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Evaluating Pavement Performance on Expansive Clay Soils Subjected to Cyclic Shrinkage and Swelling

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Abstract

Expansive soils, prone to being influenced by the environmental conditions, undergo expansion when water is introduced and shrinkage upon drying. This persistent volumetric fluctuation can induce differential movements and result in cracking of structures erected upon them. The present research focuses on characterizing the behavior of pavements erected on expansive clays subjected to swelling and shrinkage cycles. Direct shear tests and oedometer tests were conducted in the laboratory on samples of expansive soils undergoing swelling-shrinkage cycles. The experimental data reveal a significant decrease in shear strength, evidenced by a reduction in shear parameters (internal friction angle, cohesion) and a decrease in the modulus of elasticity as the number of cycles increases. A numerical model based on the finite element method was developed to simulate the behavior of a pavement on an expansive clay substrate. The model results indicate an increase in total displacements with the increase in the number of shrinkage-swelling cycles, demonstrating a progressive degradation of the soil's mechanical behavior. This study contributes to a better understanding of the complex phenomena governing the behavior of expansive soils and serves as a foundation for developing effective management and mitigation strategies for road infrastructures.

Keywords

Differential Soil Displacement, Expansive Soil, Pavement, Shear Strength, Shrinkage-Swelling Cycles, Soil Degradation Behaviour

1. Introduction

Pavements are essential components of transportation systems, enabling the movement of people and goods across extensive road networks. However, these infrastructures face significant challenges, including heavy traffic loads and environmental forces. One of the most critical issues in pavement engineering is the presence of expansive clay subgrades. These soils, common in many regions worldwide, undergo substantial volume changes due to moisture variations, a phenomenon known as shrink-swell behavior. This poses a serious threat to the integrity and durability of pavements and other structures built on such soils.

Expansive clay soils, rich in minerals like montmorillonite and smectite, shrink and swell with moisture fluctuations, leading to infrastructure damage if not properly managed. This issue is particularly problematic in regions with distinct dry and rainy seasons, where frequent moisture variations exacerbate shrink-swell behavior. Factors such as evapotranspiration during dry periods and infiltration during rainy seasons significantly influence the soil's moisture content. Understanding the effects of these cyclic changes on expansive clays is crucial for mitigating infrastructure damage.

Several studies have examined the impact of drying-wetting cycles on the mechanical behavior of expansive soils. For instance, Sayem *et al.* demonstrated that cyclic swelling and shrinkage reduce the water absorption capacity of clays and disrupt their internal structure after multiple cycles [1] [2]. Louati *et al.* showed that compressibility increases and swelling potential decreases with more drying-wetting cycles [3] [4].

Despite these contributions, most studies focus on artificial or reconstructed soils, leaving a gap in understanding the effects of cyclic drying-wetting on undisturbed expansive clays, particularly with regard to shear strength and consolidation behavior [5]-[9]. Furthermore, recent advances in expansive soil modeling, such as the BExM model by Alonso *et al.*, offer valuable insights but involve complex parameters that are difficult to quantify accurately [10]-[19].

This study addresses this gap by evaluating the effects of drying and wetting cycles on the shear strength (internal friction angle and cohesion), compressibility, and consolidation behavior of undisturbed expansive clay. Through laboratory testing and numerical modeling, this research provides essential data to improve pavement design on expansive clay subgrades under cyclic moisture conditions.

2. Material and Methods

2.1. Study Area and Sampling

The site investigation was conducted following an initial reference to the soil map of the municipality of Pobè in Republic of Benin, as depicted in **Figure 1**. Subsequently, on-site visits were carried out to identify sampling locations, prioritizing areas where the phenomenon is most pronounced within the study area. The materials were gathered within the Pobè municipality, situated in the southeast of Benin, specifically within the districts of Issaba and Ahoyèyè. Table 1 provides the geographical coordinates of each designated sampling site.

Table 1. Sampling sites' geolocation.

Location	X	Y	Latitude	Longitude
ISSABA	459660	783707	N 7˚5'23.8"	E2˚38'4.9"
AHOYEYE	465361	774802	N7˚0'33.9"	E2˚38'4.9"

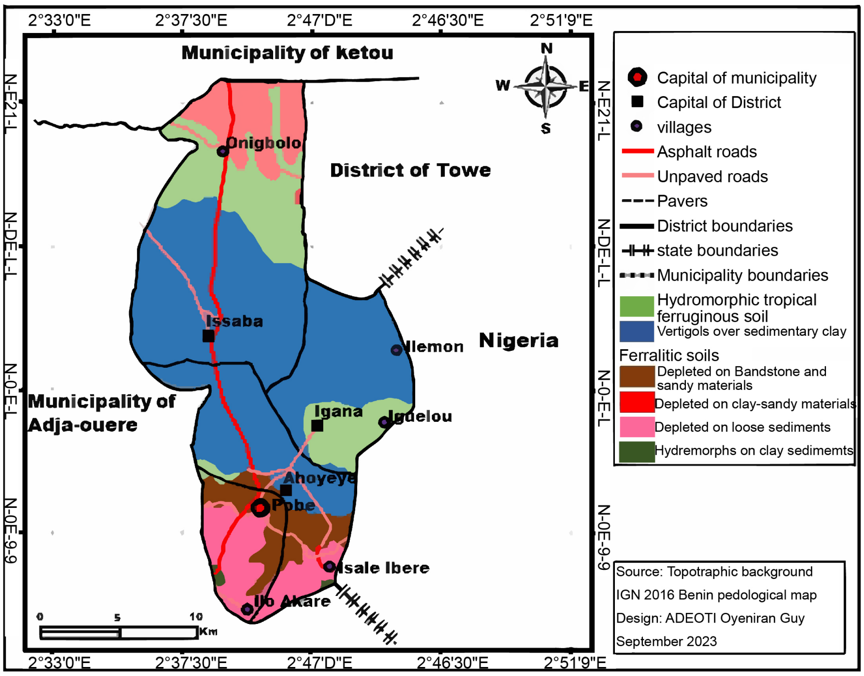

Figure 1. Pedological map of Pobè.

2.2. Sampling Techniques

Considering the required tests (identification and mechanical tests), a combination of disturbed and undisturbed samples was collected. The undisturbed samples were cored using cubic boxes designed for the collection of undisturbed samples, a compaction hammer, and wooden containers for transportation. In each study area, four (04) undisturbed samples were cored: one from 0 to 0.50 m depth, a second from 0.5 to 1.0 m, a third from 1.0 to 1.50 m, and the final one from 1.50 to 2.0 m depth.

2.3. Test Descriptions

Soil characterization was conducted using geotechnical tests for both physical and mechanical identification.

2.3.1. Identification Tests

The disturbed soil samples were subjected to the following physical tests:

- Moisture content determination in accordance with standard NF EN ISO 17892-1 [20];
- Atterberg Limits tests as per standard NF EN ISO 17892-12 [21];
- Specific gravity of solid particles determination in accordance with standard NF EN ISO 17892-3 [22];
- Organic Matter Content Determination Test in accordance with standard NF P94-055;
- Particle size distribution according to standard NF EN ISO 17892-4 [23].

2.3.2. Mechanical Tests

The oedometer test as per NF EN ISO 17892-5 [24] and the direct shear test in as per NF EN ISO 17892-10 [25] were conducted on undisturbed soil samples subjected to drying and wetting cycles.

2.4. Experimental Methodology

This study employed both oedometer and direct shear tests to investigate the mechanical behavior of undisturbed expansive clay under cyclic wetting and drying conditions. These tests were performed using specialized equipment, following established standards, to simulate natural moisture variations and their impact on shear strength, compressibility, and consolidation characteristics.

2.4.1. Oedometer Tests

The oedometer tests were conducted in accordance with the NF EN ISO 17892-5 (2017) standard to assess the compressibility and consolidation behavior of expansive clay. The testing apparatus consisted of a standard oedometer device, composed of a rigid steel frame, a vertical loading system (using weights or pneumatic pressure), and consolidation rings to hold the soil specimens (**Figure 2**). These rings, with a diameter of 75 mm and a height of 20 mm, allowed for the application of vertical loads, simulating field stress conditions, and measuring the soil's response to consolidation.

Figure 2. Standard oedometer device.

In addition, a precision balance with an accuracy of 0.01 g was used to monitor the mass of the soil samples throughout the wetting and drying cycles, which was essential for determining moisture content changes. Vertical deformations were continuously recorded using dial gauges or electronic displacement sensors, providing real-time data on the consolidation behavior of the soil samples during each loading phase. The soil specimens underwent a controlled drying process in an oven, while a water bath was employed during the wetting phase to achieve full saturation, replicating the effects of natural moisture infiltration.

The testing procedure began with the careful preparation of undisturbed soil samples. These samples were trimmed to fit within the oedometer consolidation rings, ensuring minimal disturbance to the natural structure. Once prepared, the samples were subjected to a series of incremental vertical loads, ranging from 12.5 kPa to 800 kPa, simulating real-life stress conditions. At each load increment, vertical deformations were measured over a period of 24 hours, allowing for the calculation of the compressibility index (Cc) and the swelling index (Cs) based on the stress-strain curves obtained during the loading and unloading cycles.

To simulate natural environmental moisture variations, the soil samples were subjected to multiple cycles of wetting and drying. During the wetting phase, the samples were gradually submerged in water until full saturation was reached, while during the drying phase, the samples were placed in an oven to simulate the effects of evapotranspiration. Moisture content and vertical deformations were measured at each cycle, providing a detailed understanding of how the soil's compressibility and swelling behavior evolved over time.

2.4.2. Direct Shear Tests

The direct shear tests were performed following the NF EN ISO 17892-10 (2018) standard to determine the shear strength parameters of the soil samples, specifically the internal friction angle (φ) and cohesion (Cu). The direct shear apparatus used in this study consisted of a horizontally split shear box, allowing the upper half of the box to move relative to the stationary lower half, thereby imposing a horizontal shear force on the soil sample while being confined under a vertical load (**Figure 3**).

Figure 3. Standard direct shear apparatus.

The load application system allowed for the precise application of normal stresses to the soil samples using dead weights or a hydraulic piston. Horizontal displacements were measured using high-precision displacement transducers, and shear forces were recorded through a load cell, enabling accurate calculation of the shear strength parameters. As in the oedometer tests, a precision balance and drying oven were used to regulate the moisture content of the samples before and after testing, ensuring accurate control of the sample conditions.

The experimental procedure began with the preparation of undisturbed soil samples, which were carefully trimmed to fit the dimensions of the shear box (60 mm in diameter and 20 mm in height). These samples were saturated to replicate field conditions of maximum moisture content. After saturation, normal stresses were applied to the soil samples at levels of 50, 100, and 200 kPa, simulating *in-situ* loading conditions. Horizontal shear stress was incrementally applied, and the resulting horizontal displacements were recorded.

The shear stress versus horizontal displacement curves were analyzed to determine the peak shear strength at each level of normal stress. From these results, the internal friction angle and cohesion were calculated using the Mohr-Coulomb failure criterion. This allowed for the evaluation of the degradation in shear strength parameters after several wetting-drying cycles.

2.4.3. Wetting-Drying Procedure

Wetting Procedure

The wetting process was designed to simulate the moisture infiltration that occurs during the rainy season. The following steps were followed:

1) Sample Preparation: Undisturbed soil samples were carefully extracted and placed within shear rings and oedometer rings. These rings were pre-weighed both empty and after coring. For each sample type, a control core was extracted to determine the wetting water content.

2) Placement in Jars: The cored samples were placed inside jars, each labeled with material details, the weight of the empty ring, and the combined weight of the ring and soil. Control samples for moisture content and saturation control were placed in a separate jar, while the samples intended for testing were placed in another. A perforated support plate was installed inside the jar to allow water to circulate freely and moisten the samples from beneath.

3) Water Addition: Water was poured into the jar until the samples were fully submerged, and the jar was then sealed. This ensured uniform wetting of the samples.

4) Monitoring of Saturation: Control samples were weighed every hour for 48 hours. A mass-versus-time curve was plotted for each control sample to monitor changes. Once three consecutive weight measurements showed no significant variation (less than 0.2 g), the degree of saturation was considered 100%. After wetting, one control core was placed in a drying oven to determine the moisture content, while the remaining cores were prepared for the drying phase.

Drying Procedure

Following the wetting process, the drying phase was initiated to simulate the natural drying conditions that occur during the dry season. The soil samples were subjected to sunlight exposure at temperatures ranging between +26˚C to +36˚C. The drying procedure followed these steps:

1) Exposure to Sunlight: After wetting, the samples were exposed to direct sunlight for 9 hours each day. The temperature was monitored, with morning temperatures around +26˚C and afternoon temperatures reaching up to +36˚C, based on a 3-day period of temperature measurements.

2) Target Moisture Content: The drying process continued until the soil samples reached a moisture content of 14%. This target moisture content was chosen based on literature data for expansive soils in the region, specifically from observations in the depression of La Lama during the dry season.

3) Control Core Measurements: A control core was used to monitor the moisture content during the drying process. The mass and moisture content of the control cores were measured to ensure accurate replication of the drying conditions.

Figure 4 illustrates the increase in soil sample mass over time during the wetting procedure.

Figure 5 showcases the drying kinetics, depicting moisture content evolution over time.

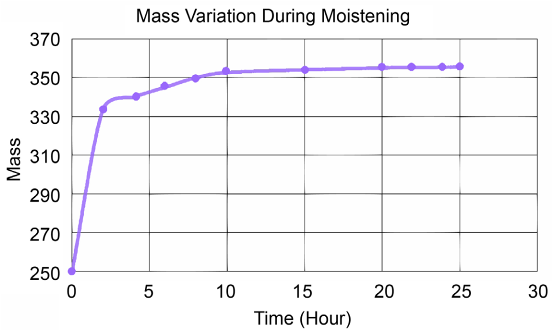

Figure 4. Moistening kinetics.

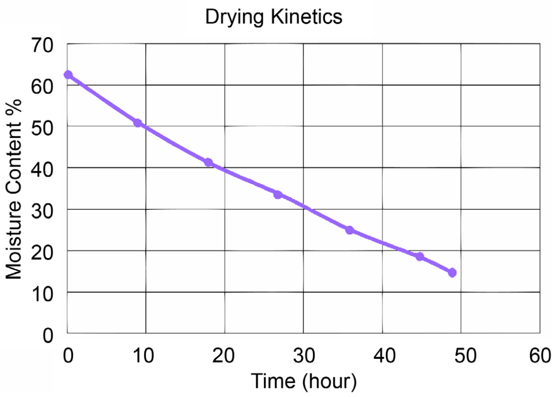

Figure 5. Drying kinetics.

2.4.4. Analysis of Experimental Data

The results of the oedometer and direct shear tests provided critical insights into the effects of cyclic wetting and drying on the mechanical properties of expansive clay. These tests allowed for the calculation of key parameters such as the compressibility index (Cc), the swelling index (Cs), and the shear strength parameters (internal friction angle φ and cohesion Cu). The data were further analyzed using numerical simulations to model the soil's behavior under cyclic moisture conditions, offering essential data for improving pavement design in regions with expansive clay subgrades.

2.5. Overall Progression of Moistening and Drying Cycle

To assess the influence of various drying-wetting cycles on the studied soil, oedometer tests and direct shear tests were conducted on the undisturbed samples. Each sample underwent the following cycles:

- C0: Undisturbed sample with no cycles;
- C1: Undisturbed sample subjected to one (01) drying-wetting cycle;
- C2: Undisturbed sample subjected to two (02) consecutive drying-wetting cycles;
- C3: Undisturbed sample subjected to three (03) consecutive drying-wetting cycles.

3. Results and Discussions

3.1. Identification Tests Results

The results of the grain-size distribution tests for the clayey soils collected in the Issaba area are presented in **Figure 6**. The classification of these soils is based on the American soil classification (HRB) and the GTR classification (NF P11-300). The soil characteristics obtained from various identification tests, including particle size distribution, plasticity index, and liquid limit, are shown in **Table 2**. According to the HRB classification, the soil samples are classified as A7-5, indicating a clayey soil, and according to the GTR classification, they are primarily categorized as A4, except for the soil at a depth of 1.5 to 2.0 m, which belongs to class A3.

Table 2. Identification test results.

Test	0 - 0.5 m	0.5 - 1.0 m	1.0 - 1.5 m	1.5 - 2.0 m
Passing by 80 (%)	92	93	95	96
In-situ moisture content w (%)	51.53	56.58	46.1	42.41
Liquidity limit (LL) (%)	92	93	93	95
Plasticity limit (PL)	51	52	52	57
Plasticity Index (IP)	41	41	41	38
Consistency Index (Ic)	0.95	0.89	1.84	1.38
Organic Matter (OM) (%)	0.8	0.7	0.6	0.8

Continued

Specific Density γ_s	2.23	2.29	2.4	2.29
Class acc. GTR	A4	A4	A4	A3
Class acc. HRB	A7-5	A7-5	A7-5	A7-5

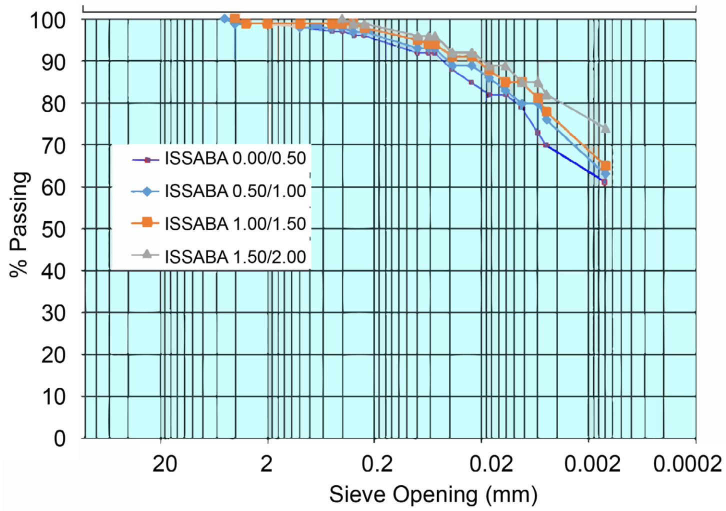

Figure 6. Grain size distribution of expansive clay.

3.2. Wetting and Drying Cycle Tests

3.2.1. Sample Textures after Swelling-Shrinking Cycles

The progressive degradation of soil samples over the course of multiple cycles of wetting and drying is evident in **Figures 7-10**. By Cycle 3, the samples exhibit significant swelling post-wetting and severe cracking post-drying (**Figure 10**), indicating progressive soil damage with increasing cycle numbers.

3.2.2. Shear Test Results

The results of the direct shear tests are summarized in **Table 3**. A clear trend of decreasing shear strength with increasing drying-wetting cycles is observed. Cohesion (C_u) generally increases between Cycle 0 and Cycle 2 but decreases significantly by Cycle 3, as shown in **Figure 11**. The friction angle (φ_u) also follows a decreasing trend (**Figure 12**), confirming that repeated cycles of shrink-swell progressively weaken the soil's resistance to shear forces.

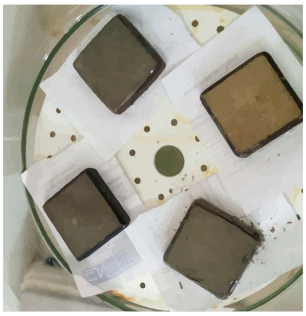

Figure 7. Samples from Cycle 0.

(a) After Moistening (b) After drying

Figure 8. Samples from Cycle 1.

(a) After Moistening (b) After drying

Figure 9. Samples from Cycle 2.

(a) After Moistening (b) After drying

Figure 10. Samples from Cycle 3.

Table 3. Shear test results.

Depth	Cycle 0		Cycle 1		Cycle 2		Cycle 3	
(m)	C_U (kPa)	φ_U (˚)	C_U (kPa)	φ_U (˚)	C_U (kPa)	φ_U (˚)	C_U (kPa)	φ_U (˚)
0 - 0.5	16.4	1.6	24.5	21.5	26.6	10.1	17.5	5.3
0.5 - 1	21.9	0.7	15.7	26.1	27.7	14.5	9.5	9.7
1 - 1.5	22.0	3.1	9.0	24.9	18.9	12.2	16.0	12.2
1.5 - 2	26.0	5.5	20.3	24.4	25.4	15.3	7.8	10.8

These experimental findings illustrate the impact of cyclic moisture variations on the mechanical properties of the expansive clay. The shear strength of the soil, measured in terms of cohesion and internal friction angle, decreases notably after three cycles, suggesting a degradation of the soil's structural integrity.

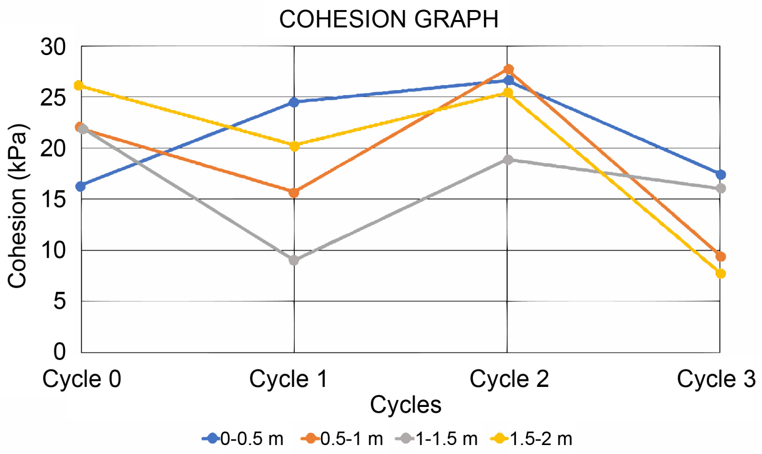

Figure 11. Cohesion evolution across cycles.

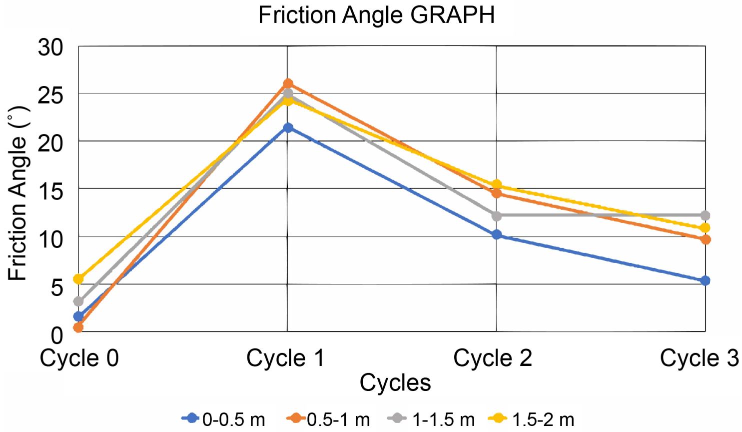

Figure 12. Friction angle evolution over cycles.

3.2.3. Oedometer Test Results

Table 4 presents the results of oedometer tests, showing variations in compressibility and swelling index across different cycles. The evolution of the compressibility index over cycles is depicted in Figure 13. There is an initial decrease in compressibility from Cycle 0 to Cycle 1, followed by an increase from Cycle 1 to Cycle 2. This could be attributed to the breakdown of soil structure and the formation of new cracks. By Cycle 3, the compressibility stabilizes but remains higher than in Cycle 0, indicating residual structural degradation.

Table 4. Oedometer test results.

Depth (m)	Cycle	σ'_p (kPa)	E_{oed} (MPa)	C_C	C_S
0 - 0.5	0	115	8.2	0.334	0.103
	1	1550	10.0	0.271	0.106
	2	50	6.6	0.480	0.140
	3	40	6.5	0.450	0.100

Continued

0.5 - 1	0	83	7.0	0.377	0.118
	1	700	11.1	0.290	0.118
	2	210	6.1	0.420	0.140
	3	49	7.4	0.400	0.100
1 - 1.5	0	130	6.9	0.423	0.139
	1	210	10.8	0.315	0.107
	2	170	6.2	0.410	0.150
	3	49	6.9	0.390	0.100
1.5 - 2	0	69	10.0	0.366	0.123
	1	700	10.3	0.323	0.134
	2	209	6.9	0.370	0.130
	3	50	6.6	0.340	0.090

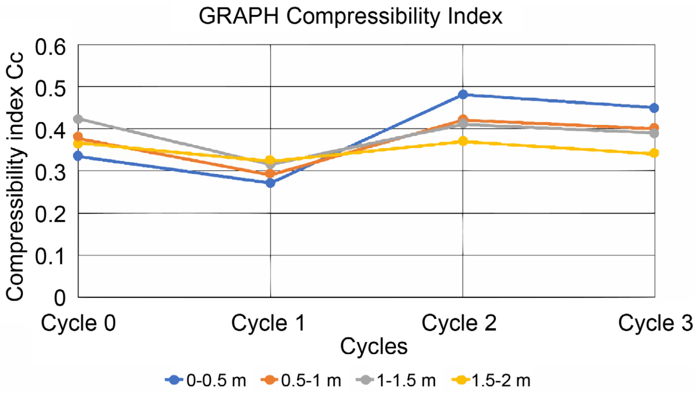

Figure 13. Evolution of compressibility index over cycles.

The swelling index, shown in **Figure 14**, follows a similar trend, with a sharp increase after Cycle 2, suggesting a higher swelling potential after prolonged exposure to shrink-swell conditions. This behavior is further confirmed by the evolution of the oedometer modulus (**Figure 15**), which shows a decline after Cycle 1, indicating a reduction in soil stiffness.

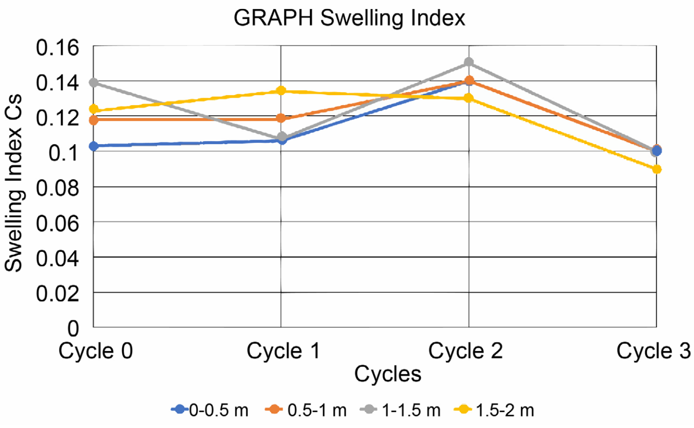

Figure 14. Evolution of swelling index throughout cycles.

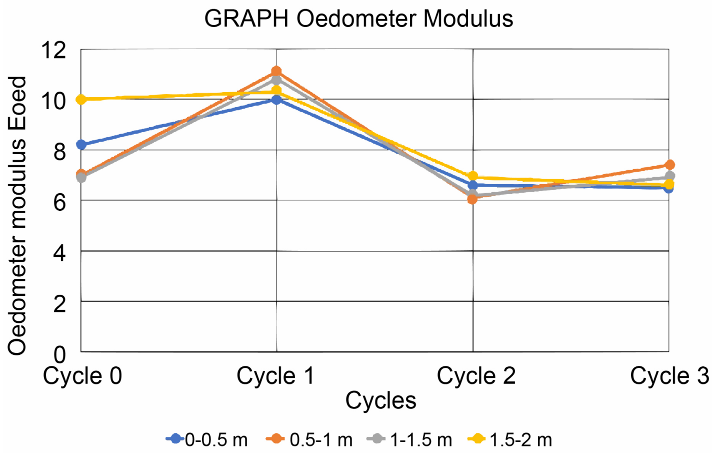

Figure 15. Evolution of oedometer modulus curve.

3.3. Numerical Modeling Results

In conjunction with the experimental findings, a two-dimensional finite element (FE) model was developed using PLAXIS 2D Foundation software to simulate the pavement system's behavior on expansive clay subjected to cyclic shrink-swell. The model configuration is shown in Figure 16, and material properties for the pavement layers are provided in Tables 5-7.

Table 5. Pavement layer and materials.

Layer Thickness	Materials
0.07 m	Bituminous Concrete
0.15 m	Untreated Gravel
0.20 m	Gravel Treated with Cement
0.20 m	Lateritic Gravel

Table 6. Properties of pavement materials.

Parameter	Value
Bituminous Concrete	
Type of Behavior	Linear Elastic
Young's Modulus E (kN/m^2)	500,000
Coefficient of Poisson ν	0.35
Untreated Gravel	
Type of Behavior	Linear Elastic
Young's Modulus E (kN/m^2)	400,000
Coefficient of Poisson ν	0.35
Bituminous Concrete	
Type of Behavior	Linear Elastic
Young's Modulus E (kN/m^2)	500,000
Coefficient of Poisson ν	0.35

Table 7. Properties of expansive clay depending on the cyclic number of shrink-swell.

Parameters	Cycle 0				Cycle 1				Cycle 2				Cycle 3			
	0 - 0.50 m	0.50 - 1 m	1 - 1.50 m	1.50 - 2 m	0 - 0.50 m	0.50 - 1 m	1 - 1.50 m	1.50 - 2 m	0 - 0.50 m	0.50 - 1 m	1 - 1.50 m	1.50 - 2 m	0 - 0.50 m	0.50 - 1 m	1 - 1.50 m	1.50 - 2 m
Saturated Density (kN·m^{-3})	17.08	16.70	16.94	17.25	14.13	14.30	14.90	15.05	13.4	13.2	12.5	14	14.95	14.95	14.95	14.95
Unsaturated Density (kN·m^{-3})	11.27	11.17	11.60	12.11	12.27	12.57	13.01	13.1	11.11	11.2	10	12.3	11.90	11.90	11.90	11.90
Young's Modulus (kpa)	5110	4360	4300	6230	6230	6920	4240	6400	4112	3800	3863	4299	4050	4610	4299	4112
Poisson's Ratio	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
Cu (kpa)	16.4	21.9	22	26	24.5	15.7	9	20.3	26.6	27.7	18.9	25.4	17.5	9.5	16	7.8
φ_u (˚)	1.6	0.7	3.1	5.5	21.5	26.1	24.9	24.4	10.1	14.5	12.2	15.3	5.34	9.7	12.17	10.75
Dilatancy Angle (˚)	0															
Interface Factor Rinte	0.600															
Coefficient of Permeability K_x (m·d^{-1})	0.012															
Coefficient of Permeability K_y (m·d^{-1})	0.012															

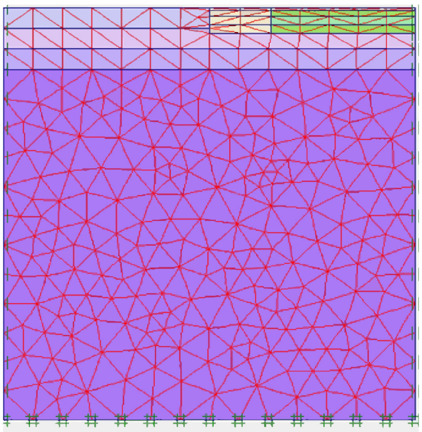

Figure 16. Finite element model of a pavement system on expansive clay.

The simulation results in **Figures 17-19**, is directly responsible for the observed increases in pavement displacement in the numerical model.

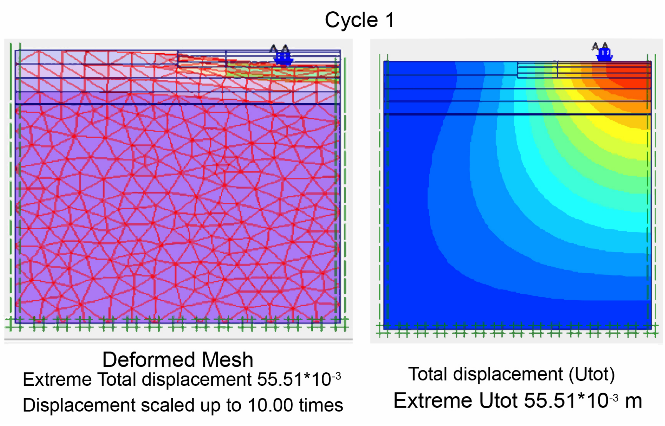

Figure 17. Deformed mesh and the total displacement of finite element model: Cycle 1.

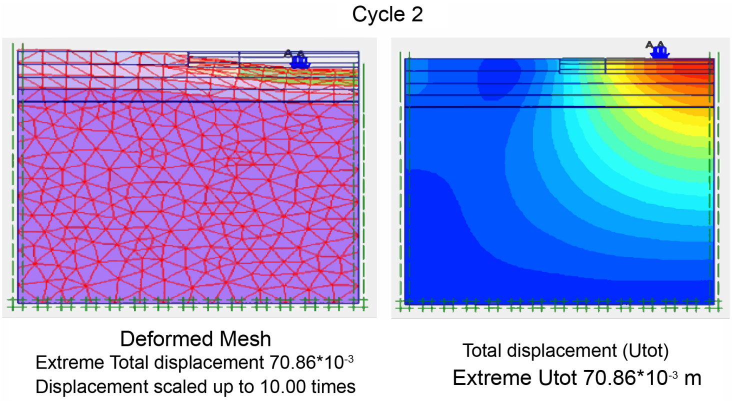

Figure 18. Deformed mesh and the total displacement of finite element model: Cycle 2.

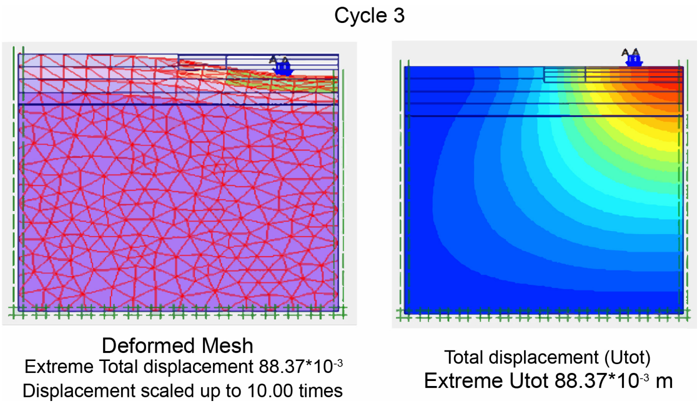

Figure 19. Deformed mesh and the total displacement of finite element model: Cycle 3.

3.4. Combined Interpretation of Experimental and Numerical Results

The experimental and numerical results together offer a comprehensive view of the mechanical behavior of expansive clays under cyclic wetting and drying. The experimental tests show that repeated cycles lead to significant changes in soil properties, including reduced cohesion, increased compressibility, and a higher swelling index. These findings are supported by the numerical model, which predicts an increase in pavement displacement as the soil beneath it degrades.

In practical terms, this study highlights the need for robust design strategies when dealing with pavements constructed on expansive clay subgrades. The numerical simulations align well with the experimental observations, showing that cyclic environmental conditions, particularly in regions with significant seasonal moisture variations, can lead to progressive pavement failure if not properly mitigated.

3.5. Engineering Implications

The findings from both the laboratory tests and numerical modeling demonstrate that cyclic shrink-swell can cause significant degradation in the mechanical properties of expansive clays, ultimately affecting pavement performance. To mitigate these effects, soil stabilization techniques or design modifications may be necessary to improve the long-term performance of pavements in areas prone to expansive clay behavior. Additionally, the integration of experimental data with numerical models provides a powerful tool for predicting pavement performance and planning for sustainable infrastructure development in such challenging environments.

3.6. Influence of Environmental Factors on Shrink-Swell Behavior

One of the critical aspects to consider when analyzing the behavior of expansive clay soils is the impact of environmental conditions, particularly temperature and drying rates. Seasonal variations, ambient temperatures, and the rate at which moisture is lost or gained in soils play a significant role in altering the mechanical response of soils subjected to drying-wetting cycles.

3.6.1. Temperature and Drying Rates

Previous studies have highlighted that expansive clay soils respond sensitively to temperature fluctuations, particularly concerning swelling and shrinkage behavior. Basma *et al.* (1996) observed that higher temperatures accelerate the drying rate of soils, leading to faster contraction, which can cause increased surface cracking and the formation of microcracks within the soil matrix. These cracks affect the permeability and mechanical strength of the soil, contributing to the progressive degradation of its physico-mechanical properties.

Regarding the drying rate, studies such as Soltani *et al.* (2020) show that rapid drying cycles exacerbate internal stresses in clay soils, increasing the potential for differential shrinkage. Faster drying leads to a rapid reduction in water content, accelerating pore desaturation and encouraging uneven contraction in different parts of the soil. This phenomenon affects the shear strength and consolidation properties of soils, as demonstrated by our oedometer and direct shear test results.

In our study, temperatures during the drying phases ranged between 26˚C and

36˚C, simulating the diurnal variations observed under natural climate conditions in the study area. These temperature ranges are comparable to those described by Louati *et al.* (2021), who found that similar daytime temperatures intensify soil shrinkage, leading to an increase in surface cracking and, consequently, changes in shear strength properties.

3.6.2. Impact of Temperature Variations on Swelling

Drying rates influenced by temperature also impact the swelling behavior of clay soils. When soils are re-saturated after rapid drying cycles, the samples tend to exhibit differential swelling, often more pronounced than in earlier cycles. This observation aligns with the findings of Basma *et al.* (1996), who noted a temporary increase in swelling capacity in soils that underwent rapid desiccation cycles. As the number of cycles increases, the intensity of swelling gradually decreases, as observed in our experimental results, suggesting a possible stabilization of the soil's behavior over time.

3.6.3. Comparison of Drying Rates

The drying rate plays a central role in the distribution of internal stresses within the soil. Slow drying, as simulated in some field studies, allows for more uniform contraction of clay layers, reducing microstructural damage within the soil. Conversely, rapid drying, observed during the phases of our study, tends to exacerbate internal stresses, promoting the formation of cracks. This behavior is particularly critical when predicting the durability of infrastructure built on expansive clay soils in arid or semi-arid regions, where prolonged drought periods are common.

The influence of temperature and drying rates on the shrink-swell behavior of expansive clay soils is evident. Our experimental observations confirm the conclusions of previous studies, suggesting that rapid drying cycles combined with high temperatures lead to a faster degradation of the soil's mechanical properties, particularly in terms of shear strength and compressibility. This underscores the importance of considering environmental conditions when assessing the behavior of expansive soils to ensure the durability and stability of infrastructure in at-risk areas.

3.7. Validation of the Numerical Model

The reliability of the numerical simulations was assessed by comparing the model's results with both field data and documented case studies. This validation process is crucial for ensuring that the finite element model accurately simulates the behavior of expansive clay soils under cyclic shrink-swell conditions, providing credible insights for real-world applications and infrastructure planning.

3.7.1. Field Data Comparison

Field data from a monitored pavement section in Pobè, Benin were employed to validate the outcomes of the numerical simulations. This site was selected due to the presence of expansive clay soils with similar characteristics to those modeled in this study. The site has been subjected to long-term cyclic wetting and drying, providing an excellent benchmark for comparison.

- Vertical displacement comparison: The predicted vertical displacements from the model were compared with settlement data observed in the field over successive shrink-swell cycles. **Figure 12** presents the comparison between the predicted displacements and the measured field data over time. The numerical model captures the overall trend of increasing displacement with the number of cycles, closely aligning with the field observations. Minor discrepancies in magnitude may arise due to field variables such as localized soil heterogeneity, unaccounted environmental factors, or differences in moisture dynamics.
- Shear strength validation: The reduction in undrained cohesion (C_u) and friction angle (φ_u) observed in field tests was simulated in the numerical model. **Figure 13** illustrates the relationship between the field shear test results and the corresponding numerical predictions. The progressive reduction in shear strength across successive cycles was well-replicated by the model. However, deviations in the deeper soil layers were observed, likely due to the incomplete representation of moisture penetration and temperature variations in the simulation.

3.7.2. Case Study Validation

In addition to field data, the model was further validated using case studies from the literature. A comparative analysis was conducted with the results of studies by Basma *et al.* (1996) and Sayem *et al.* (2016), which examined pavement performance on expansive soils under cyclic environmental loads. The numerical model's predictions demonstrated strong alignment with the documented field results from these studies, providing additional confidence in the model's accuracy.

- Oedometer modulus: The degradation of the oedometer modulus (E_{oed}) over multiple cycles, as predicted by the model, was validated against long-term consolidation data from Sayem *et al.* (2016). **Figure 14** depicts the evolution of E_{oed} in the model across different cycles, which mirrors the trends observed in Sayem's case study in Kaiping, Guangdong, China. Minor variations in the final cycle may be attributed to the challenges of precisely simulating environmental factors such as fluctuating temperature and humidity levels.
- Pavement displacement and cracking: The model effectively predicted the surface displacement and cracking patterns observed in real-world pavement systems. The crack propagation observed in Cycle 3 closely mirrored the patterns reported in a case study from Arizona, USA (Alonso *et al.*, 1999), where cracks expanded rapidly following repeated cycles of shrink-swell. This further validates the model's capacity to simulate the long-term effects of cyclic loading on expansive soils.

3.7.3. Model Limitations and Future Validation

Despite demonstrating robust accuracy through comparisons with both field data and literature-based case studies, the numerical model has some limitations:

- Environmental factors: The current model does not fully capture the complex influence of temperature variations and drying rates on the expansive behavior of clay soils. As discussed in Section 3.5, these environmental factors can significantly alter soil properties, particularly in the upper layers. Incorporating real-time temperature and humidity data could further enhance model accuracy.
- Model sensitivity: Sensitivity analyses (detailed in Section 3.7) revealed that certain input parameters, particularly Poisson's ratio and cohesion, have a significant impact on the model's output. This suggests that precise calibration of these parameters with field data is essential for improving the reliability of the model's predictions.

3.8. Sensitivity Analysis of Model Parameters

Conducting a sensitivity analysis is a crucial step in evaluating the robustness and reliability of numerical models, particularly in the context of complex soil-pavement interactions. This analysis identifies which parameters exert the greatest influence on the performance of pavement systems constructed over expansive clay soils subjected to cyclic shrink-swell conditions. By quantifying the impact of each parameter, the model can be optimized for enhanced predictive accuracy, allowing for more informed decision-making in geotechnical engineering.

3.8.1. Key Parameters for Analysis

The sensitivity analysis focused on a set of critical input parameters that govern the mechanical behavior of expansive soils and their interaction with overlying pavement structures. The parameters selected for this analysis include:

- **Young's Modulus (E)**: A key indicator of material stiffness, where higher values indicate greater resistance to deformation under applied loads.
- **Cohesion (C_u)**: Defines the soil's resistance to shear stress, particularly important for expansive clays that experience strength degradation during cyclic wetting and drying.
- **Internal Friction Angle (φ_u)**: Describes the soil's resistance to sliding, contributing significantly to its overall shear strength.
- **Poisson's Ratio (v)**: Represents the material's tendency to expand or contract laterally when subjected to axial stress, influencing deformation behavior.
- **Saturated Permeability (K_s)**: Governs the rate at which water infiltrates the soil, affecting the dynamics of the wetting phase in cyclic tests.
- **Oedometer Modulus (E_{oed})**: Relates to the compressibility of the soil under vertical stress and is critical for predicting settlement behavior.

3.8.2. Methodological Approach

To assess the sensitivity of the model, each of these key parameters was systematically varied, while all other parameters were held constant. This approach isolates the influence of each variable on the model outputs, specifically vertical displacement, shear strength, and stress distribution within the pavement system. Multiple simulations were conducted for each parameter, with incremental adjustments, to capture non-linear effects and interdependencies.

The sensitivity of the model was evaluated using two primary performance indicators:

- **Displacement Sensitivity**: Changes in the vertical displacement of the pavement surface as a function of parameter variations.
- **Shear Strength Sensitivity**: The impact on shear strength parameters, such as cohesion and internal friction angle, was analyzed to assess the system's stability.

3.8.3. Results of Sensitivity Analysis

The sensitivity analysis yielded the following insights:

Young's Modulus (E):

The numerical model exhibited significant sensitivity to variations in Young's Modulus across both the pavement layers and the expansive clay subgrade. Higher values of E resulted in reduced vertical displacements, indicating that stiffer materials lead to enhanced structural performance and resistance to deformation. Conversely, lower values of E led to greater deformations, particularly in the pavement layers, reflecting a reduction in system rigidity. Figures 17-19 illustrate the strong correlation between Young's Modulus and vertical displacement across different stages of the cyclic testing.

Cohesion (C_u):

Cohesion was identified as a critical factor influencing the shear strength of the soil. Reductions in cohesion significantly increased vertical displacement and reduced the soil's ability to resist shear forces, particularly in the deeper soil layers. Figure 11 shows the marked decline in system stability as cohesion diminishes over successive shrink-swell cycles.

Internal Friction Angle (φ_u):

The internal friction angle exhibited a moderate impact on the system's overall behavior. Although its effect on vertical displacement was less pronounced than cohesion, its influence became more significant after multiple shrink-swell cycles. This suggests that the internal friction angle plays a key role in the long-term shear resistance of the soil. The correlation between internal friction angle and shear strength is depicted in Figure 12.

Poisson's Ratio (ν):

While variations in Poisson's Ratio produced relatively minor effects on vertical displacement, they did influence lateral deformation and stress distribution within the pavement system. Higher values of ν led to greater lateral expansion under stress, which could potentially contribute to surface cracking in the pavement layers.

Saturated Permeability (K_s):

Saturated permeability emerged as one of the most influential parameters, as it controls the rate of moisture infiltration into the expansive clay. Increased permeability led to faster wetting, which exacerbated the cyclic shrink-swell behavior, resulting in higher vertical displacements. Figure 14 demonstrates the relationship between permeability and moisture infiltration rate, highlighting its significant impact on swelling and settlement behavior.

Oedometer Modulus (E_{oed}):

The oedometer modulus had a profound effect on the compressibility of the soil. Lower values of E_{oed} resulted in greater settlement, particularly in the early stages of the wetting-drying cycles. As shown in Figure 15, the reduction in soil stiffness over successive cycles indicates progressive degradation of the expansive clay's mechanical properties.

3.8.4. Critical Parameters and Engineering Implications

Based on the sensitivity analysis, the following parameters were identified as the most critical for accurately modeling the performance of pavement systems on expansive clay soils:

- **Young's Modulus (E)**: This parameter was found to be the primary determinant of pavement stiffness and overall structural performance. Accurate calibration of E is essential to predict pavement deformation under cyclic loading.
- **Cohesion (C_u)**: The soil's shear strength is heavily dependent on cohesion, especially in expansive soils where cyclic shrink-swell can lead to significant degradation. Monitoring and adjusting C_u is crucial for ensuring long-term stability.
- **Saturated Permeability (K_s)**: This parameter strongly influences the rate of moisture ingress, directly impacting the severity of shrink-swell behavior. Its accurate representation in the model is critical for assessing the long-term effects of environmental moisture variations.
- **Oedometer Modulus (E_{oed})**: The compressibility of the soil, as measured by the oedometer modulus, plays a key role in determining settlement behavior. Accurate estimation of E_{oed} is vital for predicting long-term consolidation and the associated pavement performance.

3.8.5. Conclusion of the Sensitivity Analysis

The results of the sensitivity analysis underscore the importance of precise calibration of key parameters in the numerical model to ensure reliable predictions of pavement performance over expansive clay subgrades. Parameters such as Young's Modulus, Cohesion, Saturated Permeability, and Oedometer Modulus emerged as the most critical, demonstrating the strongest influence on vertical displacement, shear strength, and overall pavement stability.

This analysis highlights the necessity for field calibration of these parameters to account for site-specific conditions and environmental factors. Further research should focus on integrating real-time environmental data, such as temperature and moisture variations, to refine the model and improve its predictive capabilities for long-term infrastructure performance.

4. Proposals for Soil Improvement Strategies and Pavement Design Modifications

Expansive soils, characterized by their shrink-swell behavior, present significant challenges to the durability and performance of pavement systems, particularly in regions subjected to cyclic moisture variations. To address these challenges, a range of soil improvement strategies and pavement design modifications have been developed to mitigate the negative effects of expansive soils on infrastructure. These approaches aim to stabilize the soil, enhance its mechanical properties, and optimize pavement design to ensure long-term performance under fluctuating environmental conditions.

4.1. Soil Stabilization Techniques

Soil stabilization has been widely recognized as an effective method to reduce the shrink-swell potential of expansive soils. The application of stabilizing agents, such as lime, cement, fly ash, and chemical polymers, can significantly improve the mechanical properties of the soil, making it more resistant to moisture-induced volume changes. Key stabilization techniques include:

4.1.1. Lime Stabilization

Lime stabilization is one of the most effective and commonly employed techniques for treating expansive clays. The chemical reaction between lime and clay minerals results in pozzolanic activity, which increases the soil's modulus of elasticity and cohesion while reducing its plasticity and swell potential. Lime treatment decreases soil permeability, thereby limiting moisture infiltration and subsequent swelling. The long-term effectiveness of lime stabilization in mitigating the effects of cyclic shrink-swell behavior has been well-documented in both laboratory and field studies [26].

4.1.2. Cement and Fly Ash Stabilization

Cement and fly ash are widely used to stabilize expansive soils, particularly in high-traffic areas. Cement improves the load-bearing capacity of the soil by forming a rigid matrix, while fly ash acts as a pozzolanic material that enhances the soil's resistance to moisture-related volume changes. These stabilizing agents significantly improve shear strength and reduce swelling potential, making them suitable for areas prone to significant traffic-induced stresses [27]. This combined approach also enhances the durability of pavements on expansive soils, contributing to long-term structural integrity.

4.1.3. Geosynthetic Reinforcement

Geosynthetics, including geogrids and geotextiles, are increasingly used to reinforce expansive soils, providing additional tensile strength and stabilizing the soil mass. When integrated into pavement systems, geosynthetics help to distribute loads more evenly across the subgrade, reducing differential settlement and mitigating the impact of soil swelling. Their effectiveness under cyclic loading conditions has been confirmed in numerous studies, making them an effective solution for enhancing pavement performance on expansive soils [28].

4.1.4. Chemical Stabilization with Polymers

Recent advancements in soil stabilization have introduced chemical polymers as environmentally friendly alternatives for improving expansive soils. Polymers form a flexible yet durable matrix within the soil, reducing plasticity and improving moisture resistance. These polymer-based stabilization techniques exhibit reduced swell-shrink behavior and increased resilience to cyclic moisture variations [29]. Given their non-toxic and environmentally sustainable nature, polymers are particularly attractive for projects subject to stringent environmental regulations.

4.2. Pavement Design Modifications

Beyond soil stabilization, certain pavement design modifications can play a crucial role in managing the challenges posed by expansive soils. These design adjustments focus on optimizing the pavement structure to accommodate soil movements and protect the pavement system from damage.

4.2.1. Thicker Pavement Layers

Increasing the thickness of pavement layers, particularly the base and subbase, can help distribute the applied loads more evenly across the expansive subgrade, thereby minimizing cracking and differential settlement caused by shrink-swell behavior. Thicker pavement layers act as a buffer, reducing the stress transferred to the subgrade and enhancing long-term pavement performance [30]. This approach is particularly effective in regions with high traffic volumes, where additional load-bearing capacity is necessary to withstand cyclic soil movements.

4.2.2. Flexible Pavement Design

Flexible pavements are better suited to accommodate the movements of expansive soils compared to rigid pavements. Their inherent flexibility allows for minor deformations without significant cracking, thus reducing the risk of damage due to soil swelling and shrinkage. Additionally, the materials used in flexible pavements can be designed to resist moisture infiltration, further protecting the subgrade from cyclic moisture variations [31]. This design strategy provides enhanced durability and reduces maintenance costs over time.

4.2.3. Drainage and Moisture Control Systems

Effective drainage systems are essential for managing the moisture content of expansive soils. Proper drainage prevents excessive moisture from infiltrating the subgrade, thereby reducing the risk of swelling and shrinking. The installation of sub-surface drains, permeable layers, and moisture barriers (e.g., geomembranes) can significantly mitigate the impact of moisture fluctuations on pavement performance [32]. These systems are particularly crucial in areas with pronounced seasonal wet and dry cycles.

4.2.4. Transition Zones and Buffer Layers

The incorporation of transition zones or buffer layers into pavement design is an effective method for absorbing differential movements caused by expansive soils. These zones typically consist of less expansive materials, such as granular soils or treated subgrade layers, that act as buffers between the expansive soil and the pavement structure. Transition zones help to minimize cracking and other forms of pavement distress by absorbing and redistributing soil movements [33]. This approach is especially beneficial in areas with severe shrink-swell cycles.

4.3. Evaluation of Improvement Strategies

The selection of appropriate soil improvement strategies and pavement design modifications depends on several factors, including the degree of soil expansivity, traffic loads, and regional environmental conditions. In highly expansive regions, a combination of soil stabilization (e.g., lime or cement) and design modifications (e.g., thicker pavement layers or flexible pavement systems) may be required to ensure long-term pavement performance.

Field trials and numerical simulations provide valuable tools for evaluating the effectiveness of these strategies. Finite element models can simulate the behavior of stabilized soils and modified pavement systems under cyclic loading, helping to identify critical parameters that influence performance and guide the selection of the most appropriate improvement techniques. This integrative approach, combining empirical data and advanced modeling, allows for a more tailored and efficient response to the challenges posed by expansive soils.

5. Conclusions

This study comprehensively investigated the effects of cyclic drying-wetting on the mechanical behavior of undisturbed expansive clay through a combination of oedometer and direct shear tests, complemented by finite element modeling. The experimental results indicated a clear degradation in the soil's mechanical properties as the number of drying-wetting cycles increased. Both shear strength parameters-internal friction angle and cohesion-exhibited progressive declines with each cycle, signifying a reduction in the soil's ability to resist shear deformation. Similarly, the oedometer modulus decreased, reflecting a reduction in stiffness, while the compressibility index increased, indicating higher susceptibility to compression. Concurrently, the swelling index showed a decrease, demonstrating diminished expansion potential with increased cycles.

The developed finite element model effectively captured these trends, illustrating a marked increase in total displacement with the rise in cyclic shrink-swell behavior. This increase in deformation highlights the cumulative impact of moisture variations on the integrity of pavement systems constructed on expansive soils. The numerical simulations provided valuable insight into the expected performance of pavements over time, underlining the importance of understanding the long-term behavior of expansive clays subjected to periodic climatic changes.

Despite these significant findings, this study has several limitations that should be considered. First, the research was limited to a specific type of undisturbed expansive clay, which may restrict the generalizability of the results to other soils with different mineralogical compositions or environmental conditions. Additionally, while the numerical model successfully captured the overall behavior of expansive soils under cyclic moisture variations, it did not fully account for critical environmental factors such as temperature fluctuations and varying drying rates, which are known to significantly influence the shrink-swell behavior.

Another limitation stems from the availability of comprehensive field data for model validation. Although the model aligned well with the experimental trends, further validation through long-term field data is essential to ensure the robustness and accuracy of the predictions, particularly under complex and variable real-world conditions.

To address these limitations and further advance understanding of expansive soil behavior, future research should focus on broadening the scope to include a wider variety of expansive soils from different geographical regions. This would enhance the applicability of the findings and provide a more comprehensive understanding of soil behavior under different environmental conditions.

Long-term field experiments, especially in regions prone to extreme climate variations, would be crucial for validating the predictions of the numerical models developed in this study. Such field-based research would help refine the models by incorporating the influence of environmental factors such as temperature, evaporation rates, and seasonal moisture fluctuations.

Exploring innovative soil improvement techniques is another promising avenue for future work. Techniques such as the use of biopolymers, nanomaterials, or other advanced sustainable stabilizers may offer novel solutions for enhancing the mechanical properties of expansive soils, potentially providing more environmentally friendly and cost-effective alternatives to traditional methods. Additionally, advanced microstructural analyses, such as scanning electron microscopy (SEM) and X-ray diffraction (XRD), would offer deeper insights into the underlying mechanisms of soil degradation and stabilization at the microscopic level.

Lastly, it is essential to evaluate the effects of varying traffic loads, construction methodologies, and extreme weather events on the long-term performance of pavements built on expansive soils. Such studies would provide critical insights into the design of more resilient pavement structures that can better withstand the dynamic challenges posed by expansive clays in the face of climate change and increasing infrastructure demands.

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Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

On behalf of all authors, the corresponding author states that there are no competing interests regarding the publication of this research.

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