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RESEARCH ARTICLE

TAKING INTO ACCOUNT THE SWELLING AND SHRINKAGE OF EXPANSIVE SOILS IN THE DESIGN AND BEHAVIOR OF PAVEMENTS

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Abstract

This work focused on the influence of swelling-shrinkage cycles on expansive soils and the behavior of pavements built on these soils in the Lama Depression, specifically on the Sehoue-Massi section of National Interstate Route No. 2 in southern Benin, a vital artery linking the north and south of the country. Its main objective was to study the variation in bearing capacity (CBR index) of swelling clay soils subjected to repeated swelling-shrinkage cycles, in order to improve pavement design and anticipate their behavior in the face of this phenomenon. After a literature review on the phenomenon and the pathologies observed on affected roads, soil samples were collected for analysis. The analysis revealed that it was a non-organic, swelling clay soil with a high susceptibility to swelling and shrinkage. The study, conducted over eight wetting-drying cycles, resulted in a 5% to 8% increase in CBR bearing capacity, representing a 60% improvement. However, these values remain low, and the studied expansive clay is still classified as S3. The pavement design, carried out according to the specifications of the Algerian CTTP 2001 catalog, favored a flexible structure adapted to the low bearing capacity of the soil. The proposed structure comprises 6 cm of bituminous concrete (BB) on the surface, 12 cm of bituminous gravel (GB) as the base course, 35 cm of untreated gravel (GNT) as the subgrade, and 70 cm of lateritic gravel (GL) distributed in two subgrade layers. These materials provide a smooth surface, dampen vibrations, distribute loads, and ensure good drainage. The numerical simulation performed with the ABAQUS software shows that deformations and deflections decrease with increasing cycles, thus guaranteeing the stability and durability of the pavement.

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Introduction:-

The development of road infrastructure is crucial for a nation's socio-economic vitality. Well-designed roads facilitate easy and immediate access to essential services, the transport of goods and people, stimulate socio-economic development, and strengthen regional and national connectivity. As one of the socio-economic lifelines of any country, it is paramount to guarantee the stability, durability, and meticulous monitoring of roads throughout their lifespan. To achieve this, it is necessary to carefully plan and examine the road structure, which consists of several layers that support traffic, ensure stability, comfort, and efficient rainwater drainage, resist deformation and settlement caused by traffic and climatic variations, and facilitate reliable maintenance and repair to extend the structure's durability and service life. Pavements, as geotechnical structures, are built on natural soils known as subgrade. These subgrades, acting as road subgrades, must be rigorously studied to ensure their capacity to support all road loads and guarantee the overall health of the road. This often-overlooked connection plays a crucial role in the long-term stability and performance of roads, particularly when the pavement is built on clay soils that are sensitive to climatic variations, causing significant volumetric changes. Water added to clay soils causes them to expand (swell), while water loss leads to contraction.(shrinkage), thus influencing the geotechnical behavior of the soil. This phenomenon of variation in the water content of clay soils (swelling-shrinkage phenomenon) causes premature failures in pavements.

This phenomenon is observed on a section of National Inter-State Route 2 (RNIE 2) in Benin, the main road linking the south to the north of Benin, crossing a depression known as the Lama Depression in the south of the country, between the Atlantique department, Toffo commune, Sehoue district, and the Zou department, Zogbodomey commune , Massi district. This region is characterized by a high concentration of swelling soils, particularly swelling clay, found to a depth of up to 30 meters. Several factors, such as mineralogical and organic composition, water content, climatic conditions, and particle size distribution, underlie the swelling-shrinking cycle of clay and strongly influence the geotechnical properties of clay soils, thus impacting the behavior of expansive soils. Finding solutions to this phenomenon remains a matter of in-depth consideration, as it is impossible to circumvent these soils in some areas. However, it should be noted that research projects have been carried out by researchers to further understand the parameters characterizing swelling clays in the Lama Depression. The study of the shear and compressibility behavior of expansive soils subjected to shrink-swell cycles under pavements: the case of the Sehoue-Massi sectionover eight cycles shows that it is a very plastic and inorganic clay (Ip = 45, MO = 0.7%), shows a decrease in cohesion to 42.98 kPa and in the friction angle to 14.6° with an increase in the compressibility index and a decrease in the swelling index, highlighting the importance of managing these variations to maintain pavement stability and minimize the adverse effects of shrink-swell cycles on road infrastructure. **[1]** . A study on the behavior of swelling soils in the Lama depression and its interaction with shallow foundations: the case of the Kho depression made it possible to observe the reduction of the swelling potential of these soils under the effect of the saline solution, to include a modeling of the interaction of these soils with shallow foundations and to propose design recommendations to minimize the settlement of structures built on these soils [2] .

Evaluation of the influence of drying-wetting cycles on the compressibility of clay soils in the commune of HoueyogbeThestudy in the Lama depression shows that the soil is class A3 clay, subjected to drying-wetting cycles with an increase in compressibility index, a decrease in swelling index, stability of pre-consolidation pressure and oedometer modulus, and a notable increase in soil permeability with the number of cycles [3] . The impact of swelling on the settlement of clay soils in the municipality of Houeyogbe in the Lama depression shows that these are plastic clays with free swelling, which partially influences the final settlement value [4] . The behavior of shallow foundations evaluated on swelling soils in the Issaba and Ahoyeye areas of the municipality of Pobe, by comparing the results of the Plaxis and Geofond software , highlighted the differences in bearing capacities [5] . The macroscopic and microscopic study of clay soils in the regions (Adjaïgbonou , Kpinnou , Ouedeme and Lokossa) shows the limitations of existing geotechnical characterization methods for determining the swelling potential of clay soils using indirect methods based on parameters such as particle size, Atterberg limits and methylene blue value [6] .

A physico-mechanical characterization of clay soils in the Issaba depression in southeastern Benin revealed that they are highly plastic clay particles with a high swelling potential and a high risk of pathology [7] . Stabilization of swelling soils in the Oran region using saline solutions, sand addition, and stabilization with lime, cement, or lime-cement resulted in a reduction of up to 80% in swelling [8] . An examination of the swelling and shrinkage potential of clay soils under road surfaces in the marshlands of southwestern France revealed a high clay content and a certain sensitivity to swelling and shrinkage [9] . The characterization and estimation of swelling in Algerian clays, specifically the clays of Medea, has shown a correlation between the empirical methods applied and the evolution of the clay structure during shrinkage-swelling. This is being monitored with the aim of understanding the swelling mechanism [10] . The effect of lime content on the bearing capacity and swelling potential of an expansive soil, through stabilization tests at 0%, 2%, 4%, 6%, 8%, and 10% lime, resulted in an improvement in the bearing capacity and a decrease in the swelling potential of the expansive soil with the addition of lime [11] . Prediction of California rolling rate of expansive soils using Gaussian process regression by hydrated lime-activated rice hull ash (HARHA) of treated soil input data: hybrid geometric binder, liquid limit, plasticity limit, plasticity index, optimum moisture content and maximum dry density, affirmed that HARHA was the key sensitive parameter affecting the CBR of expansive soils [12] .

The jute fiber test on the CBR value of expansive soil demonstrated that adding 10 mm and 30 mm jute fibers at various percentages (0.25%, 0.50%, 0.75%, 1%, 1.25%, and 1.50% of the soil dry weight) significantly improves the CBR value of the expansive soil, with a maximum increase of 226.92% for an optimal jute fiber content of 1.25%. This suggests an economical solution for strengthening clay soils with agricultural waste [13] . An experimental study of the geotechnical properties and microstructure of expansive soils stabilized with granite dust showed that adding up to 20% granite dust significantly improves the unconfined compression and CBR of expansive soils. Further research was conducted to optimize the stabilization of these soils.With this in mind, the present work aims to contribute to the understanding of the swelling-shrinking phenomenon of expansive soils in order to create a parametric connection between pavement design and the characterization of clay soils under the stresses of swelling-shrinking cycles to anticipate their movement under pavements in the long term by exploring eight cycles to ensure the stability and durability of pavements.

Method:-

Study area and sampling:-

Clay samples were collected from the Lama depression near National Interstate Route No. 2 (RNIE No. 2) in Benin, on the Akassato -Bohicon section between Sehoue and Massi. The geographical coordinates of the sampling point are shown in Table 1:

Table 1: Geographic coordinates of the sample

Contact details			
X	Y	Latitude	Longitude
69454217	22630897	N: 767774.54m	E: 418566.822m

Sampling techniques:-

To carry out the physico-mechanical tests encompassing both identification and mechanical tests, a mixture of samples taken from the following depths: 0 to 0.50 m; 0.5 to 1.0 m; 1.0 to 1.50 m; 1.50 to 2 m and 2 m to 2.50 m were obtained.

Description of the tests:-

- **Identification tests:**
  - Determination of water content NF EN ISO 17892-1
  - Particle size analysis by sieving and sedimentation (NF EN ISO 17892-4)
  - Atterberg limit tests NF EN ISO 17892-12
  - Methylene blue value test NF EN 933-9
  - Specific weight EN ISO 17892-3
  - Organic matter content NF P 94 – 055

- **Mechanical tests:**
  - Modified Proctor test NF P94-093.
  - The samples of disturbed soil that had undergone wetting-drying cycles were subjected to the CBR NF P 94-078 test.

Operating procedure for the humidification and drying cycle:-

a) Clay samples were placed in Dangote bags and immersed in water. After 24 hours, they were weighed hourly until their mass stabilized, indicating complete water saturation. Simultaneously, control samples were dried in an oven and in the sun to measure the water content after wetting and natural drying.

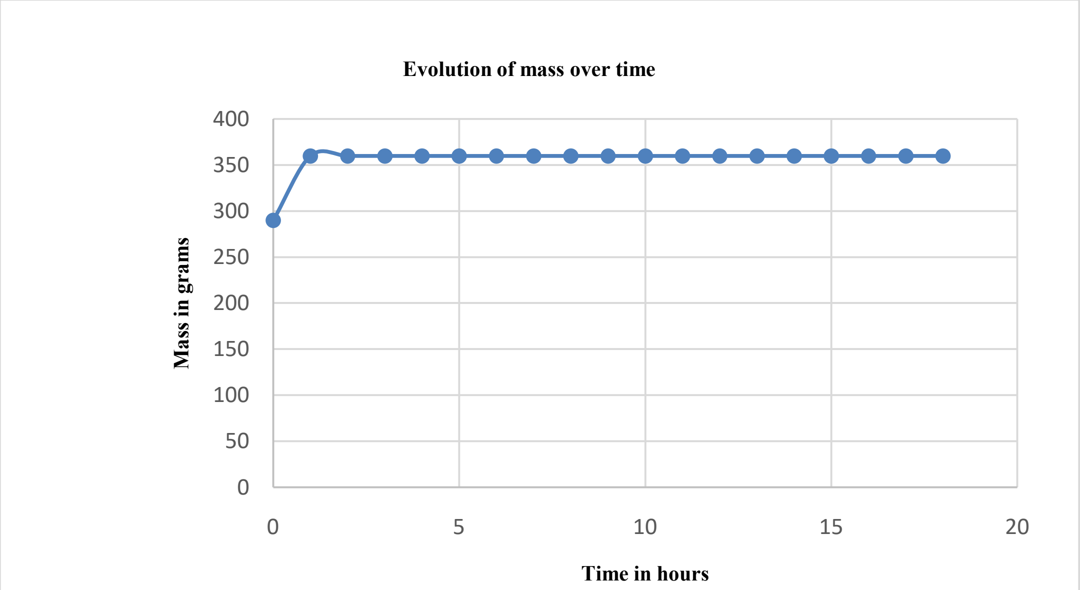


Figure 1: Humidification kinetics

b) The clay samples are dried in the sun at temperatures ranging from 24°C to 48°C for 9 hours a day, simulating the shrinkage phenomenon during the dry season. This allows them to reach a drying moisture content of 14%, similar to that measured in the swelling clays of the Lama depression.

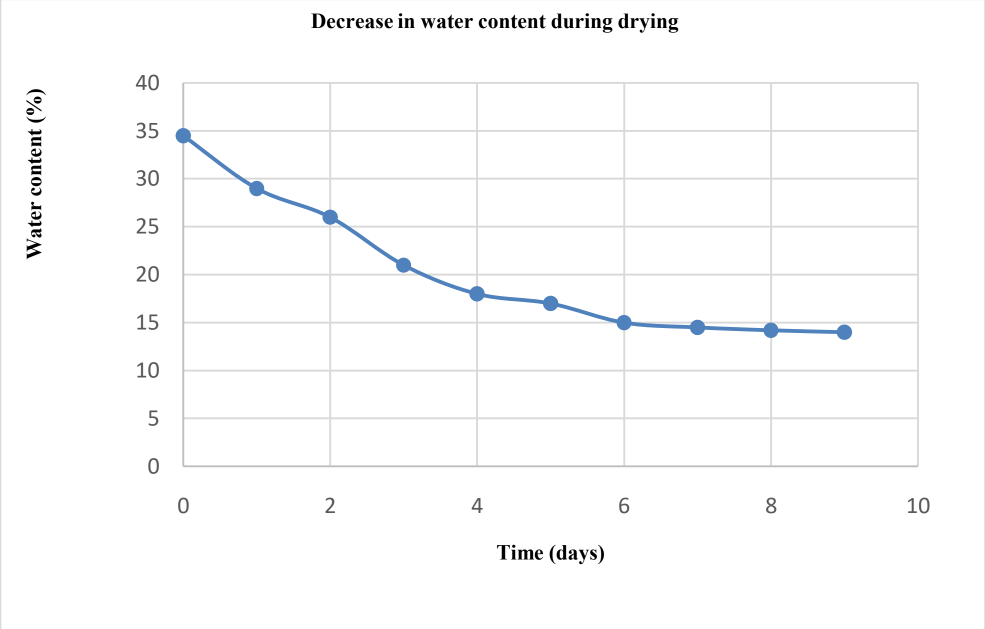


Figure 2: Drying kinetics

c) Description and interpretation of sample textures during cycles

When wet, clay absorbs water, causing it to expand and increase in volume. As it dries, the evaporated water causes the clay to contract, leading to cracks on its surface. With each cycle of wetting and drying, the clay becomes more susceptible to volume changes, resulting in a weakening of its structure. This material fatigue is due to the progressive breaking of bonds between clay particles, resulting in a more cracked and brittle texture as the cycle repeats.

Photo 1: Illustration of the texture of samples that have undergone humidification-drying cycles After each drying cycle, the material is ground in a metal mold and sieved through a 5 mm sieve. The sieve passages are then used to determine the moisture content of the ground material, in order to perform the CBR test.

Photo 2: Preparing the sample to be used

Results:-

Identification tests:-

Figure 4 shows the particle size distribution of the soil studied. The percentage passing through the 80 µm sieve is 91.50%, which is greater than 35%, therefore the soil studied is a fine soil.

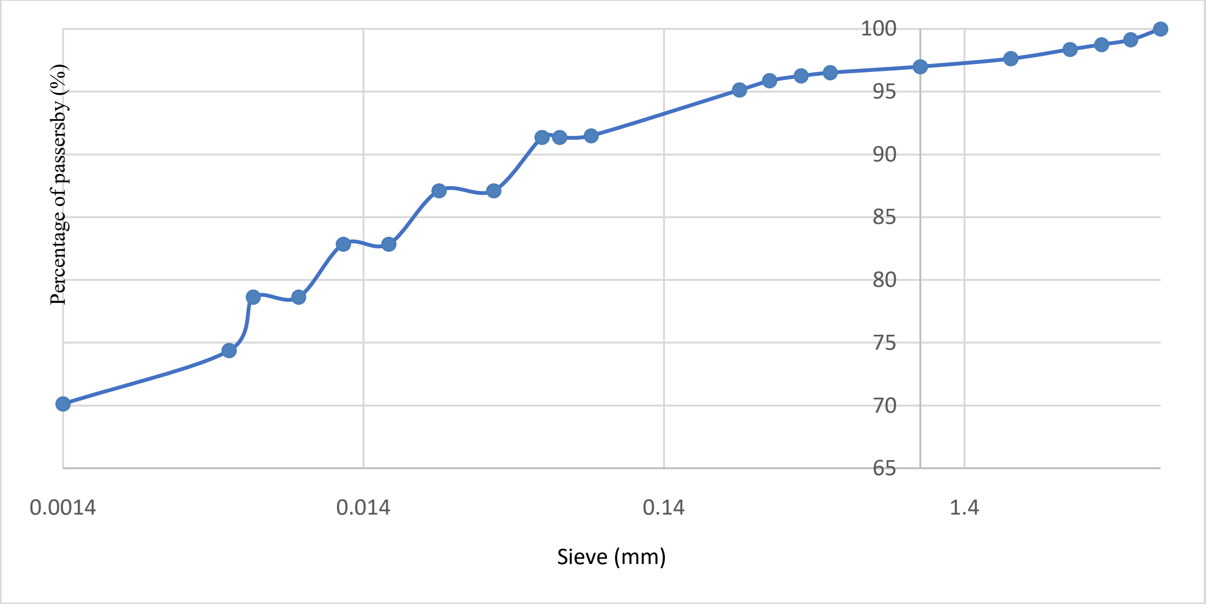


Figure 3: Particle size distribution curve of the clay from the Lama depression (Sehoue-Massi section)

Table 2: Summary of identification tests

Parameters Values	
Natural water content w (%)	35.85
Passage through 80µm (%)	91.50
Passing through a 2µm sieve C_2 (%)	71
Methylene blue value VBS	13,714
Liquidity limit w_L (%)	83.3
Plastic limit w_P (%)	47
Plasticity Index I_P (%)	36.3
Consistency Index I_C	1.31
Organic matter OM (%)	0.65
Specific weight γs ($g.cm^{-3}$)	2,101
Blue activity of the clay fractionA $_{CB}$	19.315>18

Mechanical tests:-

Figure 5 shows the Proctor curve of the soil studied. The maximum dry density is 1.52 t/m3, obtained at an optimal content of 27.5%.

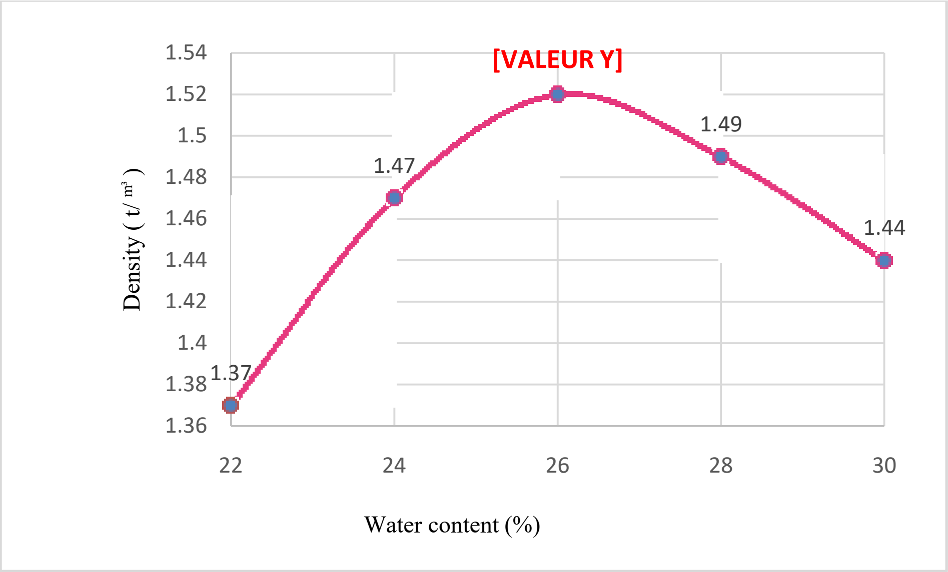


Figure 4: Modified Proctor curve of the studied clay

To assess the influence of swelling-shrinkage cycles on the bearing capacity of the clay studied, the CBR indices of the samples were determined over eight wetting-drying cycles. Figure 6 shows the variation of the CBR index as a function of the number of wetting-drying cycles, where the CBR index, taken at 95%, increases by approximately 60% with the number of cycles.

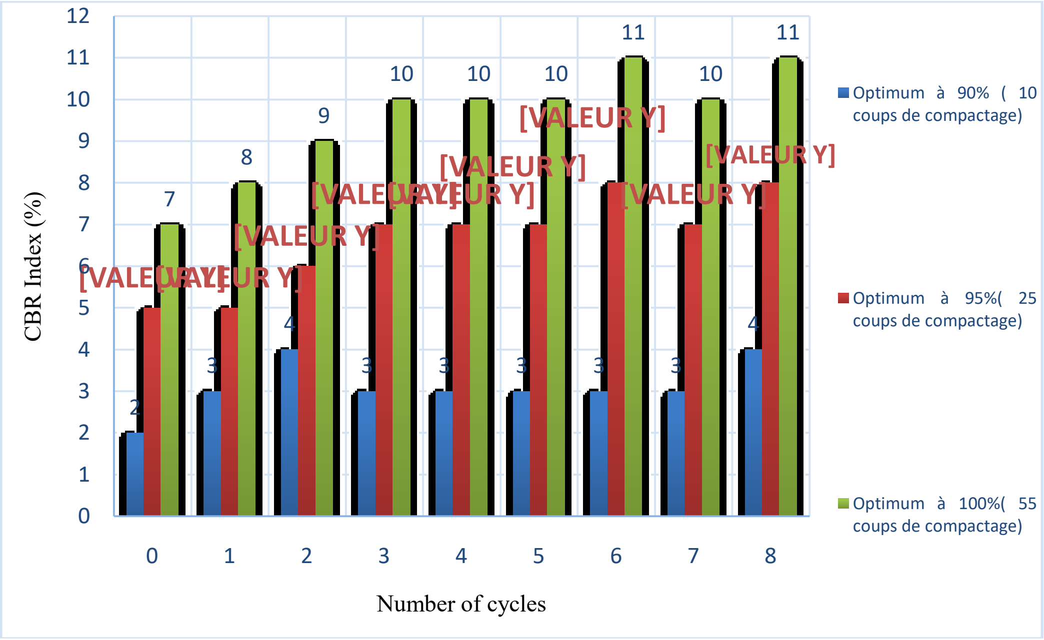


Figure 5: Variation of the soil CBR index as a function of the wetting-drying cycle

Figure 8 illustrates the evolution of CBR mold swelling as a function of wetting-drying cycles, which gradually decreases as the cycle increases.

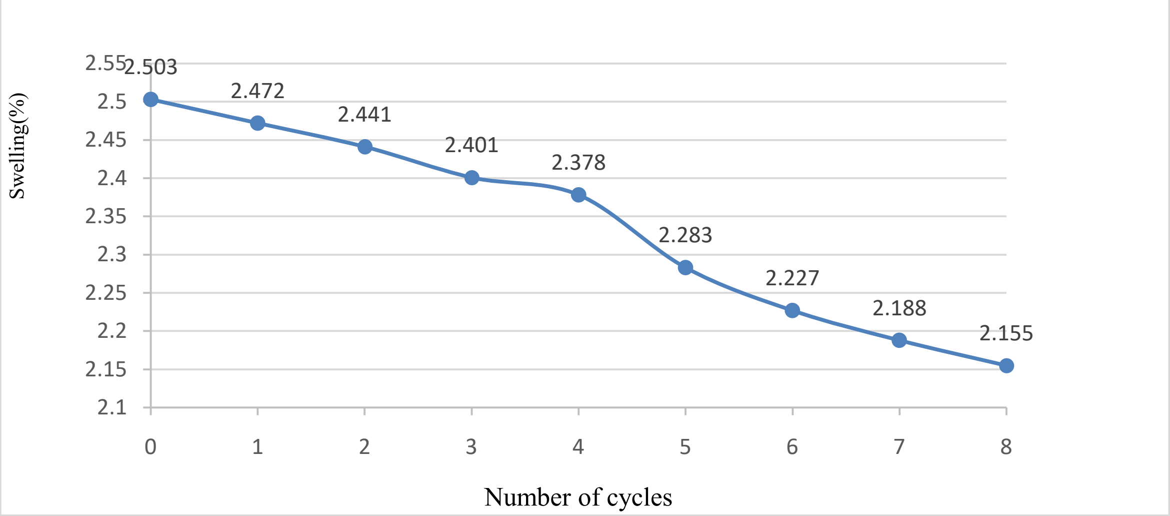


Figure 6: Evolution of swelling in the CBR mold as a function of wetting-drying cycles

Pavement structure design (Sehoue- Massi section) :-

The pavement design for the Sehoue-Massi section of National Highway 2 (RNIE 2), crossing the Lama depression, was carried out using the Algerian catalog for the design of new pavements (CTTP 2001),adapted to the CBR index and extreme design parameters. The 7-meter-wide, two-way pavement extends from the southern access road to Sehoue (km 78+456) to the northern exit of Massi (km 86+720), with an estimated traffic volume of 820 heavy goods vehicles per day in each direction in 2026, corresponding to a reference load of 13 tonnes (traffic class TPL5). The method used for classifying the studied soil is based on an empirical formula where the Young's modulus E (in MPa) is equal to five times the soil's CBR bearing capacity index **.**The values obtained remain low, and the soil has been classified as S3, requiring upgrading to S1 to guarantee the stability of the structure. The area is classified as climate zone III, with a projected service life of 15 years and a geometric growth of 3%. The pavement structure selected according to catalog booklet 3 comprises: 6 cm of bituminous concrete (BB) as a surface course, 12 cm of bituminous gravel (GB) as a base course, 35 cm of untreated gravel (GNT) as a subbase, and 70 cm of lateritic gravel (GL) distributed in two subgrade layers. This design has been optimized to address the problems caused by soil swelling and shrinkage phenomena in order to guarantee the stability and durability of the pavement under seasonal variations.

Table 3: Properties of pavement and subgrade materials according to the cycle

Pavement layers	Materials	Layer thicknesses (m)	Young's modulus (MPa)	Poisson's ratio ($\boldsymbol{\nu}$)
Wearing course	Bituminous concrete (BB)	0.06	3500	0.35
Base layer	Bituminous gravel (GB)	0.12	5500	0.35
Foundation layer	Severe untreated (GNT)	0.35	350	0.25
Form layer	Gravelly lateritic GL	0.35	280	0.25
	Gravelly lateritic GL	0.35	280	0.25
Swelling clay soil	Cycle 0	Infinity	25	0.35
	Cycle 1	Infinity	25	0.35
	Cycle 2	Infinity	30	0.35
	Cycle 3	Infinity	35	0.35
	Cycle 4	Infinity	35	0.35
	Cycle 5	Infinity	35	0.35
	Cycle 6	Infinity	40	0.35
	Cycle 7	Infinity	35	0.35
	Cycle 8	Infinity	40	0.35

The base layer is made of bitumen-treated materials, so we check if ε_t and ε_z, calculated using Alize III, are below the permissible values.

Table 4: Summary of deformations at the base of the bituminous gravel and in the subgrade according to the cycle

Number of cycles	Calculated vertical deformation ε_z (10^{-6})	Allowable vertical deformation $\varepsilon_{z,adm}$(10^{-6})	Tensile deformation at the base of GB ε_t (10^{-6})	Allowable tensile deformation (ε_t) $_{,adm}$(10^{-6})
0	183.1	660.84	114.8	128,292
1	183.1		114.8	
2	171.5		114.8	
3	161.8		114.9	
4	161.8		114.9	
5	161.8		114.9	
6	153.4		114.9	
7	161.8		114.9	
8	153.4		114.9	

The vertical strain εz decreases by about 16.2% while the tensile strain εt increases slightly by 0.09%, but in both cases they remain below the allowable values εz $_{,adm}$ andεt $_{,adm}$, verifying the design conditions in each case.

$$\varepsilon_t<\varepsilon_{t,adm} \; ; \; \varepsilon_z<\varepsilon_{z,adm}$$

Numerical modeling and simulation of the pavement using the ABAQUS finite element software:-

The pavement, designed for expansive clay soil, was modeled using ABAQUS 2021 software, taking into account the swelling and shrinkage cycles.

- **Model geometry and characteristics of the supporting soil:-**

Tableau 5: Proprietes de cisaillement du sol etudie

Number of cycles	Young's modulus E MPa	Poisson's ratio (ν)	Angle of friction φ_u (°)	Cohesion C_u Kpa	Unsaturated density kg/m3	density (kg /m³)
0	25	0.35	14.6	42.98	1465.85	1800.2
1	25	0.35	6.9	16.81	1695.21	2264.02
2	30	0.35	5.5	15.89	1307.85	2360.86
3	35	0.35	5.2	14.72	1320.08	2545.36
4	35	0.35	5.1	14.21	1357.8	2628.95
5	35	0.35	5.05	13.50	1147.81	2300.71
6	40	0.35	5	13.30	1314.98	2545.36
7	35	0.35	4.8	12.9	1357.8	2628.95
8	40	0.35	4.71	11.47	1357.8	2628.95

Shear properties are used in the Morh-Colomb model under ABAQUS to simulate the behavior of expansive soils subjected to shrink-swell cycles, with a 3D geometric model of dimensions 10x10x10m.

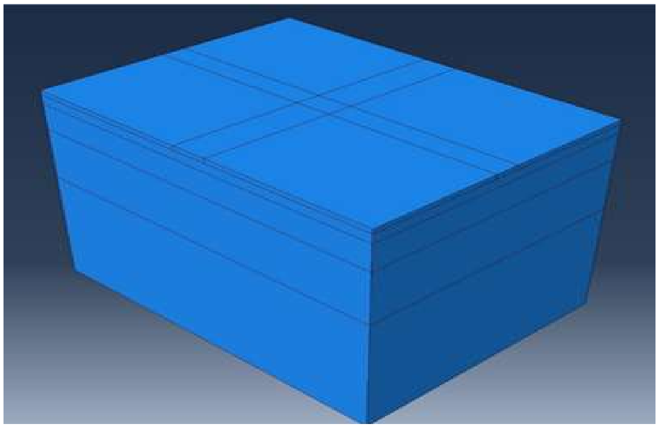
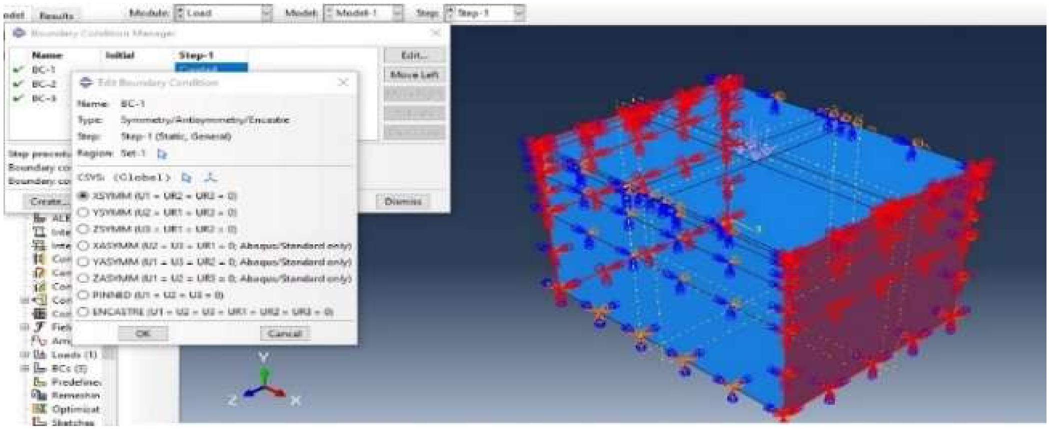


Figure 8: Geometrie du modele



Name: BC-1
Type: Symmetry/Antisymmetry/Encastre
Step: Step-1 (Static, General)
Region: Set-1
CSYS: (Global)

- ● XSYMM (U1 = UR2 = UR3 = 0)
- ○ YSYMM (U2 = UR1 = UR3 = 0)
- ○ ZSYMM (U3 = UR1 = UR2 = 0)
- ○ XASYMM (U2 = U3 = UR1 = 0; Abaqus/Standard only)
- ○ YASYMM (U1 = U3 = UR2 = 0; Abaqus/Standard only)
- ○ ZASYMM (U1 = U2 = UR3 = 0; Abaqus/Standard only)
- ○ PINNED (U1 = U2 = U3 = 0)
- ○ ENCASTRE (U1 = U2 = U3 = UR1 = UR2 = UR3 = 0)

Figure 9: Contions aux limites du modele

The traffic load applied to the pavement, modeled as a circle in ALIZE, is converted into a rectangular load 0.38 m long and 0.26 m wide for use in ABAQUS, with a force of 65 kN and a pressure of 0.329 MPa. The model was discretized with CAX4R elements in ABAQUS, using finer elements near the loading area and coarser elements elsewhere, and a parametric study assessed the impact of the number of elements on the convergence of the results.

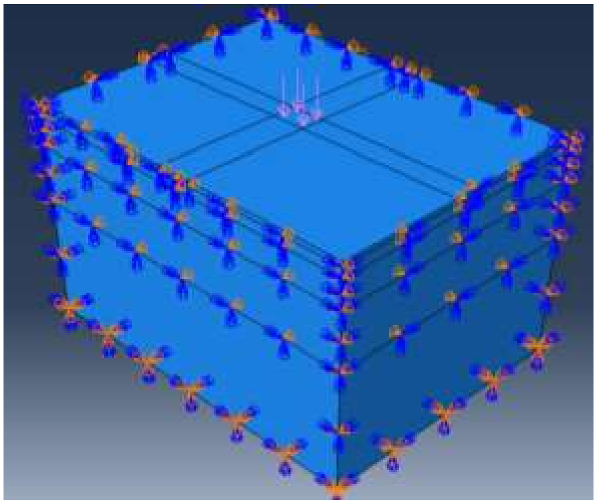


Figure 10 : Application de la charge surfacique

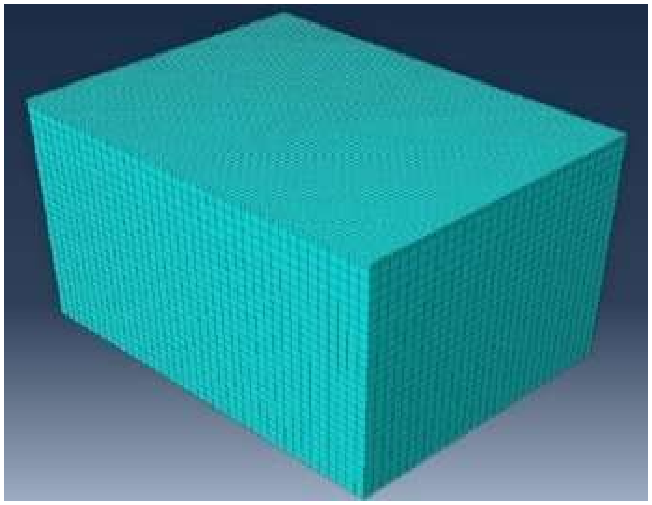


Figure 11 : Maillage

- **Simulation results:-**

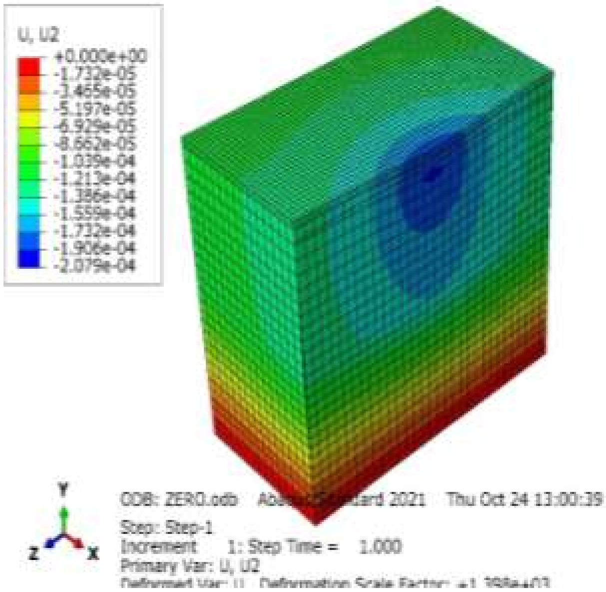


Figure 12: Champ de deflexions à la surface de la chaussee (cycle 0)

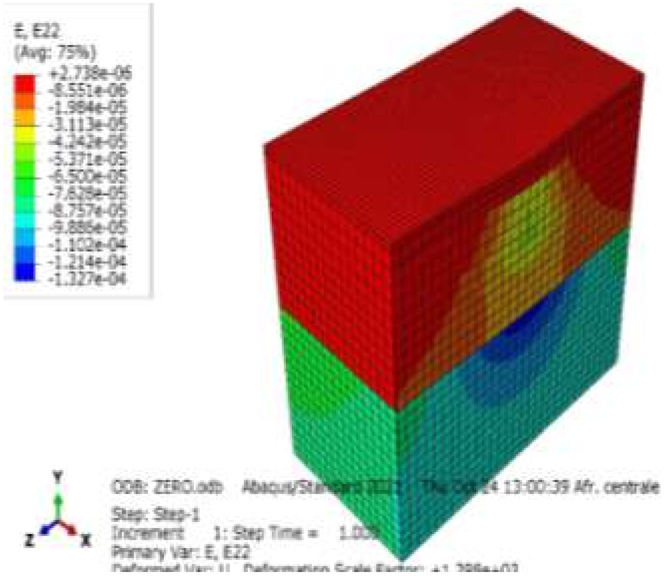
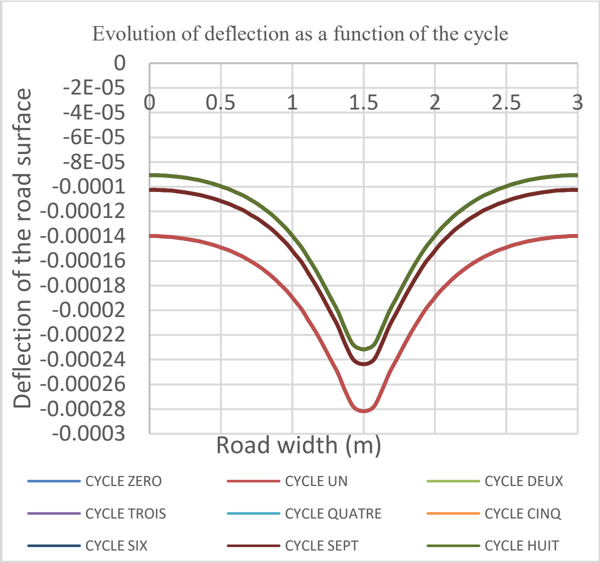


Figure 13 : Champ de deformations à la base de la couche de forme (cycle 0)



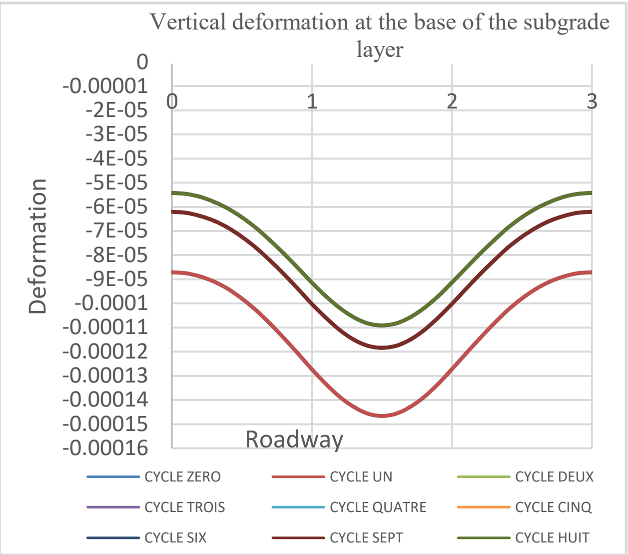


Figure 14 : Deflexions à la surface de chaussee en fonction du cycle

Figure 15 : Deformations verticales à la base de la couche de forme en fonction du cycle

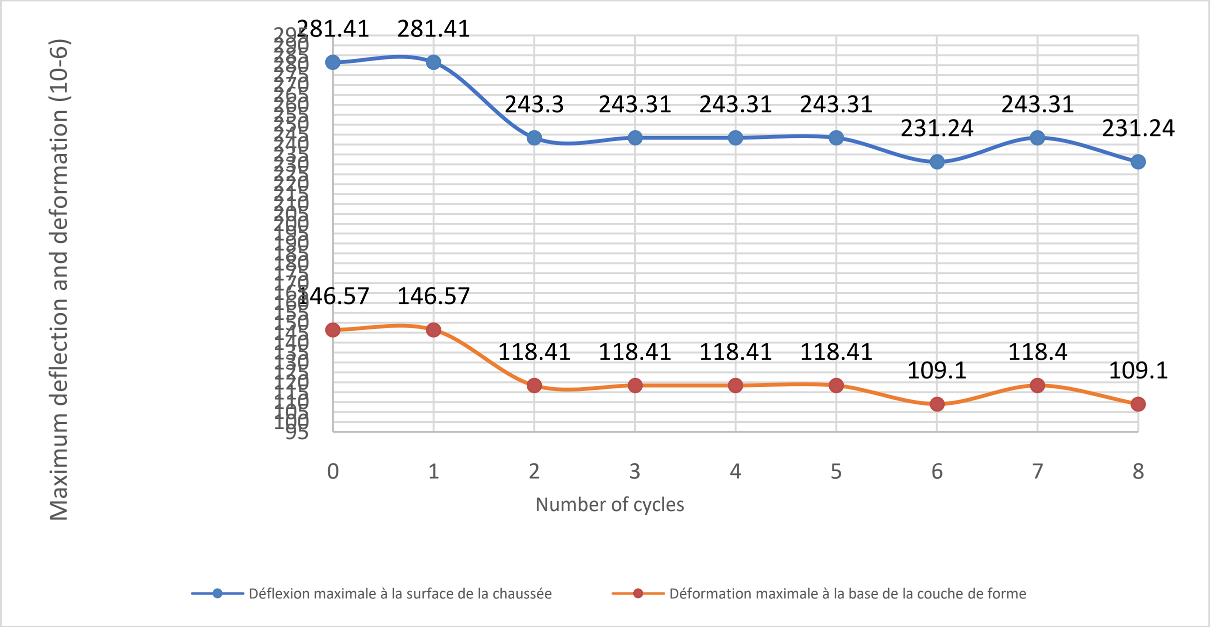


Figure 16: Evolution des deflexions maximales à la surface de la chaussee et des deformations verticales maximales à la base de la couche de forme en fonction du cycle

The overall results reveal that the deflection at the surface of the pavement and the deformation at the base of the subgrade decrease by 17.82% and 25.56% respectively as the cycles progress.

Discussion:-

Test results show that the soil studied is a swelling clay, very consistent and inorganic, with a high susceptibility to shrinkage and swelling. The maximum dry density is 1.52 t/m³, obtained at an optimal water content of 27.5%. The CBR index, measured at 95% of optimum, indicates an improvement in bearing capacity of approximately 60%, increasing from 5% to 8% after eight wetting-drying cycles, with swelling gradually decreasing and providing better stability. These cycles promote particle reorganization, reducing plasticity and limiting deformations due to moisture variations. The pavement design, carried out taking into account seasonal cycles according to the CTTP 2001 method, allows for the selection of materials ensuring good durability, stability, drainage, resistance to climatic variations, and a reduction in the risk of cracking. Simulation results show that the proposed multi-layer design improves pavement performance by reducing deflections and deformations. The soil will benefit from improved stability thanks to the management of water conditions, thus increasing its load-bearing capacity. To guarantee the longevity of the infrastructure, regular monitoring and maintenance, with targeted interventions, ensures a reliable and durable pavement that can withstand climatic hazards and load variations.

Conclusion:-

Some roads in Benin cross the Lama Depression, a swelling clay zone, notably the National Interstate Route No. 2 linking the South and the North. This study, entitled "Consideration of Swelling-Shrinking of Expansive Soils in the Design and Behavior of Pavements," examines the impact of swelling and shrinking cycles on the bearing capacity of clay soils and its consideration in pavement design. The results show that these cycles improve the soil's mechanical resistance, thus promoting pavement stability and durability. Numerical simulations in ABAQUS demonstrate that increasing the frequency of cycles reduces deflections and deformations, thereby enhancing the stability and longevity of the road infrastructure.

The results of this study led us to formulate the following recommendations to improve pavement performance:

- To implement real-time monitoring systems for soil conditions and pavement performance in order to anticipate failures;
- To explore innovative soil stabilization techniques such as the use of geopolymers and economical chemical treatments to strengthen the clay structure while respecting the environment;
- Encourage in-depth scientific research on the long-term behavior of swelling clay.

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