavior of the soil and its response to stabilization.

3.2.1. Natural Moisture Content

The natural moisture content of the OES sample was determined using the Oven Dry Method in accordance with BS 1377 (1990) Part 2 2 [28]. This method involved drying a weighed sample of soil in an oven at a specified temperature until a constant weight was achieved. The difference in weight before and after drying was used to calculate the natural moisture content, providing an indication of the soil's water retention capacity under field conditions.

3.2.2. Specific Gravity

The specific gravity of the soil was measured using the density bottle method, as outlined in BS 1377 (1990) Part 2 2 [28]. This procedure involved filling a calibrated bottle with a known volume of soil and water, then calculating the ratio of the soil’s density to that of water. Specific gravity is a key parameter used in understanding the soil's composition and its relative density compared to water, which has direct implications for the behavior of the soil when saturated or stabilized.

3.2.3. Atterberg Limits

The Atterberg limits, which define the critical water content at which soil transitions between its plastic and liquid states, were determined using the liquid limit and plastic limit tests. The liquid limit was measured using Casagrande's apparatus, which involves repeatedly applying a controlled force to a soil sample until it begins to flow like a liquid. The plastic limit, on the other hand, was established by rolling small soil threads by hand until they cracked. Both tests were conducted according to BS 1377 (1990) Part 2 2 [28], providing essential data on the soil's plasticity and its tendency to expand or contract when exposed to varying moisture conditions.

3.2.4. California Bearing Ratio

The CBR test was performed to assess the bearing capacity of the untreated expansive soil (OES) and OES stabilized with RHA-based geopolymer, following the guidelines provided in BS 1377, Part 4 (1990) 2 [28]. The CBR test evaluates the strength of subgrade soils under soaked and unsoaked conditions, providing a measure of the soil’s suitability for road construction. In this study, the soaked condition for all mixes was evaluated during the wetting cycles, while the unsoaked condition was assessed during the drying cycles. This approach allowed for a comparison of soil performance under both moisture conditions, which is essential in determining the material's response to varying environmental conditions such as rainfall and drying periods. All soil samples used for the CBR determination were subjected to a 7-day curing period before being tested in the CBR machine. The test results helped establish a threshold in terms of the number of wetting-drying cycles at which the CBR values of the stabilized subgrade materials dropped below allowable limits. This is crucial because once the CBR values fall below acceptable standards, the subgrade is considered unsuitable for use in road construction.

3.2.5. Unconfined Compressive Strength

The UCS test was conducted for all soil mixtures following the procedure outlined in BS 1377 (1990) Part 7 [29]. Cylindrical samples of the untreated and RHA-geopolymer stabilized expansive soil (OES) were prepared and cured for 7 and 28 days in a controlled environment. This curing period was essential to allow the geopolymer binder to fully react with the soil, thereby enhancing its strength and durability. After curing, the samples were subjected to a vertical compressive load using a compression testing machine, with the load applied at a constant rate of 0.2 inches per minute. Throughout the test, the axial load and deformation of the samples were carefully monitored until they either reached failure or a predetermined strain limit. At the point of failure, the peak load and the corresponding deformation were recorded. The UCS value was calculated by dividing the peak failure load by the initial cross-sectional area of the sample. These UCS values represented the initial strength of the soil before exposure to environmental stressors. Additionally, residual UCS values were determined for a new set of specimens that had undergone cyclic wetting-drying tests. This allowed for the assessment of the soil's strength retention after being subjected to cycles of moisture and drying, simulating real-world conditions such as seasonal flooding or exposure to moisture fluctuations. The results of both the initial and residual UCS tests provided valuable insights into the strength and durability of both untreated and stabilized OES at different stages of wetting-drying cycles. These values are critical for evaluating the suitability of the soil for various construction applications, particularly in areas prone to moisture fluctuations or water inundation.

3.3. Geopolymer Preparation

In this study, a NaOH molarity of 6 and an alkaline solution-to-precursor ratio (A/P) of 0.7 were adopted based on the findings of Khanday et al. [29]. These parameters have been shown to enhance the performance of RHA-based geopolymers in improving expansive soils. This selection was made because the soil conditions and material availability in this study align closely with those in Khanday et al.'s work. However, additional trial mixes were conducted to confirm the suitability of these parameters for the local soil conditions. The primary precursor (RHA) was combined with commercial alumina in proportions that maintained the Si/Al of 3. The alkaline solution was prepared by dissolving sodium hydroxide (NaOH) pellets with 98% purity in distilled water while stirring gently. This step was conducted at ambient temperature to prevent excessive heat generation, which could affect solution consistency. The solution was then cooled for 24 hours to stabilize the molarity and enhance its reactivity with the precursor during geopolymerization. After the alkaline solution had cooled, the precursor (RHA and alumina mix) was gradually added while stirring continuously to maintain the desired A/P ratio of 0.7. This mixing process ensured a uniform distribution of the activator within the precursor, forming a cohesive geopolymer mix. The resulting mix was poured into cylindrical molds of dimensions 50 mm × 100 mm and sealed with plastic film to minimize moisture loss during curing. The curing process was conducted at a controlled room temperature of 25°C ± 2°C and 60% ± 5% relative humidity for 24 hours. These conditions were selected to simulate ambient field conditions. After curing, the geopolymer samples were demolded and subsequently pulverized to increase their surface area. This pulverization step was essential to enhance the material's reactivity and facilitate better integration with the soil during stabilization. The prepared geopolymer was then stored in an air-tight container until further use in soil stabilization experiments. The schematic of the preparation is presented in Figure 3.

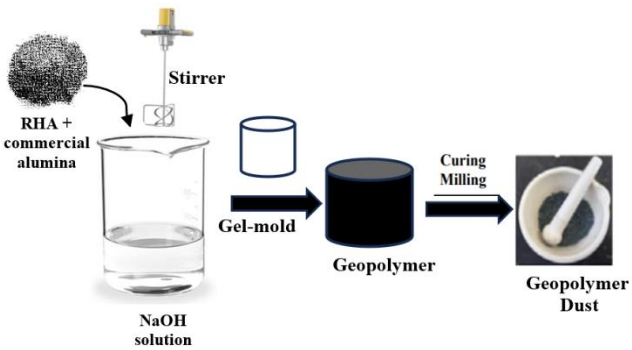

Figure 3. Schematic of geopolymer preparation.

3.4. Specimen Preparation

To prepare the specimens for testing, the RHA-geopolymer was mixed with OES at proportions of 0%, 10%, 20%, and 30% by the dry weight of the soil. These proportions were selected based on prior studies that demonstrated the effectiveness of RHA-geopolymers within this range for soil stabilization. The mixtures were designated as EGO (0%), EG10 (10%), EG20 (20%), and EG30 (30%). Compaction tests were initially conducted for each mixture to determine the optimum moisture content (OMC) and maximum dry density (MDD) in accordance with BS 1377, Part 2 [28]. These parameters served as a baseline for evaluating the stabilization effect. For the CBR and UCS tests, samples were molded using cylindrical molds of standard dimensions: 150 mm in diameter and 175 mm in height for CBR tests, and 38 mm in diameter and 75 mm in height for UCS tests. The specimens were compacted to their respective OMCs to ensure uniformity. To prevent moisture loss during curing, the samples were wrapped in a thin plastic film and cured in a controlled environment for specified durations—7 days for CBR tests and 7 and 28 days for UCS tests. After curing, the plastic film was carefully removed, and the samples were wrapped with scotch tape around their lateral surfaces, leaving the top and bottom exposed. This step was taken to maintain structural integrity during the wetting-drying cycles. The effectiveness of the scotch tape was verified through preliminary trials, ensuring minimal impact on the test outcomes.

The wetting-drying cycle test was conducted following ASTM D559 [30] with slight modifications. Each cycle consisted of a 5-hour soaking phase, during which the samples were fully submerged in water at a controlled room temperature of 20 ± 2°C, simulating conditions typical of heavy rainfall and flooding. After soaking, the samples were removed, their masses recorded, and one specimen was tested for CBR to represent the wetting phase. The remaining soaked samples were dried in an oven at 71 ± 3°C for 42 hours, replicating conditions of extreme heat or drought. After drying, the samples were weighed again, and another specimen was tested for CBR, representing the drying phase. The soaking and drying durations were chosen to align with environmental conditions in the study area and prior studies, ensuring realistic simulation of field scenarios. Each complete cycle (48 hours) was repeated for a total of 12 cycles to evaluate the durability of the stabilized soil under prolonged wetting and drying conditions.

For UCS testing, the initial strength of the specimens was determined immediately after curing, while residual strength was evaluated on a new set of specimens subjected to the full 12 wetting-drying cycles. The UCS specimens provided insight into the soil's strength retention and intrinsic durability under cyclic environmental stresses. The slight modification to ASTM D559 was the omission of the wire scratch brush, which is typically used to simulate mechanical wear. This study focused on assessing intrinsic durability under cyclic wetting and drying without the confounding effects of abrasion. The procedure was repeated for a total of 12 cycles to assess the durability of the stabilized subgrade under repeated wetting and drying conditions. The flowchart of the experiment is presented in Figure 4.

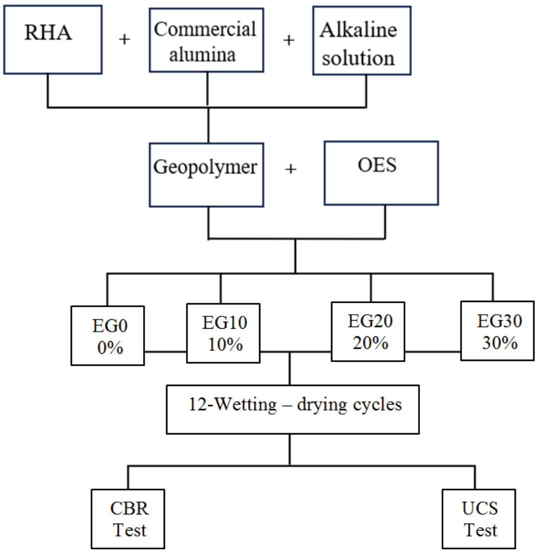

Figure 4. *Flowchart showing the experimental procedure for the durability performance.*

4. Results and Discussion

4.1. Geotechnical Properties of RHA-geopolymer Treated Soil: Wetting-drying Cycles

4.1.1. Weight Loss

The percentage of weight loss for various OES-RHA geopolymer mixtures across 12 wetting-drying cycles for 7 and 28 curing periods is presented in Figures 5 and 6. As observed in Figure 5, the untreated OES and 10% OES- RHA mixture show a significant increase in weight loss, especially within the initial cycles (up to around 3 and 7 cycles respectively). For the untreated OES, weight loss rapidly reaches 100% by the third cycle, indicating that the sample has likely disintegrated completely under the wetting-drying conditions. This suggests a lack of durability in these mixtures without any or with minimal RHA-geopolymer content. 10% RHA geopolymer on OES also shows considerable weight loss, with a steady rise throughout the cycles, reaching around 100% by cycle 7. The high weight loss for these mixes suggests that the low geopolymer content is insufficient to stabilize the expansive soil effectively. When OES was mixed with 20% RHA geopolymer, a gradual increase in weight loss but at a significantly lower rate compared to untreated OES and 10% OES-RHA geopolymer mix was observed. The percentage loss remains below 50% throughout the 12 cycles. With 30% RHA-geopolymer content, the least weight loss throughout the 12 cycles, remaining below 10% was seen. As the RHA content increases the availability of reactive SiO_2 and Al_2O_3 from RHA significantly enhances the geopolymerization process. The reaction between these components and alkaline activators leads to the formation of a denser and more stable aluminosilicate matrix, creating a network of N-A-S-H and C-A-S-H gels. This result highlights the enhanced durability and stabilization properties conferred by the higher proportion of RHA-geopolymer, as it better withstands the stresses of repeated wetting and drying. Similar trend was observed in Figure 6 representing 28 days curing period. However, the 28-day curing period samples show improved performance across all mixtures compared to the 7-day curing period. While untreated OES and 10% RHA geopolymer on OES still experience significant weight loss, the impact is less pronounced in the 28-day results. 20% and 30% RHA-geopolymer demonstrated a clear improvement in durability, suggesting that extended curing times allow for better pozzolanic reactions, enhancing the overall properties of the geopolymer matrix. This finding supports the idea that extended curing allows for better bonding and structure formation within the geopolymer, which is essential for achieving the desired mechanical and durability properties in field applications [31].

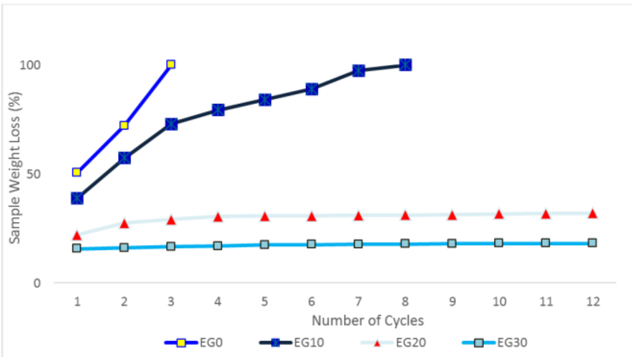

Figure 5. *Weight loss in wetting-drying cycles at 7 days curing period.*

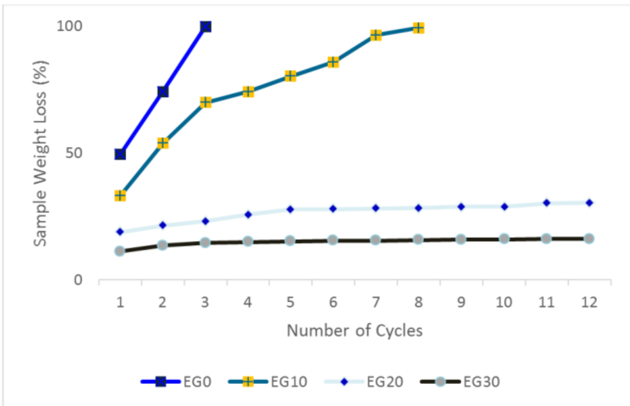

Figure 6. *Weight loss in wetting-drying cycles at 28 days curing period.*

4.1.2. CBR

The CBR behavior of different OES-RHA geopolymer mixtures under wetting-drying cycles for 7 days curing period is shown in Figure 7. It can be observed that the CBR of all mixtures decreases steadily with an increase in the number of wetting-drying cycles. This trend aligns with findings by Abbey et al. [23]. The decrease in CBR values with an increase in wetting-drying cycles can be attributed to the continuous swelling and shrinking of the samples. This repetitive expansion and contraction weaken the binder within the mixtures, leading to a gradual loss of strength [32]. For all mixtures, the dry CBR values are higher than the wet values, suggesting that water exposure during wetting-drying cycles significantly affects the strength and stability of the mixtures. This suggests that Higher RHA content in the geopolymer mixtures (especially 20% and 30%) generally leads to improved CBR values, particularly under dry conditions. This indicates better stabilization and bonding within the mixture, contributing to its structural strength. Lower RHA percentages (untreated OES and 10%) are more susceptible to reductions in CBR, showing less resilience to moisture and cyclic wetting-drying effects.

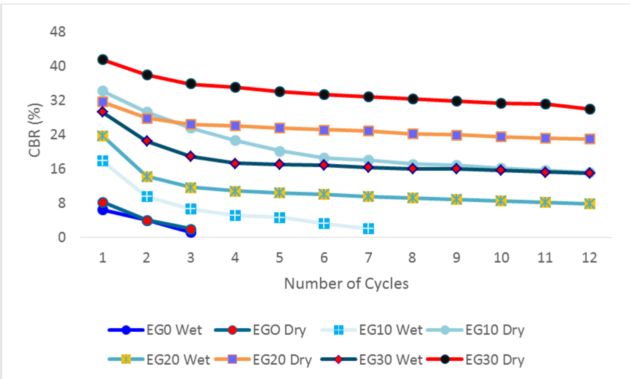

Figure 7. *The CBR behavior of different OES-RHA geopolymer mixtures under wetting-drying cycles for 7 days curing period.*

4.1.3. UCS

The initial and residual UCS of different OES-RHA geopolymer mixtures for curing periods of 7 days and 28 days is presented in Figure 8. Although untreated OES and 10% RHA geopolymer mixtures could not survive beyond 3 and 7 wetting-drying cycles, it was observed that increase in number of cycles decreases the value of UCS, hence the initial strength were higher than the residual strength in all mixtures for both 7- and 28-day curing periods. This is because continuous cycle of wetting and drying can weaken the bonds formed by the geopolymerization process between the soil and the RHA, leading to a reduction in the overall cohesion of the mixture [33]. For all the geopolymer mixtures, there is an increase in UCS from the 7-day curing period to the 28-day curing period. This indicates that as curing time increases, the strength of the mixtures improves, likely due to ongoing geopolymerization processes. This is because during the 7 to 28-day curing period, the polymeric gels mature and gain strength. This maturation process allows the gels to crystallize and become more tightly packed, further enhancing the UCS of the mixture. It is also observed in Figure 6 that increasing the RHA- geopolymer content in the OES mixture leads to a substantial improvement in initial UCS as well as better retention of strength after exposure to wetting-drying cycles. This improvement can be attributed to aluminosilicate network in geopolymer which involves the formation of Si-O-Al and Si-O-Si bonds, which create a dense and cohesive structure [34]. The geopolymer matrix provides a strong and rigid framework that improves the UCS of the mixture. The higher the RHA content, the denser and more interconnected this network becomes, leading to increased initial compressive strength.

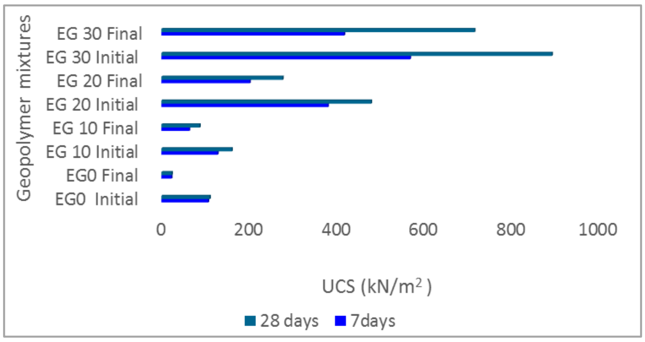

Figure 8. *The UCS variation for OES-RHA geopolymer mixtures at 7 and 28 curing periods.*

4.2. Implications of RHA-Geopolymer Stabilization on Pavement Performance

The findings of this study have practical implications for the design and construction of road pavements in regions with expansive soils like those found in Onna, Akwa Ibom State. The enhanced durability and strength exhibited by mixtures containing 30% RHA-based geopolymer highlight the potential of this sustainable solution to improve pavement lifespan. This is particularly relevant in areas prone to seasonal flooding and drying, where subgrades are subjected to constant moisture fluctuations. The residual UCS and CBR values observed after multiple wetting-drying cycles confirm the long-term performance benefits of geopolymer stabilization, especially when compared to conventional untreated soils. Moreover, the ability of the geopolymer matrix to retain integrity under environmental stresses makes it a viable alternative to traditional chemical stabilizers like lime or cement, with the added advantage of utilizing agricultural waste. Incorporating RHA-based geopolymer in subgrade treatment not only enhances mechanical stability but also aligns with global goals of sustainability and waste valorization. Its adoption could reduce reliance on non-renewable resources while mitigating environmental pollution associated with rice husk disposal. These outcomes serve as a valuable reference for pavement engineers, policymakers, and infrastructure planners aiming to develop cost-effective and environmentally responsible road systems.

5. Conclusion

This study investigated the durability behavior of Onna Expansive Soil (OES) mixed with Rice Husk Ash (RHA)-based geopolymer across 12 wetting-drying cycles, simulating natural climatic variations, to assess its geotechnical properties. Based on the results, the following conclusions can be drawn:

1) Stabilizing OES with a low content of RHA-based geopolymer (10%) resulted in a slight improvement in durability. However, the stabilized samples did not endure beyond the initial cycles.
2) A medium blend of OES with 20% RHA-based geopolymer survived the intermediate cycles but failed to withstand the final cycle.
3) Using a high content (30%) of RHA-based geopolymer in OES led to an overall improvement in durability. The samples successfully endured all 12 cycles of wetting-drying tests.
4) The mixture containing 30% RHA-based geopolymer exhibited optimal durability, with mass loss percentages of 18.13% and 16.1% at the end of 12 cycles for 7 and 28 days of curing, respectively.
5) The California Bearing Ratio (CBR) of the 30% RHA-based geopolymer mix demonstrated significant durability, achieving a soaked CBR value of 14.97% after 12 wetting-drying cycles at 7 days of curing, compared to an untreated OES value of 3% under the same conditions.
6) The residual strength of the optimal 30% RHA-based geopolymer mixture at the end of 12 cycles showed marked improvement, with compressive strengths of 417 kN/m^2 and 714 kN/m^2 for 7-day and 28-day curing periods, respectively.

6. Recommendations for Future Research

Although this study demonstrated the effectiveness of RHA-based geopolymer in enhancing the durability and strength of expansive soils under cyclic wetting and drying, further research is recommended to investigate its performance under other environmental stressors such as freeze-thaw cycles and sulfate-rich conditions. Long-term field validation studies are also necessary to assess the in-situ behavior of stabilized soils under real traffic loading and seasonal climatic changes. Additionally, exploring the synergistic effects of combining RHA with other industrial or agricultural by-products (e.g., fly ash, sugarcane bagasse ash) may offer new insights into optimizing geopolymer formulations for diverse soil types.

Abbreviations

OES	Onna Expansive Soil
RHA	Rice Husk Ash
UCS	Unconfined Compressive Strength
CBR	California Bearing Ratio
USCS	Unified Soil Classification System
AASHTO	American Association of State Highway and Transportation Officials
NaOH	Sodium Hydroxide
AA	Alkaline Activator
A/P	Alkaline Solution-to-precursor Ratio
CH	Clay of High Plasticity
ASTM	American Society for Testing and Materials
BS	British Standard
OMC	Optimum Moisture Content
AC	Asphalt Concrete
Al_2O_3	Aluminium Oxide
Si: Al	Silica-To-Alumina Ratio
MDD	Maximum Dry Density
EG	Expansive Soil Mixed with Geopolymer

Author Contributions

All authors significantly contributed to this study. Kufreabasi Usanga conceptualized this study, prepared the manuscript introduction, methodology and the analysis of results. Prof. Aniekan Eket reviewed the manuscript and prepared the conclusion. Dr. Idorenyin Usanga contributed to the discussion of results and also reviewed the manuscript.

Ethical Declaration

Not required.

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Data Availability Statement

The authors confirm that the data supporting the findings of this study are available within the article.

Conflicts of Interest

The authors declare no conflicts of interest.

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