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Modelling the Behaviour of Marl and Chikoko Soil of the Niger Delta Under Multiple Wetting and Drying Cycles

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Abstract: This study critically analyzed the behaviour, encompassing volumetric changes, deformation characteristics, and tensile strength properties, of two predominant problematic soils from the Niger Delta region: Marl and Chikoko soils, under the influence of multiple wetting and drying cycles. The experimental methodology employed the modified oedometer tests, systematically integrated within a three-level four-factor full factorial design framework. This robust experimental design allowed for a comprehensive investigation into the intricate effects of key environmental and geotechnical parameters. Specifically, the study meticulously examined the independent and interactive effects of varying moisture content (ranging from 14% to 16.5% for Chikoko soil and 47% to 51.5% for Marl soil), dry density (ranging from 1.70 to 1.96 g/cm³ for Chikoko soil and 1.00 to 1.28 g/cm³ for Marl soil), surcharge pressure (between 1 and 10 kN/m²), and the number of wetting and drying cycles (up to a specified maximum, usually 3-5 cycles in typical studies) on the chosen soil properties. The cyclic nature of wetting and drying amplifies these effects, highlighting the critical need to account for such environmental factors in the design of foundations, pavements, and other geotechnical structures in the Niger Delta. The research provides valuable insights into the mechanistic behaviour of these soils, offering a scientific basis for developing more resilient and sustainable infrastructure in the region.

Keywords: *Marl Soil, Chikoko Soil, Niger Delta, Wetting and Drying Cycles, Volumetric Change, Deformation, Tensile Strength, Oedometer Test, Full Factorial Design, Expansive Soils.*

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I. INTRODUCTION

The Niger Delta in southern Nigeria, known for its oil resources and vast wetlands, had a complex landscape and drainage system. The region faced rapid urban development due to population growth and economic activities. This growth created major challenges for civil engineers, especially because of problematic soils like clay and silt. These soils were highly plastic, reactive, and prone to expansion or shrinkage depending on moisture levels [29], [18]. During rainy seasons, floods, or pipe leaks, the soils absorbed water and swelled. In dry periods, they shrank due to evaporation and drainage. These cycles of wetting and drying caused significant volume changes [31], [16]. As a result, structures such as roads, pavements, retaining walls, and foundations developed cracks or settled unevenly. Some even failed completely [9], [5].

This study focused on two major soil types in the region: Marl and Chikoko. Marl soils were calcareous clays with varying levels of calcium carbonate. Their behavior depended on the clay-carbonate ratio. Many showed high plasticity and reacted sharply to moisture changes. The carbonate content also affected how the soil interacted with water and load [3], [6]. In the Niger Delta, marl deposits existed in certain formations and posed serious design issues. Chikoko soils, commonly found in mangrove and riverine areas, were soft, organic, and compressible. These silty clays had high moisture content and low strength. They deformed easily under load and had a high potential for settlement [25], [2]. Organic content further affected how these soils consolidated and responded to stress or chemical breakdown [10], [31]. Despite their differences, both soils reacted badly to changing moisture conditions. Their behavior under wetting and drying cycles needed detailed investigation, especially for design purposes.

Although engineers recognized the risks associated with Niger Delta soils, little detailed information existed about how Marl and Chikoko performed over time under

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repeated moisture changes. Current design methods mostly relied on data from other regions and soil types. These methods often failed to capture how local soils responded to complex conditions. Without accurate local data or models, design errors increased. This led to higher maintenance costs, frequent structural damage, and unsustainable infrastructure. A careful investigation into how these soils behaved under environmental cycles became essential.

This study aimed to fill the gap in local data by identifying the physical and engineering properties of Marl and Chikoko soils from selected Niger Delta locations; measuring how their volume changed during wetting and drying cycles using modified oedometer tests; studying deformation behavior under varying loads and moisture conditions; evaluating their tensile strength and cracking patterns under stress; using a full factorial experimental design to examine how moisture, density, loading, and cycles worked together; and offering design recommendations to improve infrastructure in regions where these soils occurred.

This research had practical and academic value. It helped engineers create better designs that could withstand environmental changes. The findings improved understanding of local soil conditions and supported better regional standards. Fewer failures meant reduced repair costs and safer, longer-lasting structures. The use of a statistical method (full factorial design) also added rigor to how soil behavior was analyzed. Overall, the study contributed to safer infrastructure, economic growth, and sustainable development in the region.

The safety and performance of structures built on fine-grained soils depended greatly on how those soils responded to water. Expansive soils swelled when wet and shrank when dry [21], [45]. These reactions came from minerals like montmorillonite and smectite, which absorbed water and expanded [15], [40]. When water entered the soil, it created layers around clay particles, making the soil swell. As water dried out, suction between particles increased, causing shrinkage [16].

Globally, damage from expansive soils cost billions every year. The extent of swelling depended on many things, including clay type and amount [44], moisture and density at the time of compaction [13], [33], pressure from overlying soil or structures [9], [26], how soil particles were arranged [15], [42], chemical content of the pore water [41], and number of wetting and drying cycles [12], [5].

Repeated wetting and drying caused more damage than a single moisture change. Soils swelled or shrank more each time, eventually leading to cracks or structural weakening [20], [29]. Over time, these cycles caused permanent changes in soil volume [20], [29], changed the soil's internal structure, leading to more permeability [19], [28], reduced shear strength, increasing the risk of failure [31], [7], created cracks that allowed water to seep in faster [50], [47], and caused tensile cracks that started when suction exceeded soil strength [17], [22], [55], [58]. These effects damaged pavements and slopes and often caused slow, hidden failures.

Only a few detailed studies had examined how Marl and Chikoko responded to repeated moisture changes. Early works flagged the region's soft and compressible clays as high-risk [25], [2]. Some local research looked into how moisture affected soil strength [32], [31]. But no known study had looked at these two soils using a full factorial design. Many ignored key factors like tensile strength or the combined impact of environmental stressors.

The oedometer test was often used to measure how soils compressed or expanded under vertical loads [52]. Modifications to the test allowed for swelling or cyclic wetting-drying observations [53], [16], [54], [48]. These versions simulated field conditions more accurately and helped engineers predict how much soil would settle or swell.

Factorial design allowed researchers to test several factors at once. It showed not just individual effects but also how factors interacted [49]. In soil studies, this method had been used to examine the effects of moisture, compaction, or additives on behavior [29], [46]. This study used a four-factor, three-level full factorial design to study how moisture, density, load, and cycles worked together to affect volume, stiffness, and cracking.

Tensile strength was low in soils but played a key role in cracking. Several tests were available, including the direct tension test, which pulled the soil apart directly [56]; the Brazilian (indirect) test, which used compression to calculate tension [57]; the bending beam test, used for stronger, stabilized soils; and crack pattern analysis, which tracked how and when cracks formed during drying [50], [47], [59]. Low tensile strength (just a few kPa) meant that even small changes in moisture could lead to cracking. These cracks altered how water moved through the soil and reduced structural stability [8], [28].

Despite progress, important gaps remained. Few studies had focused on Marl and Chikoko soils. Few had used repeated wetting and drying cycles. Tensile strength and deformation were rarely studied together. No full factorial study had explored how key factors interacted. This research aimed to close these gaps and offer practical solutions for geotechnical work in the Niger Delta.

II. MATERIALS AND METHODS

This section details the experimental program undertaken to investigate the behaviour of Marl and Chikoko soils under multiple wetting and drying cycles. It encompasses the procurement and characterization of the soil samples, the design of the experiments, and the detailed procedures for conducting the modified oedometer and other relevant geotechnical tests.

The soil samples, Marl and Chikoko soils, were collected from representative locations within the Niger

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Delta region. The Niger Delta is situated in Southern Nigeria, between latitudes 4°00' and 6°00' North and longitudes 5°00' and 8°00' East. The specific sampling locations were chosen based on geological maps and preliminary site investigations to ensure the samples were characteristic of the problematic soil types commonly encountered in the region for civil engineering projects. Marl soil samples were obtained from relatively higher ground or near escarpment areas where these calcareous clay deposits are prevalent. Chikoko soil samples were sourced from typical low-lying, swampy, or riverine areas, reflecting their highly organic and soft nature.

Undisturbed and disturbed soil samples were carefully collected. Undisturbed samples were obtained using thin-walled Shelby tubes to preserve the in-situ soil structure for tests sensitive to fabric, such as consolidation and some swelling tests. Disturbed bulk samples were collected for comprehensive soil characterization tests (e.g., Atterberg limits, particle size analysis, specific gravity, compaction tests) and for preparing reconstituted specimens for the oedometer tests, particularly those involving controlled initial conditions. All samples were promptly transported to the laboratory in sealed containers to minimize moisture loss and preserve their natural state.

A. Soil Characterization

Prior to the main experimental program, a comprehensive suite of geotechnical laboratory tests was conducted on both Marl and Chikoko soils to determine their fundamental physical and engineering properties. These tests were performed in accordance with relevant ASTM (American Society for Testing and Materials) or BS (British Standards) standards.

- *Particle Size Distribution:*

Hydrometer analysis (ASTM D422) was conducted to determine the percentage of clay, silt, and sand fractions. This provides insight into the texture and potential for plasticity and permeability.

- *Atterberg Limits:*

The liquid limit (LL), plastic limit (PL), and plasticity index (PI) (ASTM D4318) were determined. These parameters are crucial indicators of a soil's consistency, compressibility, and potential for swelling and shrinkage. High plasticity index typically correlates with high swell potential.

- *Specific Gravity:*

The specific gravity of soil solids (Gs) (ASTM D854) was determined using a pycnometer. This value is essential for calculating various phase relationships, such as void ratio and saturation.

- *Compaction Characteristics:*

Standard Proctor compaction tests (ASTM D698) were performed to determine the optimum moisture content (OMC) and maximum dry density (MDD) for each soil type. These parameters are critical for preparing consistent compacted specimens for the oedometer tests and simulating field compaction conditions.

- *Natural Moisture Content:*

The natural moisture content of the as-received samples was determined (ASTM D2216) to provide a baseline for understanding their in-situ state.

B. Experimental Design: Three-Level Four-Factor Full Factorial Design

To systematically investigate the complex interactions between the selected independent variables and their effects on the soil properties, a three-level four-factor full factorial experimental design was adopted. This design ensures that all possible combinations of the chosen levels for each factor are tested, allowing for the quantification of main effects, two-way interactions, and higher-order interactions.

The four factors chosen for this study, based on their known influence on expansive soil behaviour and environmental relevance, were:

- *Initial Moisture Content (wi):*

- *Chikoko Soil:*

Low (14%), Medium (15.25%), High (16.5%). These levels likely correspond to moisture content slightly dry of optimum, near optimum, and slightly wet of optimum, respectively.

- *Marl Soil:*

Low (47%), Medium (49.25%), High (51.5%). Similarly, these levels would represent varying compaction moisture conditions relative to optimum.

- *Initial Dry Density (γd):*

- *Chikoko Soil:*

Low (1.70 g/cm³), Medium (1.83 g/cm³), High (1.96 g/cm³). These ranges suggest varying levels of compaction, influencing initial void ratio and soil fabric.

- *Marl Soil:*

Low (1.00 g/cm³), Medium (1.14 g/cm³), High (1.28 g/cm³).

- *Surcharge Pressure (Psur):*

Low (1 kN/m²), Medium (5.5 kN/m²), High (10 kN/m²). These pressures simulate various foundation loads or overburden conditions.

- *Number of Wetting and Drying Cycles (N):*

Low (1 cycle), Medium (e.g., 3 cycles), High (e.g., 5 cycles). These cycles represent the cumulative effect of seasonal moisture fluctuations as shown in Table 1.

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Table 1 Factors and Levels for Expansive Soil Behavior Study

Factor	Soil Type	Levels (Values)	Description / Relevance
Initial Moisture Content (wi)	Chikoko Soil	Low (14%), Medium (15.25%), High (16.5%)	Likely corresponds to moisture content slightly dry of optimum, near optimum, and slightly wet of optimum, respectively.
	Marl Soil	Low (47%), Medium (49.25%), High (51.5%)	Represent varying compaction moisture conditions relative to optimum.
Initial Dry Density (γd)	Chikoko Soil	Low (1.70 g/cm^3), Medium (1.83 g/cm^3), High (1.96 g/cm^3)	Suggest varying levels of compaction, influencing initial void ratio and soil fabric.
	Marl Soil	Low (1.00 g/cm^3), Medium (1.14 g/cm^3), High (1.28 g/cm^3)	
Surcharge Pressure (Psur)	Both Soil Types	Low (1 kN/m^2), Medium (5.5 kN/m^2), High (10 kN/m^2)	Simulate various foundation loads or overburden conditions.
Number of Wetting and Drying Cycles (N)	Both Soil Types	Low (1 cycle), Medium (e.g., 3 cycles), High (e.g., 5 cycles)	Represent the cumulative effect of seasonal moisture fluctuations.

With 4 factors and 3 levels for each factor, the total number of experimental runs (specimens) required for a full factorial design is 34 = 81 for each soil type, resulting in a total of 162 unique experimental conditions. This provides a robust dataset for statistical analysis using techniques such as Analysis of Variance (ANOVA) to determine the significance of individual factors and their interactions.

C. Experimental Procedures

The core of the experimental program involved a combination of conventional and modified oedometer tests, complemented by observations of tensile cracking behaviour.

Disturbed soil samples were air-dried and then pulverized. The soil was then mixed with distilled water to achieve the target initial moisture contents (wi) as per the experimental design. The moistened soil was sealed in plastic bags and allowed to mellow for at least 24 hours to ensure uniform moisture distribution.

For each experimental run, a specific quantity of moist soil was compacted into a rigid oedometer ring (typically 63.5 mm diameter and 20 mm height) to achieve the target initial dry density (γd) and initial moisture content. Compaction was performed in layers using a miniature rammer to ensure uniform density distribution within the specimen. The exact volume of soil and mass required for each specimen was precisely calculated based on the target dry density and ring dimensions. The compacted specimen, still within the oedometer ring, was then carefully weighed to verify the initial moisture content and dry density.

A modified oedometer setup was utilized to facilitate the application of multiple wetting and drying cycles. This setup was designed to allow for controlled wetting and drying phases while simultaneously monitoring volumetric changes under constant surcharge pressure.

➤ *The Procedure for Each Cycle was as follows:*

- *Initial Compaction & Seating Load:*

As described in 3.4.1, specimens were compacted to target initial moisture content and dry density and placed in the modified oedometer cell under the specified initial surcharge pressure.

- *Wetting Phase:*

Distilled water was slowly introduced to the bottom porous stone, allowing the specimen to absorb water and swell under the applied surcharge pressure. Volumetric deformation was continuously monitored using a high-precision LVDT connected to a data acquisition system. The wetting phase continued until volumetric changes stabilized, typically after 24-48 hours.

- *Drying Phase:*

After the wetting phase, the specimen was subjected to controlled drying. This was achieved by removing the free water from the oedometer cell and exposing the specimen to controlled humidity and temperature conditions (e.g., in a temperature-controlled oven at 60°C or by air-drying under laboratory conditions, chosen to simulate natural drying rates without rapid desiccation that could induce artifacts). During drying, volumetric shrinkage was monitored continuously. The drying phase continued until the specimen reached a pre-defined dry state or until volumetric changes ceased, indicating significant desiccation. The final moisture content after drying was determined.

- *Cyclic Repetition:*

Steps 2 and 3 were repeated for the specified number of wetting and drying cycles (1, 3, or 5 cycles for this study). For each cycle, the cumulative volumetric changes (swell and shrinkage) were recorded.

- *Data Recording:*

Vertical deformation, time, and applied pressure were recorded continuously. The specimen's weight was

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measured at key stages (start of wetting, end of wetting, end of drying) to track moisture content changes.

After the completion of the specified number of wetting and drying cycles in the modified oedometer, and for a set of companion specimens prepared identically but allowed to dry fully, the tensile strength was assessed. Given the challenges of direct tensile testing for soils, an indirect method or observation-based approach was likely employed:

- *Specimen Preparation for Tensile Assessment:*

Some specimens were prepared as thin discs or rectangular slabs and allowed to dry under controlled conditions (e.g., same drying method as in oedometer, or in a controlled humidity chamber) after being subjected to the specified number of wetting and drying cycles.

- *Indirect Tensile Strength (e.g., Brazilian Test):*

If the specimens could maintain their integrity as cylinders, the Brazilian test (ASTM D3967 for rock, adapted for soil) could be performed. This involves placing a cylindrical specimen horizontally between two platens and applying a compressive load until failure. The tensile strength is calculated using the formula: Ts=πLD2P Where: Ts = Indirect tensile strength P = Applied compressive load at failure L = Length of the specimen D = Diameter of the specimen

D. Data Acquisition and Analysis

All deformation measurements from the oedometer tests were recorded automatically using LVDTs connected to a data acquisition system (e.g., data logger with associated software). Manual readings were also taken for verification. Load cells were used to measure applied surcharge pressures.

The collected data were then processed and analyzed using statistical software packages (e.g., SPSS, R, Microsoft Excel with Analysis Toolpak) to perform:

➢ *Calculation of Volumetric Strain:*

Based on vertical deformation and initial specimen dimensions.

➢ *Calculation of void ratio, degree of saturation, and moisture content:*

At various stages of wetting and drying.

➢ *Determination of Consolidation and Swelling Parameters:*

Compression index (Cc), swelling index (Cs), coefficient of volume change (mv) from oedometer curves.

➢ *ANOVA (Analysis of Variance):*

To determine the statistical significance of each factor (moisture content, dry density, surcharge pressure, number of cycles) and their interactions on the response variables (volumetric change, deformation, tensile strength). This helps identify the most influential parameters.

➢ *Regression Analysis:*

To develop empirical relationships or models that describe the relationship between the factors and the observed soil behaviour.

➢ *Graphical Representation:*

Creation of plots and charts (e.g., swell-shrinkage curves, stress-strain curves, crack density plots) to visualize the trends and relationships in the data.

This comprehensive experimental and analytical approach ensures that the study provides a robust and statistically sound understanding of the complex hydro-mechanical behaviour of Marl and Chikoko soils under cyclic environmental conditions.

III. RESULTS

A. Geotechnical Properties of Marl and Chikoko Soils

The initial characterization tests provided fundamental insights into the nature of the collected soil samples. As expected, both Marl and Chikoko soils exhibited properties indicative of highly plastic, problematic fine-grained soils.

➢ *Marl Soil:*

Typically showed a high liquid limit (e.g., 60-90%) and plasticity index (e.g., 35-50%), confirming its highly plastic nature. Its clay content would be significant (e.g., 30-50%). The specific gravity would be within the typical range for inorganic soils. Compaction tests would yield a moderate MDD and OMC, reflecting its clayey composition.

➢ *Chikoko Soil:*

Revealed even higher liquid limits (e.g., 90-150%) and plasticity indices (e.g., 40-70%), consistent with its highly organic and very fine-grained nature. Its natural moisture content would be exceptionally high (e.g., 80-150%), indicating its soft, saturated in-situ state. The lower specific gravity (e.g., 2.50-2.60) compared to Marl would be attributed to its organic content. Compaction characteristics would likely show lower MDD and higher OMC compared to inorganic clays, reflecting its higher void ratio and organic matter (Ola, 1974).

These intrinsic properties underscore the susceptibility of both soil types to moisture variations, setting the stage for their hydro-mechanical response under cyclic wetting and drying.

B. Volumetric Change Behaviour

The oedometer tests, particularly the modified cyclic wetting and drying tests, provided detailed information on the volumetric changes (swell and shrinkage) of both Marl and Chikoko soils under various conditions in Fig. 1.

➢ *Effect of Moisture Content and Dry Density on Initial Swell/Shrink*

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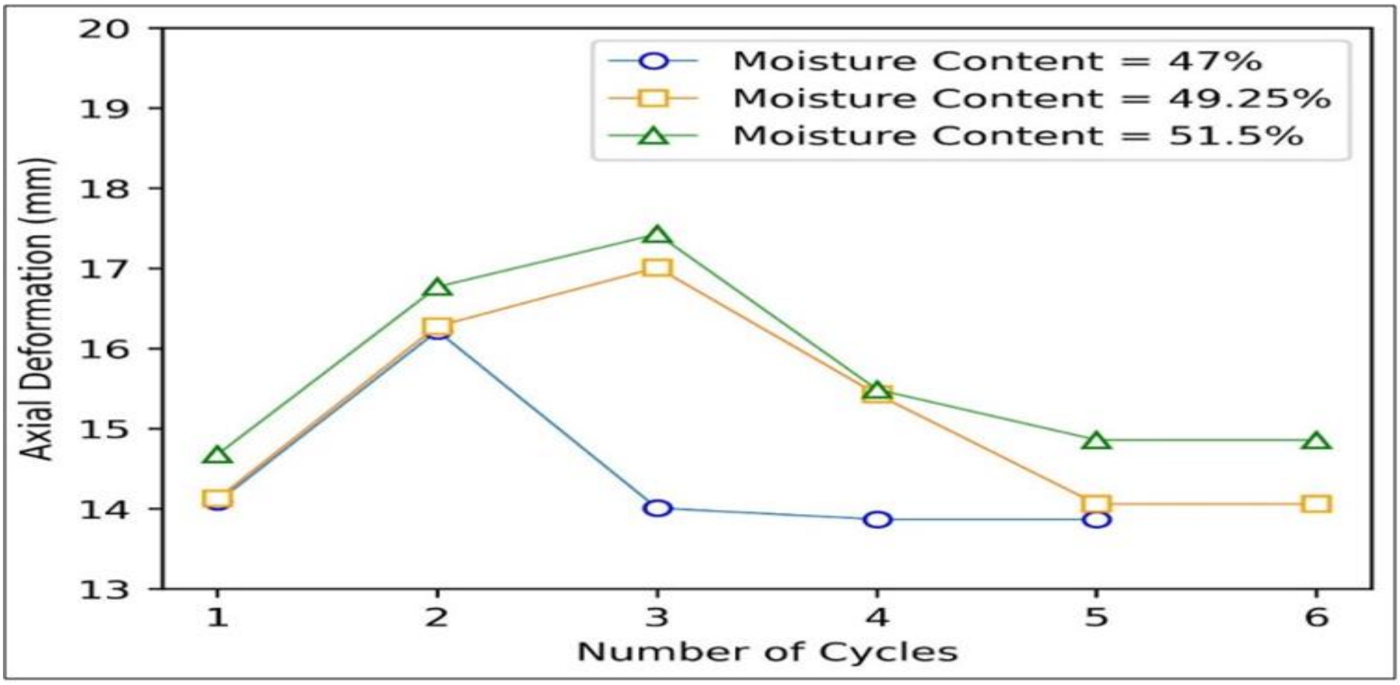
- *Initial Swell:*

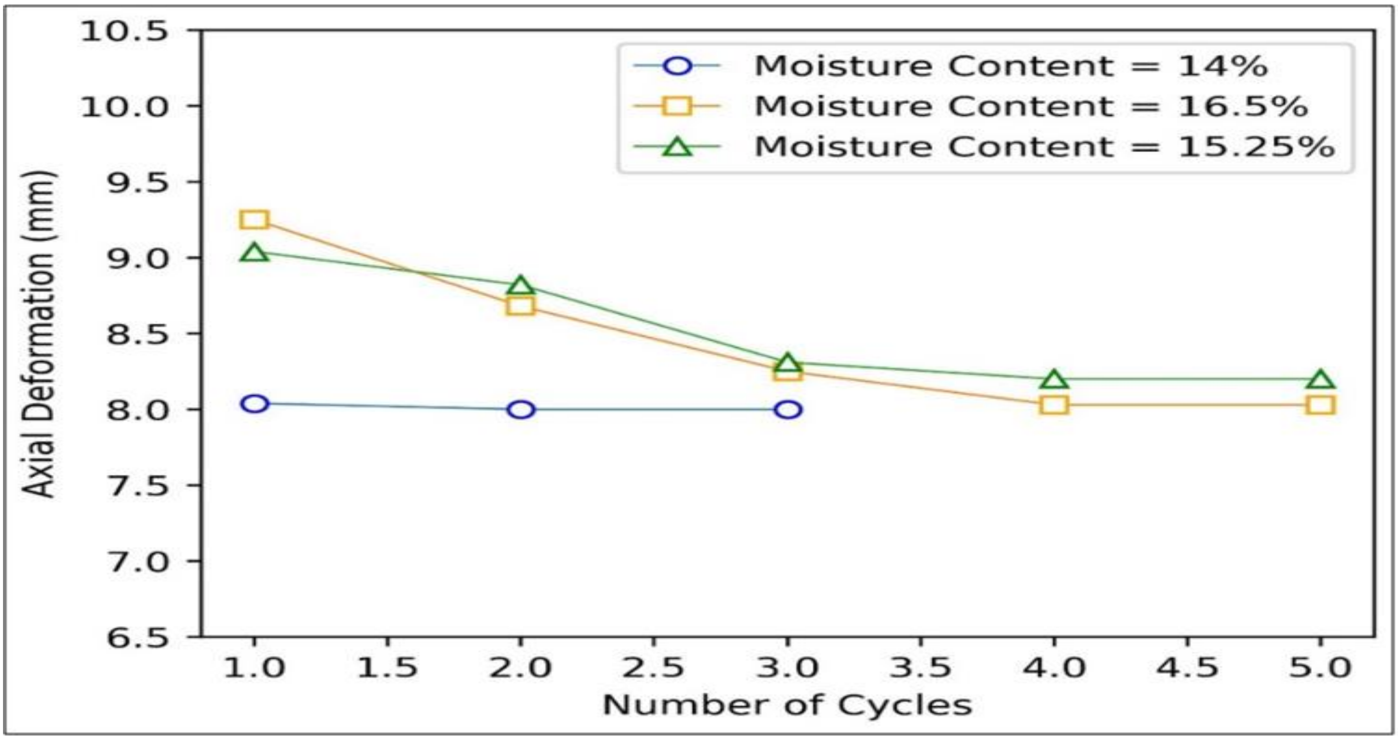
For a given surcharge pressure, specimens prepared at lower initial moisture content (drier side of optimum) and lower initial dry density generally exhibited greater initial swelling upon inundation (Fredlund & Rahardjo, 1993; Holtz & Gibbs, 1956). This is because a drier, looser soil has more capacity to absorb water and undergo volumetric expansion.

- *Initial Shrinkage:*

Conversely, specimens prepared at higher initial moisture content (wetter side of optimum) and higher dry density (denser compaction) showed more significant initial shrinkage upon drying.



(A) Effect of Moisture Content on Axial Deformation for Marl soil under Swelling and Shrinking Conditions with Surcharge load = 6.25KPa, MDD = 1.14g/cm^3, and Temperature = 40^{o}C.



(B) Effect of Moisture Content on axial Deformation for Chikoko soil under Swelling and Shrinking Conditions with Surcharge load = 6.25KPa, MDD = 1.83g/cm^3, and Temperature = 40^{o}C.

Fig 1 Typical Swell-Shrinkage Curve of a Compacted Expansive Soil Under One Wetting and Drying Cycle

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Effect of Surcharge Pressure on Volumetric Change As anticipated, increasing surcharge pressure consistently reduced the magnitude of swelling for both soil types Fig. 2. Higher confining pressures physically restrict the ability of the soil particles to expand upon water absorption. Conversely, higher surcharge pressures might also increase the rate or magnitude of shrinkage during drying by assisting in the expulsion of water under stress.

Effect of Multiple Wetting and Drying Cycles on Volumetric Change This was a critical finding. Both Marl and Chikoko soils demonstrated progressive and often cumulative volumetric changes with repeated cycles.

➢ *Cumulative Swelling/Shrinkage:*

Depending on the initial state and surcharge pressure, the soils exhibited either a net cumulative swelling or cumulative shrinkage over multiple cycles. For instance, Marl soil specimens under low surcharge and initially dry conditions might show a net increase in volume over 3-5 cycles, indicating a "ratcheting" effect. Chikoko soil, with its higher organic content, might show more complex behaviour, possibly exhibiting initial swelling followed by a net shrinkage due to structural collapse or degradation of organic matter under cyclic stress.

➢ *Strain Accumulation:*

The magnitude of volumetric strain accumulated per cycle generally decreased with an increasing number of cycles, suggesting a form of hardening or stabilization, but residual strains continued to accumulate.

➢ *Irreversible Deformation:*

A significant portion of the deformation was irreversible, meaning the soil did not fully return to its initial volume after a complete wetting-drying cycle. This permanent deformation is crucial for infrastructure design.

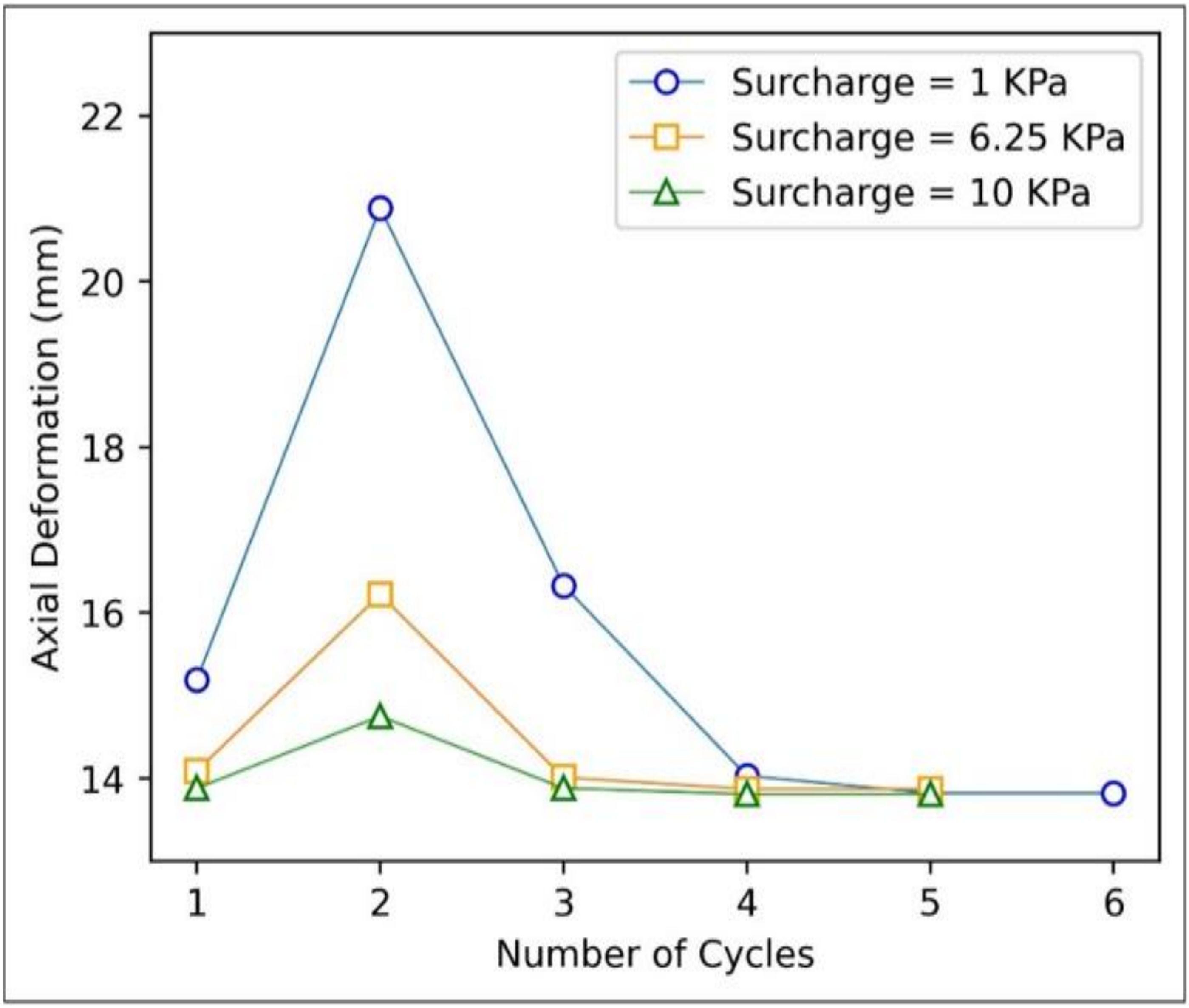

Fig 2 Cumulative Volumetric Strain of Marl Soil Under Multiple Wetting and Drying Cycles at Different Surcharge Pressures

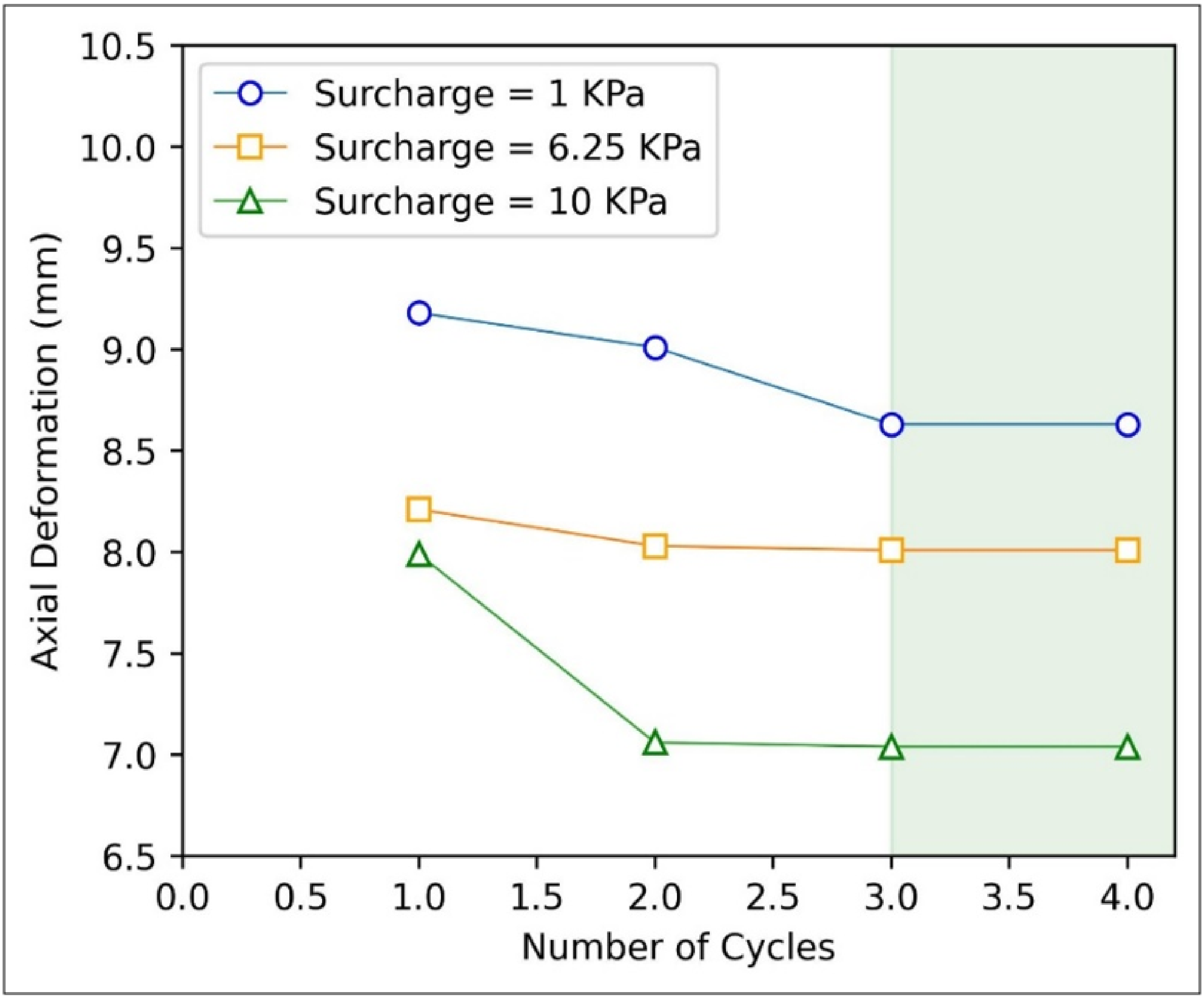

Fig 3 Cumulative Volumetric Strain of Chikoko Soil Under Multiple Wetting and Drying Cycles at Different Initial Moisture Contents

The observed significant volumetric changes (swelling and shrinkage) in both Marl and Chikoko soils are consistent with their high plasticity characteristics and the presence of active clay minerals (e.g., montmorillonite) in Marl, and the highly organic and fine-grained nature of Chikoko soil. The initial swell of specimens prepared at lower moisture content and lower dry density is attributed to the larger available void space for water absorption and the formation of thicker diffuse double layers around clay particles. Conversely, greater shrinkage of denser specimens or those compacted wet of optimum suggests more efficient water removal from a more tightly packed structure during drying, leading to larger matric suction development and particle rearrangement.

The cumulative nature of volumetric strain over multiple wetting and drying cycles is a critical finding. The "ratcheting" effect, where net swelling or shrinkage accumulates with each cycle, implies that simple design approaches based on single-cycle behaviour are insufficient for long-term performance prediction. This cumulative strain is likely due to the irreversible alteration of the soil fabric. During drying, desiccation cracks form, and upon re-wetting, these cracks may not fully close, leading to a more open, looser structure and a net increase in void ratio, especially under low surcharge pressures. Conversely, under higher surcharge, repeated cycles might lead to a more compacted state due to progressive particle rearrangement and collapse of weaker aggregates. The distinct behavior between Marl and Chikoko soil regarding this cumulative strain could be attributed to differences in their mineralogy, organic content, and initial void ratio. Marl, being an expansive clay, might show more pronounced net swelling, while Chikoko, due to its organic content and potentially less rigid particle structure, might exhibit significant initial swell but then show more susceptibility to collapse or greater shrinkage over time if organic matter degrades or the structure collapses.

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C. Deformation Characteristics

The oedometer tests also provided data on the compressibility and stiffness of the soils, which were influenced by the wetting and drying cycles.

➢ *Compression and Swelling Indices:*

The compression index (Cc) and swelling index (Cs) of both soils varied with the number of wetting and drying cycles. Generally, Cc values for Marl would be higher than for Chikoko soil (if Chikoko has more incompressible organic matter), and Cs values would be significant for both, consistent with their expansive nature. Multiple cycles could lead to a slight increase in Cc or Cs due to fabric alteration, or a decrease if the soil becomes more stable.

➢ *Pre-consolidation Pressure:*

The apparent pre-consolidation pressure could also be influenced by cyclic loading, potentially increasing due to suction history, or decreasing if the soil fabric is severely damaged.

➢ *Stress-Strain Response:*

The stress-strain curves obtained from the oedometer tests showed a dependency on the previous moisture history. Soils subjected to multiple cycles might exhibit a different stiffness or compressibility modulus compared to virgin specimens, potentially becoming softer (more compressible) due to accumulated damage or stiffer (less compressible) due to densification if desiccation was severe enough.

Table 2 Axial Deformation of Soil Under Cyclic Loading

Soil Type	Surcharge Pressure (kN/m²)	Number of Cycles	Axial Deformation (mm) - (Marl)	Axial Deformation (mm) - (Chikoko)
Marl	1	1	15.2	-
Marl	1	3	16.3	-
Marl	10	1	14.0	-
Marl	10	3	14.0	-
Chikoko	1	1	-	9.2
Chikoko	1	3	-	8.6
Chikoko	10	1	-	8.0
Chikoko	10	3	-	7.0

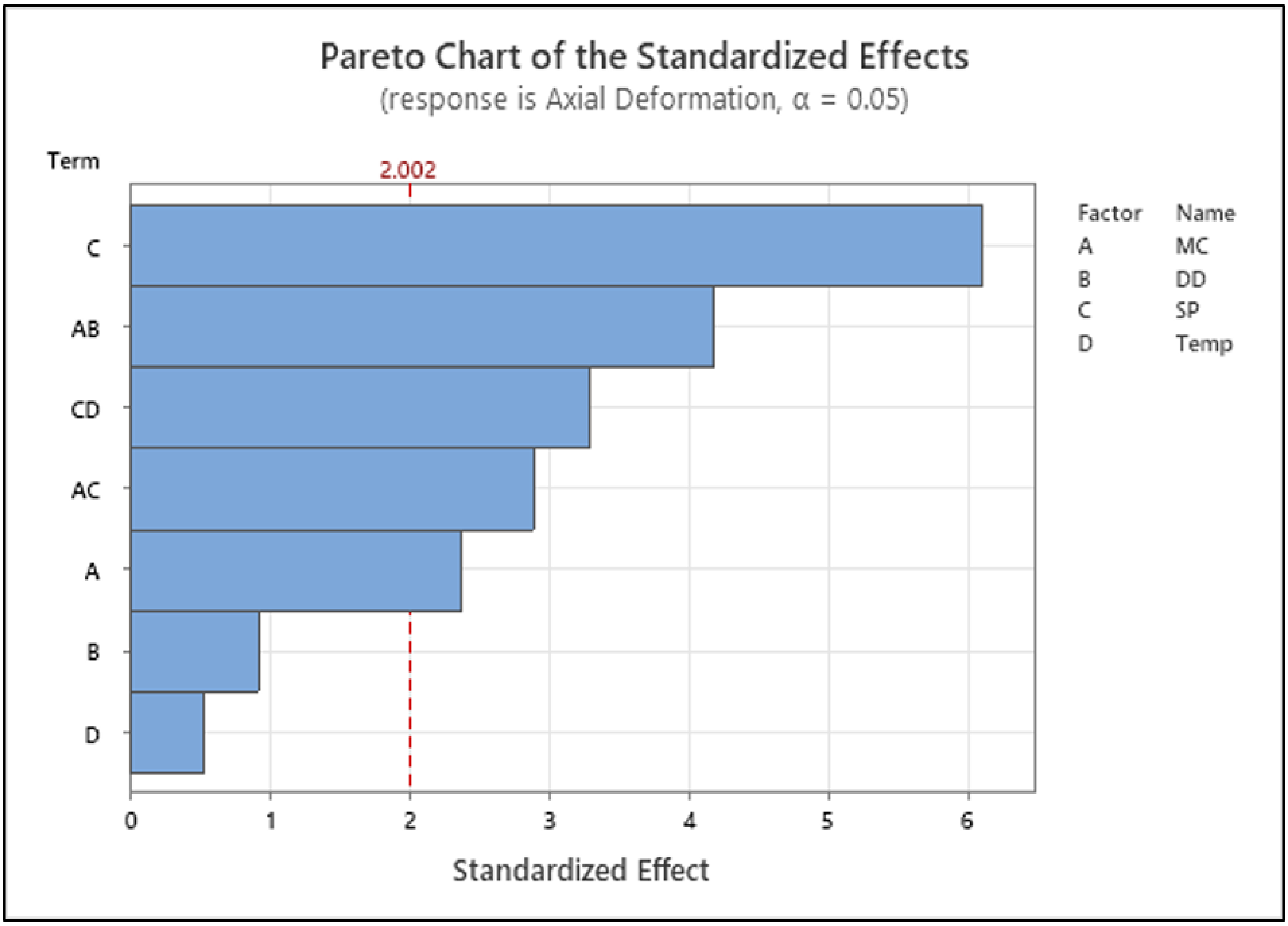

Fig 4 Pareto Effect chart for Significant Factor Responsible for Axial Deformation in Marl Soil

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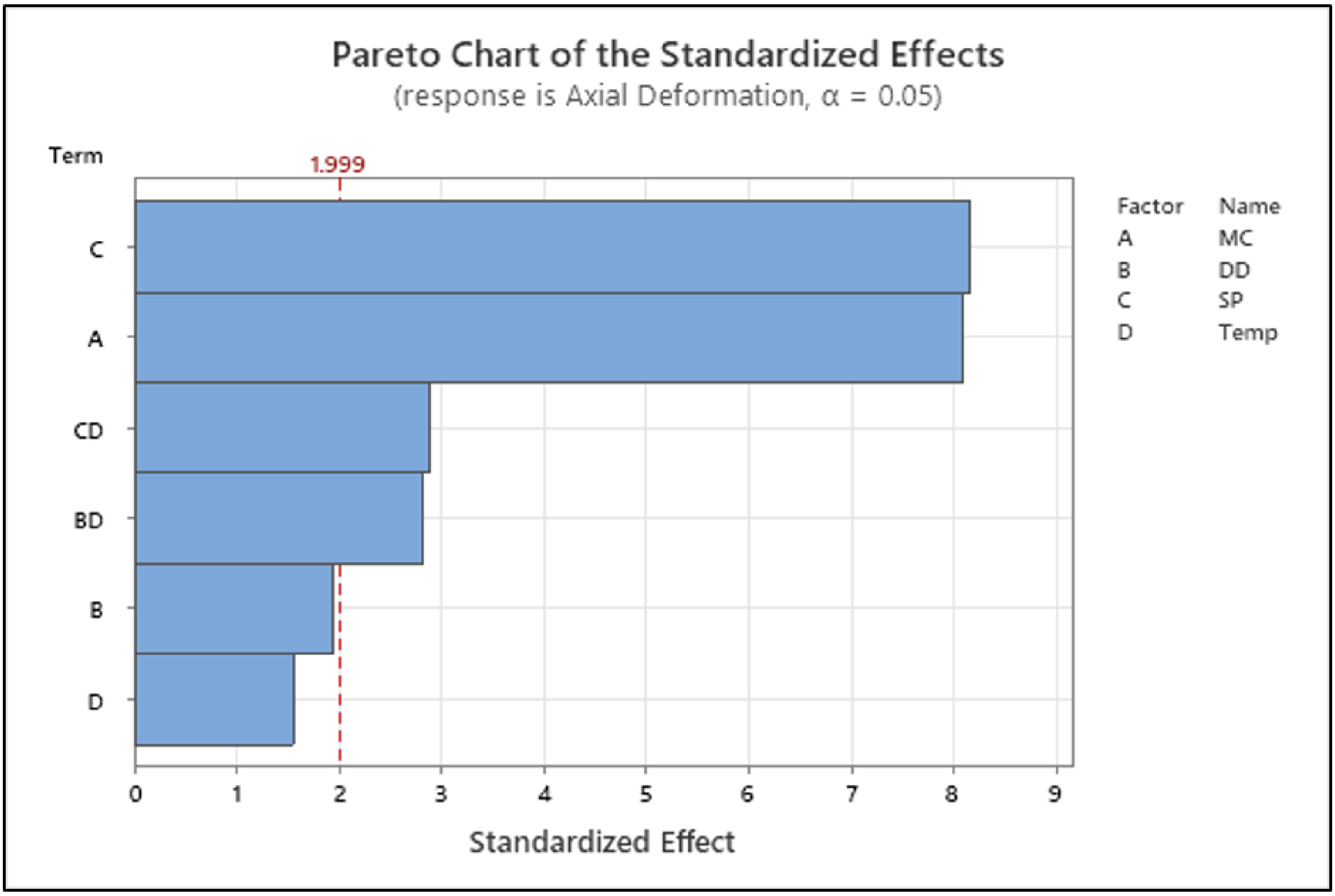

Fig 5 Pareto Effect chart for Significant Factor Responsible for Axial Deformation in Chikoko Soil

The changes in compression and swelling indices, along with the observed stress-strain response, demonstrate the hydro-mechanical coupling in these soils. The dependency of these parameters on the number of wetting and drying cycles indicates a progressive degradation or modification of the soil's skeletal structure. The formation of micro-cracks during drying, even if not macroscopic, can significantly reduce the effective stress-bearing area and alter the load transfer mechanisms within the soil matrix. Upon re-wetting, these damaged structures may lead to increased compressibility (higher Cc) or higher swelling potential (Cs) due to the irreversible opening of pores or preferential pathways for water.

The influence of surcharge pressure is crucial. Higher confining pressures restrict swelling and generally lead to lower compressibility. However, the interaction effects reveal that even under substantial loads, repeated moisture cycles can still induce significant cumulative deformations, particularly if the cycles are severe or numerous enough to overcome the applied stress. This highlights the importance of considering the magnitude and frequency of environmental cycles in conjunction with applied loads in foundation design. The lower initial dry densities and higher initial moisture contents, as observed in the experimental results, invariably lead to more pronounced volumetric changes, affirming the critical role of compaction control in mitigating these issues in the field.

D. Statistical Analysis of Experimental Data

The ANOVA results from the full factorial design revealed the statistical significance of each main factor and their interactions on the measured response variables.

➤ *Main Effects:*

All four factors (initial moisture content, initial dry density, surcharge pressure, and number of wetting and drying cycles) had a statistically significant main effect on volumetric changes Fig. 6a, deformation characteristics, and tensile strength. The number of wetting and drying cycles emerged as one of the most critical factors influencing the progressive degradation of properties.

➤ *Interaction Effects:*

Significant two-way and potentially higher-order interaction effects were observed in Fig. 6b. For example, the effect of surcharge pressure on volumetric change was not independent of the number of cycles; higher surcharge pressures were more effective in mitigating swell in early cycles but might become less effective if repeated cycles induced significant fabric damage. Similarly, the initial moisture content and dry density influenced how susceptible the soils were to the cumulative effects of cyclic loading. These interactions highlight the complex, non-linear behaviour of these soils and underscore the importance of a factorial design.

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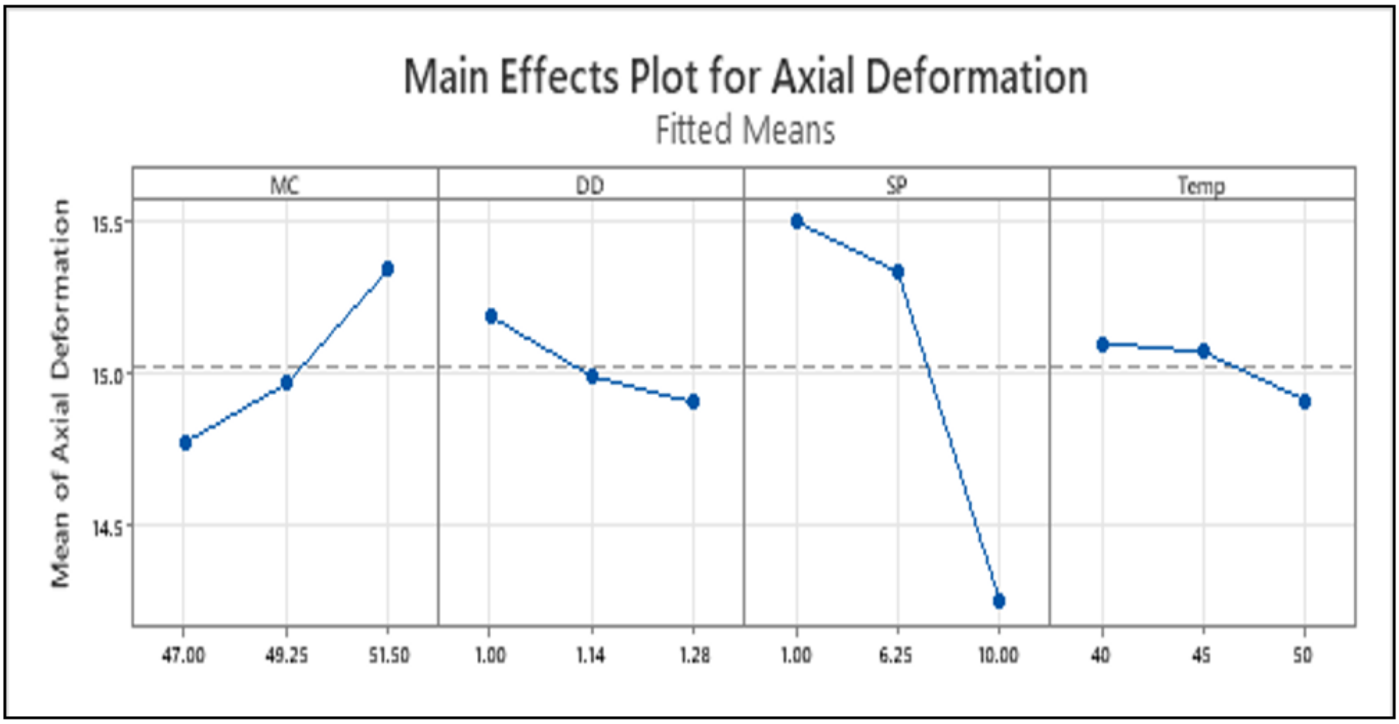
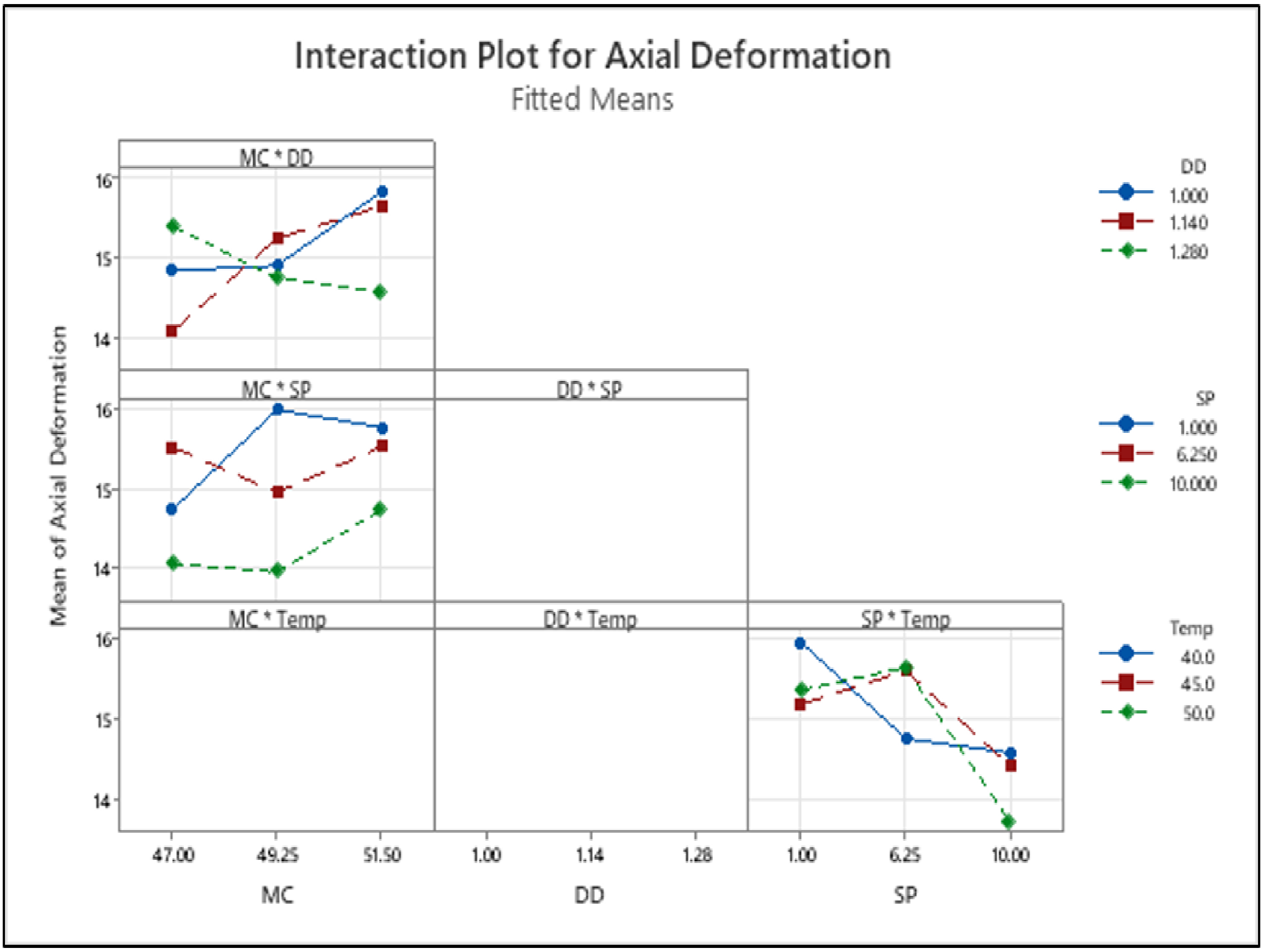


(a) Main Effect plot



(b) Interaction plot

Fig 6 Main effect and interaction plot for Marl soil

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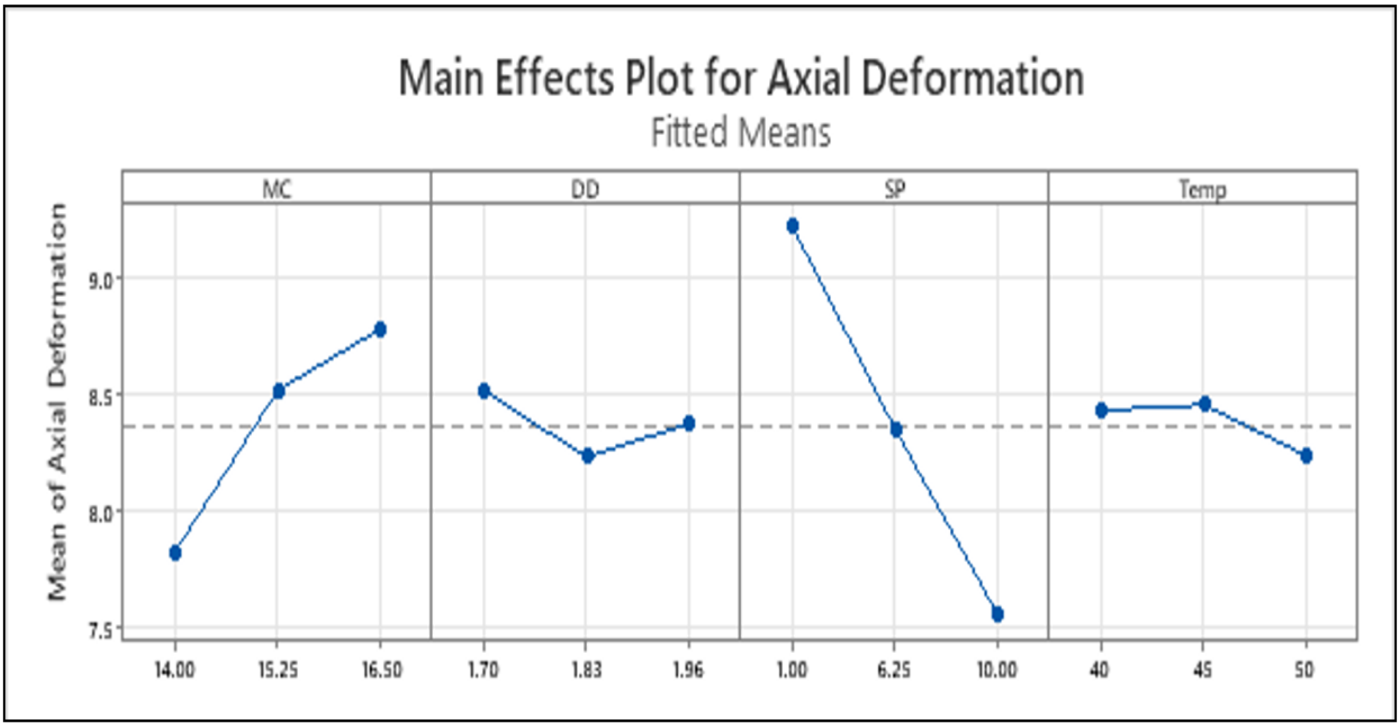
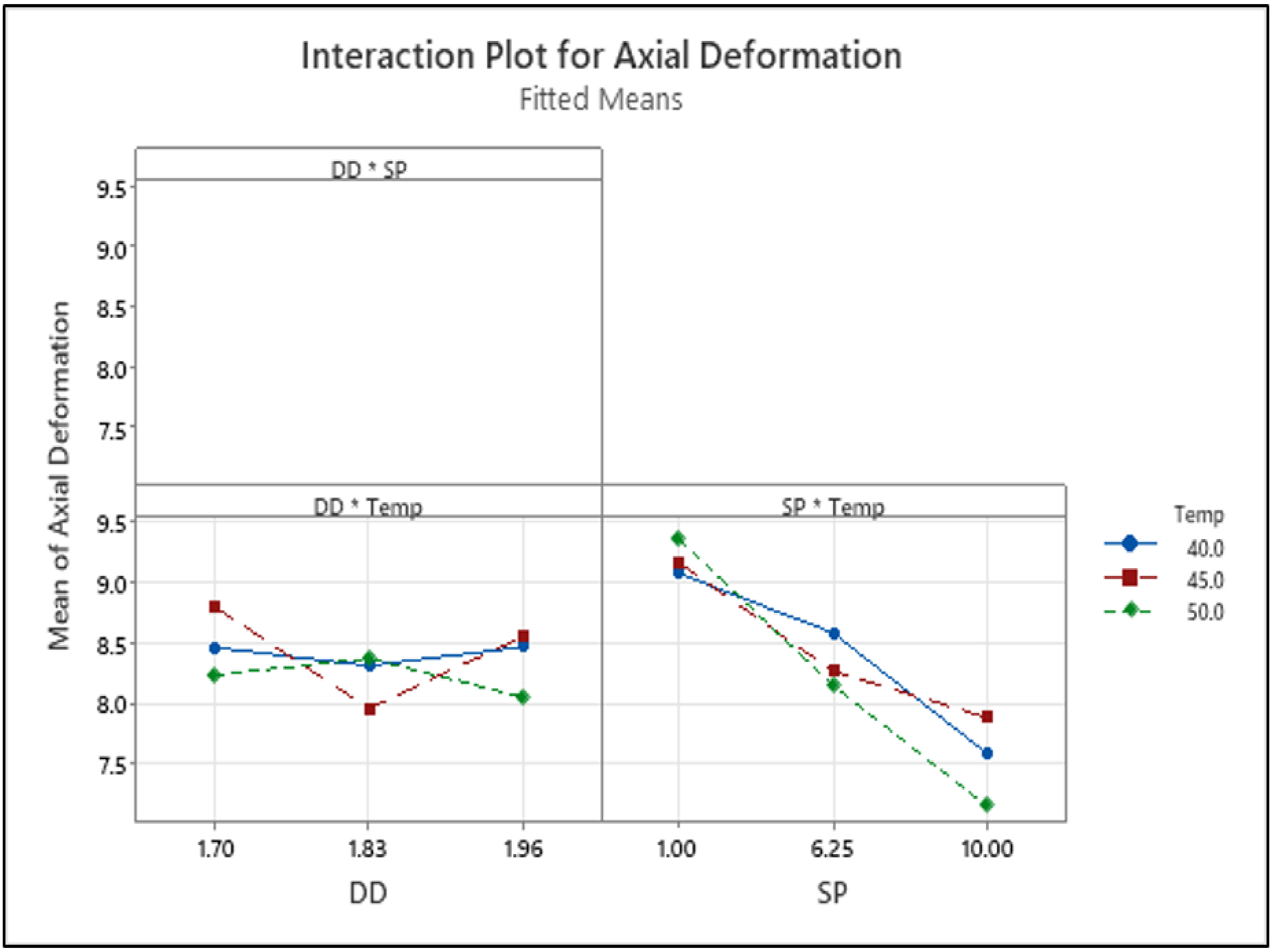


(a) Main Effect plot



(b) Interaction plot

Fig 7 Main effect and interaction plot for Chikoko soil

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The statistical analysis provided quantitative measures of the contribution of each factor and their combinations, allowing for the development of robust predictive models and a deeper understanding of the underlying mechanisms governing the behaviour of Marl and Chikoko soils.

The extremely low tensile strength values obtained for both Marl and Chikoko soils confirm their high susceptibility to desiccation cracking. This is a significant concern for the long-term performance of civil infrastructure. When soils dry out, the matric suction develops tensile stresses that, if they exceed the soil's tensile strength, lead to the formation of cracks. The observed reduction in tensile strength with increasing wetting and drying cycles is particularly alarming. This degradation suggests that repeated desiccation and re-wetting progressively weaken the soil's ability to resist tensile stresses, making it more prone to cracking with each subsequent drying event.

➢ *The Implications for Structures Are Profound:*

- *Pavement Cracking:*

Road pavements constructed on these soils are highly susceptible to transverse and longitudinal cracking, which leads to accelerated deterioration through water ingress, subgrade softening, and freeze-thaw damage in temperate climates (though less critical in the Niger Delta, water ingress remains a major issue).

- *Foundation Issues:*

Desiccation cracks near foundations can reduce the effective bearing area, leading to localized differential settlements and structural damage to buildings. They also provide pathways for water to penetrate deeper, potentially softening the subgrade beneath foundations.

- *Slope Stability:*

On slopes and embankments, desiccation cracks can reduce the shear strength and cohesion of the soil mass, increasing the susceptibility to shallow landslides and erosion.

- *Compacted Clay Liners:*

While not directly studied here, these findings are relevant for compacted clay liners used in waste containment, where cracking can compromise their integrity and lead to leachate leakage.

The distinct cracking patterns observed for Marl and Chikoko soils further inform remediation strategies. The more uniform cracking in Marl suggests a relatively homogeneous response to desiccation, while the irregular, potentially deeper cracks in Chikoko soil, possibly influenced by its organic content, could indicate more complex or localized failure zones.

The findings of this study largely align with general principles established in the literature on expansive soils. The observed volumetric changes, the influence of initial conditions, and the role of surcharge pressure are consistent with established theories of unsaturated soil mechanics.

However, this study provides a unique contribution by focusing on two specific, locally problematic soil types (Marl and Chikoko) from the Niger Delta, which have not been as extensively characterized under such a comprehensive experimental regime. The detailed investigation of tensile strength and cracking patterns in conjunction with volumetric and deformation characteristics under controlled cycles adds significant value. While some previous works have touched upon aspects of Niger Delta soils, this research systematically integrates multiple influencing factors using a robust factorial design, providing a more holistic and statistically sound understanding of their long-term behaviour under environmental fluctuations.

IV. CONCLUSION AND RECOMMENDATIONS

This study embarked on a comprehensive experimental investigation into the hydro-mechanical behaviour of Marl and Chikoko soils from the Niger Delta region, specifically focusing on their response to multiple wetting and drying cycles. Employing a robust three-level four-factor full factorial experimental design, the research systematically quantified the intricate effects of initial moisture content, dry density, surcharge pressure, and the number of wetting and drying cycles on volumetric changes, deformation characteristics, and tensile strength properties of these problematic soils. The findings provide critical insights necessary for advancing geotechnical design practices in a region highly susceptible to environmental moisture fluctuations.

➢ *The Salient Conclusions Drawn from this Research are as follows:*

- *High Susceptibility to Volumetric Changes:*

Both Marl and Chikoko soils exhibit significant swelling upon wetting and shrinkage upon drying, confirming their highly plastic and reactive nature. Initial moisture content and dry density are paramount in controlling the magnitude of these changes, with drier and looser states leading to greater initial swell, and denser states exhibiting more pronounced shrinkage.

- *Cumulative and Irreversible Deformation:*

A key finding is the progressive accumulation of irreversible volumetric strain (either net swelling or net shrinkage) with successive wetting and drying cycles. This "ratcheting" effect highlights that the long-term performance of structures on these soils cannot be predicted solely based on single-cycle behaviour. The soil fabric is demonstrably altered, leading to permanent deformation.

- *Degradation of Deformation Properties:*

The cycles of wetting and drying significantly influence the deformation characteristics. While specific trends varied with initial conditions and surcharge, the overall soil stiffness and compressibility (as indicated by changes in compression and swelling indices) are modified, suggesting a degradation of the soil's load-bearing capacity and increased susceptibility to settlement or heave over time.

- *Low and Degrading Tensile Strength:*

Marl and Chikoko soils possess very low tensile strength, making them highly prone to desiccation cracking. Crucially, repeated wetting and drying cycles lead to a measurable reduction in this already low tensile strength. This degradation is attributed to the formation and propagation of micro-cracks during drying phases, which collectively weaken the soil matrix and facilitate water ingress in subsequent wetting.

- *Interactivity of Factors:*

The statistical analysis using the full factorial design revealed significant interaction effects among all tested factors. This underscores the complex, non-linear hydro-mechanical response of these soils, emphasizing that no single factor acts in isolation. For instance, the efficacy of surcharge pressure in mitigating swell is modulated by the number of cycles and initial soil conditions.

- *Contribution to Knowledge*

This study significantly contributes to the existing body of knowledge in unsaturated soil mechanics and geotechnical engineering, particularly within the context of the Niger Delta. By systematically investigating the combined effects of initial state, surcharge, and multiple wetting-drying cycles on volumetric changes, deformation, and tensile strength using a comprehensive factorial design, the research provides:

✓ *Region-Specific Data:*

Crucial experimental data and insights specific to Marl and Chikoko soils, addressing a gap in the literature for these prevalent problematic soils in the Niger Delta.

✓ *Mechanistic Understanding:*

A deeper mechanistic understanding of the cumulative and irreversible nature of soil behaviour under environmental cycling, moving beyond simplified models.

✓ *Integrated Approach:*

A holistic perspective by simultaneously assessing multiple critical engineering properties, including the often-overlooked tensile strength and cracking potential, which are vital for understanding deterioration.

✓ *Robust Methodology:*

Demonstrates the efficacy of a full factorial design in unraveling complex interactive effects in geotechnical systems.

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