Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Resource-Efficient Laterite-Bentonite Barriers for Urban Waste Containment: Hydro-Chemo-Microstructural Controls on Suction Evolution

Haroon Ahmed
Chengdu University of Technology
Wei Meng
Chengdu University of Technology
Adnan Altaf
Chengdu University of Technology
Muhammad Awais Hussain
awaishussain@zju.edu.cn

Chengdu University of Technology
Muhammad Akbar
Northern Border University
Ayed Eid Alluqmani
Islamic University of Madinah
Masamba Pinto
Kabale University

Article

Keywords: Laterite-bentonite barriers, Sustainable containment infrastructure, Hydro-chemo-microstructural coupling, Water retention, Ionic valence, Urban environmental infrastructure

Posted Date: November 23rd, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11620505/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: Competing interest reported. The authors also extend their appreciation to the Deanship of Scientific Research at Northern Border University, Arar, KSA, for funding this research work through the project number NBU-FFR-2026-3879-11.

Resource-Efficient Laterite-Bentonite Barriers for Urban Waste Containment: Hydro-Chemo-Microstructural Controls on Suction Evolution

Haroon Ahmed[1, 2], Wei Meng[1, 2], Adnan Altaf[1, 2], Muhammad Awais Hussain[1,2,3]*, Muhammad Akbar[4], Ayed Eid Alluqmani[5], Masamba Pinto[6]*

[1] College of Environment and Civil Engineering, Chengdu University of Technology, Chengdu, 610059, Sichuan, P.R. China. haroongeologist@gmail.com; 2008010041@alu.cdut.edu.cn; engr.adnanaltaf@gmail.com

[2] State Key Laboratory of Geohazards Prevention and Geoenvironmental Protection (SKLGP), Chengdu University of Technology, Chengdu, 610059, Sichuan, P.R. China.

[3] College of Civil Engineering and Architecture, Zhejiang University, Hangzhou 310058, Zhejiang, China; awaishussain@zju.edu.cn

[4] Department of Civil Engineering, College of Engineering, Northern Border University, 73222 Arar, Saudi Arabia; Akbarmohamamd0092@gmail.com

[5] Department of Civil Engineering, Faculty of Engineering, Islamic University of Madinah, Al-Madinah Al Munawarah, Medina 42351, Kingdom of Saudi Arabia, KSA, aayed@iu.edu.sa

[6] Department of Civil Engineering, Faculty of Engineering, Technology, Art and Design, Kabale University, Kabale, Uganda. pmasamba@kab.ac.ug

Corresponding authors email: awaishussain@zju.edu.cn (M.A.H); pmasamba@kab.ac.ug (M.P)

Abstract:

Sustainable urban development requires durable environmental containment infrastructure, such as systems in contaminated sites, barriers, and landfill liners, that are subjected to chemically variable pore fluids. Laterite–bentonite mixtures represent a potential resource-efficient barrier material, as small additions of bentonite can improve the water-retention properties of lateritic matrices. Yet, the interplay between bentonite content, dry density, and pore-fluid chemistry in controlling suction and microstructure remains poorly understood. The study focuses on compacted laterite-bentonite mixtures containing 3-7% bentonite, tested at dry densities of 1.5 and 1.6 g/cm³ in deionised water, NaCl, and $CaCl_2$. The filter paper method and WP4C were used to assess matric and total suction, respectively, while mercury intrusion porosimetry and scanning electron microscopy characterised pore-size distribution and microstructural evolution, respectively. The findings show a nonlinear suction response, with an approximate threshold of 5% bentonite coinciding with a change in the primary pore-structural response. Fluid pore chemistry affects water-retention characteristics, while pore constriction caused by increased dry density typically increases suction. Na^+ and Ca^{2+} produce different microstructural responses, with Ca^{2+} favouring flocculation and aggregation, increasing macroporosity, and decreasing microporosity. The use of suction, MIP and SEM observations constitutes a hydro-chemo-microstructural relationship between ionic interactions and the evolution of suction and pore-size redistribution. The results offer a mechanistic understanding to optimise laterite-bentonite formulations for durable, resource-efficient environmental containment infrastructure.

Keywords: Laterite-bentonite barriers; Sustainable containment infrastructure; Hydro-chemo-microstructural coupling; Water retention; Ionic valence; Urban environmental infrastructure

1 Introduction:

Landfill liners and contaminated-site barriers and systems require hydraulic integrity under varying environmental conditions, a critical requirement for sustainable urban development. Laterite–bentonite mixtures can be effective barrier materials because bentonite improves water retention and refines pores, but only small amounts of bentonite need to be added to lateritic soil. However, bentonite content, compaction, and pore-fluid chemistry influence hydraulic properties, as these factors can alter interactions between clay particles and the pore structure.[1,2]. Recent investigations confirm that ionic valence and salinity significantly influence microstructure and water retention[3].

In unsaturated soils, suction is the fundamental parameter governing water retention and strongly influencing engineering behavior, permeability, shear strength, and deformation characteristics[4] [5, 6]. Total suction consists of matric suction, controlled by capillary forces and pore structure, and osmotic suction, related to dissolved salts in the pore fluid [7-11]. Hydro-chemical alteration and microstructural changes affect both components. Consequently, the coupled influence of matric and osmotic suction is critical for predicting the hydro-mechanical behavior of clay-based barriers under chemically aggressive conditions[12-14].

The hydro-mechanical behavior of bentonite and sand-bentonite systems has been widely studied, with bentonite content, dry density, and water content identified as key controlling factors[15, 16]. Higher bentonite content increases water retention due to the swelling behavior of bentonite, while higher dry density reduces pore size and increases suction[8, 17, 18]. However, these relationships are often nonlinear and sensitive to environmental conditions. Through alteration of physicochemical forces, dissolved salts significantly affect clay interactions, leading to changes in pore structure, suction, and hydraulic performance[19, 20].

Pore fluid chemistry plays a crucial role in soil performance, with variations in salinity and ion concentrations as important components of the physicochemical processes that determine soil behavior [23-26]. Monovalent ions enhance water retention through dispersion, whereas divalent ions cause flocculation, double-layer contraction, and aggregation, resulting in a coarser pore structure. Such microstructural effects affect matric and osmotic suction and, subsequently, the soil's hydraulic and mechanical properties [27, 28]. Understanding these chemical effects is crucial in engineering durable barrier systems for aggressive environments.

Despite extensive research on bentonite-based materials, the hydro-chemical behavior of laterite-bentonite mixtures remains insufficiently understood, particularly under varying chemical conditions, a crucial factor for designing effective barrier systems in chemically aggressive environments. Laterite soils are cost-effective and widely available but differ from conventional clays in mineralogy and microstructure. When combined with bentonite, complex interactions arise from competing mechanisms, including clay swelling, cation-induced aggregation, and pore restructuring, that influence hydraulic behavior. These coupled processes significantly influence water retention and hydraulic performance. Understanding these coupled effects is essential to designing efficient, sustainable barrier systems.

Extensive studies of the coupled hydro-chemical-mechanical controls on suction and microstructure in laterite-bentonite systems remain poorly understood. In particular, the threshold behavior of bentonite content and the

contrasting influence of monovalent and divalent ions on water retention and pore structure have not been systematically quantified. Addressing these gaps is vital for developing innovative barrier designs and improving long-term stability under chemically aggressive conditions.

To address these gaps, this study examines the coupled hydro-chemical and microstructural behaviour of compacted laterite-bentonite mixtures under controlled pore-fluid conditions. The objectives are to

i. Determine the combined effects of bentonite content (3-7%) and dry density (1.5-1.6 g/cm³) on matric and total suction.
ii. Evaluate the impact of NaCl and $CaCl_2$ on water retention.
iii. Analyse microstructural evolution using scanning electron microscopy (SEM) and mercury intrusion porosimetry (MIP); and
iv. Relate ionic interactions to pore structure and suction behavior.

Results of suction measurements, along with MIP and SEM observations, are integrated to establish a hydro-chemo-microstructural framework that clarifies how bentonite content, compaction, and pore-fluid chemistry interact to influence the hydraulic behavior of laterite-bentonite mixtures. This mechanistic understanding could help optimise bentonite dosage and dry density and inform the design of long-term, resource-efficient materials for environmental infrastructure containment.

2 Materials and Methods:

Laterite soil was collected from Chenzou City, Hunan Province, China, and was air-dried, ground, and sieved to remove large particles and homogenise the soil. Commercially obtained sodium bentonite (Na-bentonite) was used as a binding agent. The primary minerals of laterite and bentonite are listed in Table 1. The Montmorillonite-dominant bentonite soil used in this research is characterised by a high PI (plasticity index of 239%), high adsorption capacity (SSA = 570 m2 g-1), and high cation exchange capacity (77.30 meq/100 g).

Table 1. Physical Properties of Na-Bentonite and Laterite

Properties	Bentonite	Laterite
Main minerals	Montomorlite Quartz Felspar Cristobalite	Kaolinite Quartz Orthoclase Iron silicate
Specific gravity	2.66	2.71
Plastic limit	37	27
Liquid limit	276	69.9

Air-dried bentonite and laterite samples with 3%, 5%, 7% B, and 12%, 16%, and 25% water were prepared for testing. Use bentonite sparingly because it is cost-effective, but handle it carefully. Determine the soil sample's water content; press it to the desired MDD. Samples were oven-dried at 105°C. After drying, add water and chemicals, and keep the samples for 24 hours to homogenise before compaction. Salt solutions of NaCl and $CaCl_2$(1 mol/L) were

prepared for soil mixing. We selected these salts because of their natural abundance, chemical interactions, and applications, as they occur at high concentrations and influence bentonite layer structure.

These salts can exchange ions with clay particles, making them valuable for testing. We assessed the actual water content using saline solutions before mould compression, as per Equation 2.

$$w = \frac{m_w - m_d}{m_d(m_w - m_d)\cdot\frac{c_f - M_f}{\rho_f - c_f.M_f}} * 100\% \quad (2)$$

w =actual water content,m_w and $m_d$are the sample wet and oven-dry mass, respectively. While c_f & $\rho_f$are the molar concentration of the wetting fluid and the density of the wetting fluid, respectively. $M_f$is the molar mass of the solvent in the fluid. The Figure shows the overall graphical experimental design of the research. The experimental program (Figure 1) was designed to systematically investigate the coupled effects of mechanical and chemical variables on suction behavior. Table 2 lists the primary variables considered in this study.

FPT was used to accurately predict the soil suction. Using the FP method, we determined the osmotic and matric suction of soil samples using filter-paper weights (hanging and contact). The sample diameter and height are 61 mm and 20 mm. The soil was compacted using various MDDs. The only difference is that in this study, the sample is prepared using distilled water, a 1 M NaCl solution, and $CaCl_2$. The solutions are prepared at 1 M to compare the effects of different ions at the same molality.

Table 2. Primary variables used in experiments

Bentonite content	3%, 5%, 7%
Dry density	1.5 g/cm³ & 1.6 g/cm³
Initial water content	12%, 16%, 25%
Pore fluid type	Distilled water, NaCl (1 M), $CaCl_2$ (1 M)

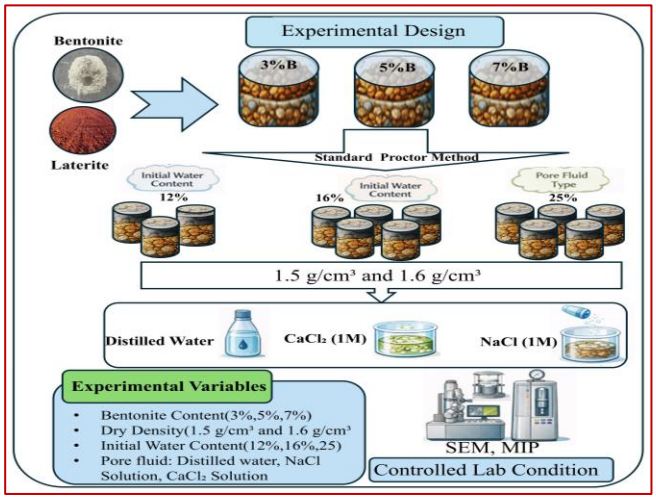


Figure 1. Graphical experimental design for investigating the coupled effects of bentonite content, dry density, initial water content, and pore-fluid chemistry on suction behavior

1.1. Suction(Ψ) measurement

The FP (Filter Paper) method was used to determine the matric suction of soil samples in accordance with ASTM D5298-10 (2010)[29]. Whatman FP No. 42 was oven-dried prior to use. Three stacked FPs were interposed between soil samples, as shown in Figures 2a and 2b. The central FP had a diameter of 42.5 mm, which was smaller than the two supporting FPs, each measuring 61.8 mm (Figure 3a). This apparatus measured matric suction (ψ_m), with one suspended FP positioned above the sample without contact for osmotic suction measurements. The supporting FP was employed to prevent direct contact between the Whatman no. 42-FP and soil samples. The complete assembly was then encased in plastic film and maintained at 25 °C for 15 days to achieve moisture equilibrium (Figure 3b). After equilibration, we assessed the water content of the soil sample and central FP.

According to ASTM D5298-10 (2010), for Whatman No. 42, we used equations (3,4) and the FP calibration curves to convert the FP water content to the soil sample ψ. The following equation has been derived for suction values.

As w_f was less than 26, we would use the equation for total suction ($w_f < 26$).

$$\log \psi = 5.31 - 0.0879 w_f \quad (3)$$

And for total suction ψ, since w_f >26, we use:

$$\log \psi = 4.945 - 0.0673 w_f \quad (4)$$

where ψ is the suction of the soil sample (kPa), and w_f is the water content of FP (%). The mean values of ψ The water content in the two replicated measurements was considered.

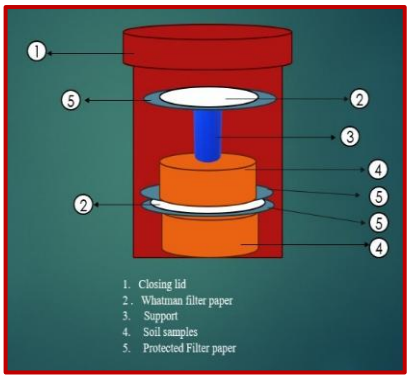


Figure 2a. Schematic diagram

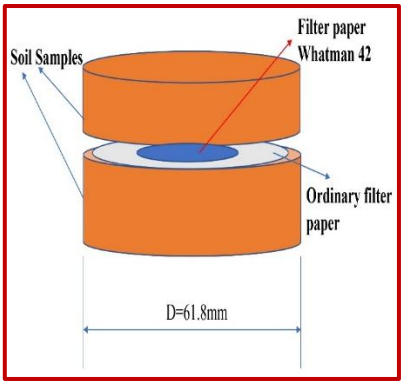


Figure 2b.Test Scheme.

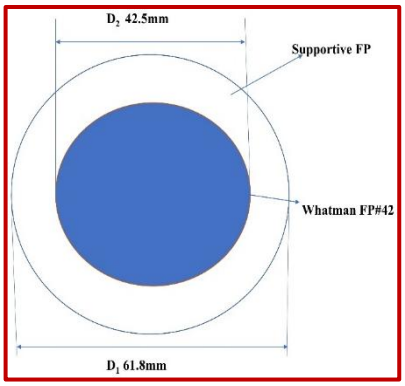


Figure 3a. Diameter ratio FP

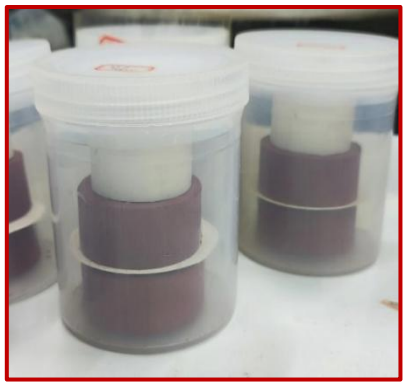


Figure 3b. Laboratory Setup

The WP4C device measures total soil suction using the chilled-mirror dew point technique. The method establishes thermodynamic equilibrium between soil pore water and water vapour in a sealed chamber under isothermal conditions. During testing, a Peltier cooling system lowers the mirror temperature until dew forms on its surface, which an optical sensor detects. A thermocouple attached to the mirror measures the dew point temperature, while an infrared sensor monitors the soil sample temperature. The system determines relative humidity (RH) from the measured temperatures and then converts it to total suction using Kelvin's equation.

The measured RH is converted to total suction using Kelvin's equation:

$$\psi = -\frac{RT}{v_w}\ln\left(\frac{RH}{100}\right) \quad (5)$$

where:

ψ= total suction (kPa)

R= universal gas constant (8.314 J mol^{-1} K^{-1})

T= absolute temperature (K)

v_w= molar volume of water (18×10^{-6} m3 mol^{-1})

RH= relative humidity (%)

The WP4C provides rapid total suction measurements over approximately 500 kPa to 100 MPa, with each measurement requiring about 10 minutes in fast mode. For testing, compacted soil specimens (5 mm thick and 30 mm in diameter) were placed in the sample cup, filling about half of its volume. Measurements were taken after vapour equilibrium was achieved between the soil sample and the chamber atmosphere.

2.2 Soil Suction Concept:

In engineering, unsaturated soils, which contain air-water pores, pose several problems. This creates suction, or negative pore-water pressure, which strongly affects the soil's stress regime. Thus, understanding unsaturated soil mechanics requires precise measurement and interpretation of soil suction. Soil suctions range from 0 to 1 GPa, and suction detection equipment only works in certain ranges[30-32].

The ability of porous materials to absorb and retain water is known as suction, or negative water stress, and is an essential attribute in soil science and engineering. Two separate components, matric suction and osmotic suction, make up the phenomenon of soil suction [33, 34]. Total suction is the sum of these two types. Osmotic suction is caused by dissolved salts in the soil's moisture, whereas capillarity, texture, and surface forces attract water to the soil,

creating suction. An equation that defines total suction as the sum of matric and osmotic suction concisely expresses this idea.

$$\psi_t = \psi_m + \psi_\pi \quad (6)$$

here ψ_t is total suction (kPa), ψ_m $matric\ suction$(kPa) and $\psi_\pi$is osmotic suction.

Total suction can be calculated by the Kelvin equation derived from the ideal gas law using principles of thermodynamics, and given by

$$\psi_t = \frac{RT}{V} \ln(\frac{P}{P_o}) \quad (7)$$

Where R= universal gas constant, V=molecular volume of water, T=absolute temperature, $\frac{P}{P_o}$= relative humidity, P=partial pressure, P_o = The saturation pressure of water vapour over a flat surface of pure water at the same temperature.

Matric and osmotic soil suction are unaffected by each other. Granular, salt-free soils lack osmotic suction; matric suction and total suction are equivalent. Clays have higher total suction because their salts lower the vapour pressure. This spike represents the energy required to turn water into vapour via osmotic suction [35]. Matric suction affects soil stability and fluctuates with environmental variables. These differences may result from changes in one or both forms of soil suction. Although osmotic suction is more commonly associated with unsaturated soils, it also affects saturated soils because its effect depends on the salt content of pore water. Osmotic suction, in turn, is caused by changes in soil salt concentration, and it significantly affects soil volume and shear strength. [36, 37]

Changes in soil salinity from chemical contaminants can affect soil behavior by altering osmotic suction. In these cases, it is important to consider how osmotic suction affects the stress profile in both saturated and unsaturated soils. The effects of osmotic suction on soil mechanical properties may differ from those of matric suction. Osmotic suction relates to the electrical environment around clay particles (i.e., the diffuse double layer), whereas matric suction relates to the air-water interface (i.e., the contractile skin).

2.3 Microstructure Analysis:

2.3.1 MIP Test

The pore-size distribution (PSD) and changes in void shape in the samples were measured using MIP tests. The microstructural samples were prepared as described above. After testing, the specimens were selected and freeze-dried. Specimens were rapidly frozen in liquid nitrogen to a temperature below -196 °C, then the excess ice was sublimed at -63 °C in a vacuum freeze dryer for 48 hours. This helps preserve the pore structure. The MIP test was conducted using the Micromeritics AutoPore IV-9500. The pore size was measured in two pressure ranges: low pressure (3.4 kPa-2 MPa) and high pressure (2 MPa-227.5 MPa). The Washburn equation [38]was used to calculate the injected pore diameter. Thus, the pore diameters detected ranged from 6.9nm to 199.93 μm. The relation between the pore diameter and the void ratio (e) and de/dlogD is shown in Figures 4(a-b). Table 3 shows the sample composition.

Table 3. Samples having different Bentonite percentages with initial water content

Sample ID	Material (%)
Sample 1	3%B97%L12%W

Sample 2	3%B97%L16%W
Sample 3	5%B95%L12%W
Sample 4	5%B95%L16%W
Sample 5	7%B93%L12%W
Sample 6	7%B93%L16%W

198

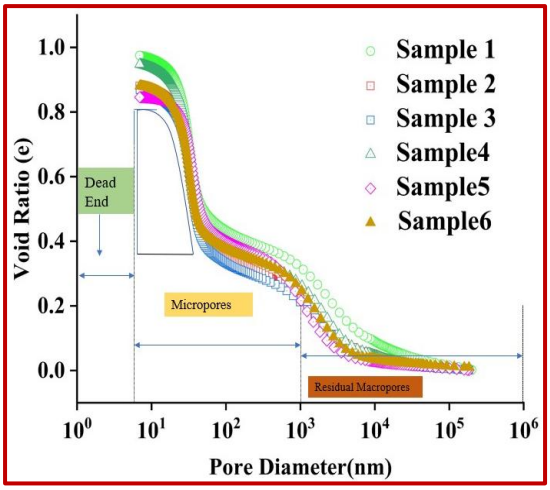


Figure 4(a). Void ratio vs Pore diameter

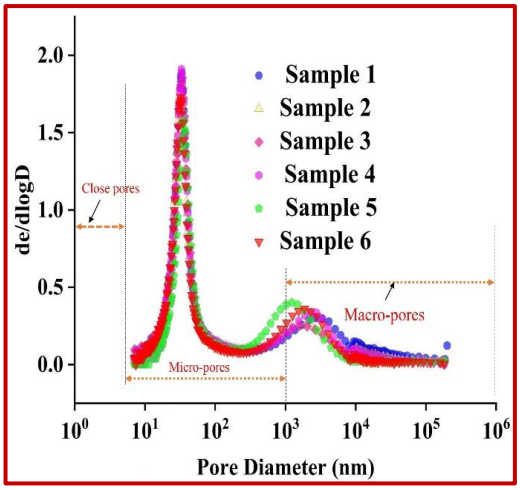
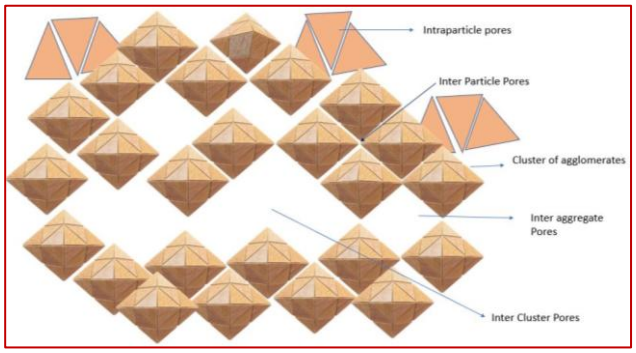


Figure 4(b). de/dlogD vs Pore diameter

199

200 Cheremskoj (1985) classified pore types based on relative pore size as structural elements of porous materials
201 [39, 40]. In pore classification, macropores (r > 1000nm) are pores with a radius greater than 1000nm. The pore size
202 is much larger than the element's size. Micro-pores (100<r<100nm) are about the same size as structural elements.
203 Sub-micropores (r<100nm) are smaller than structural elements. Ultra-micro-pores (r<1nm) can be found within
204 structural elements (known as dead ends). Instead, authors J. Kodikara (1999) suggested the pore size in clay structure
205 as intra-cluster (macropores 104-106nm), inter-aggregate (micropores 103nm), inter-particle (sub-micro-pore less
206 than 1000nm), and intra-particles (ultra-micro-pores 3-4nm[41, 42].Pore setting in aggregate can be demonstrated in
207 Figure 5.



208

209 **Figure 5.** Conceptual classification of pore domains within the laterite–bentonite aggregate structure

2.3.2 SEM

SEM analysis evaluated microstructural changes in sand–bentonite mixtures under different chemical conditions. Samples were freeze-dried, fractured, and gold-coated prior to imaging (TESCAN MIRA3). The investigation focused on ionic effects: NaCl promotes dispersion, and $CaCl_2$ induces flocculation, altering particle arrangement and pore structure. These observations helped interpret the role of hydro-chemical interactions in governing material behaviour.

3 Results and discussion:

3.1 Effect of Bentonite Content and Dry Density on Matric Suction

Figure 6 depicts the water retention results (FP method) of samples wetted with distilled water having an initial water content of 12% and different MDD ($1.5g/cc$ & $1.6g/cc$), in which the relationship of matric suction ψ_m and bentonite content has been plotted. The relationship between bentonite content and matric suction (ψ_m) exhibits a nonlinear trend with a distinct threshold behaviour. For specimens wetted with distilled water, ψ_m initially decreases as bentonite content increases from 3% to approximately 5%, then increases markedly beyond this threshold. This behaviour reflects a transition between two competing mechanisms: (i) initial dispersion and pore structure rearrangement, and (ii) swelling-induced pore refinement.

At lower bentonite concentrations (3-5%), bentonite disrupts the laterite structure, transiently increasing pore channels and reducing capillary stresses, which drops matric suction (ψ_m). At higher bentonite contents (>5%), montmorillonite swelling capacity becomes the dominant factor, systematically decreasing pore size and increasing the specific surface area available for water adsorption, thereby increasing ψ_m.

Dry density plays a key role in determining suction. Samples with lower porosity and stronger capillary effects in more compacted soils with a higher MDD (1.6 g/cm³) consistently show higher matric suction (ψ_m) than those compacted to 1.5 g/cm³. Porosity reduction has a stronger influence at higher bentonite contents because swelling constricts pores.

The observed trend indicates a stronger relationship between water content (12-16%) and suction behaviour. Higher water content exhibits a greater decrease in suction due to hydration and swelling of the bentonite. Suction(ψ) in the latter stage is controlled by the transition between saturated and unsaturated soils.

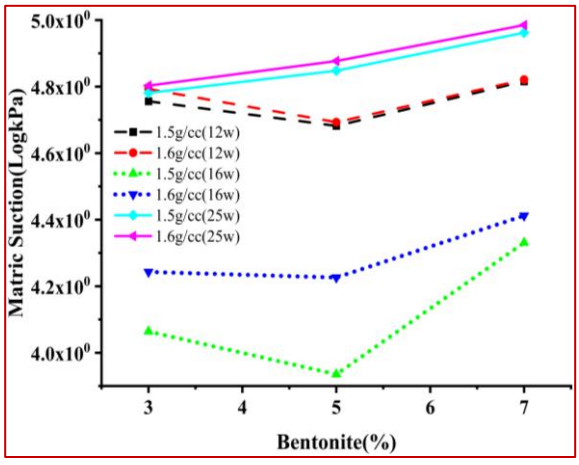


Figure 6. Effect of bentonite content and dry density on matric suction under distilled water.

3.2 Influence of Pore Fluid Chemistry on Matric Suction

Saline solutions significantly modify suction behaviour through electrochemical interactions and changes in clay fabric.

3.2.1 Effect of NaCl (Monovalent Cations)

The trends in Figure 7 differ with 1 M NaCl solution: MDD increases, and suction also increases because capillary forces tend to increase in soil. The trend in NaCl-treated samples is similar to that of the distilled water, but with higher suction. Na^+ ions partially disperse the clay particles, reducing attractive forces while preserving sufficient swelling potential. This produces a more uniform pore distribution and improved capillary formation, thereby increasing ψ_m.

The osmotic component of total suction also increases because the pore fluid has a higher ion concentration. However, this effect is not significant because monovalent ions don't substantially reduce the diffuse double-layer thickness.

Other researchers also report an increase in water retention capacity [43, 44]. [45]He et al. show the opposite of Zhang et al. (2012) regarding suction capacity: the salinity effect on suction is more pronounced. As shown in the graphs (Figure 6), matric suction increases with bentonite content, then decreases with increasing chemical content, and then increases with Bentonite content, in contrast to the trend observed in distilled water.

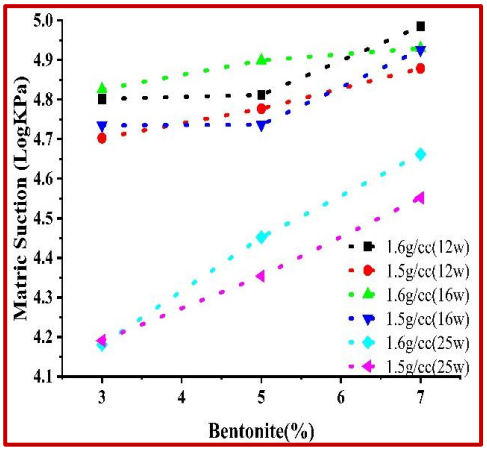


Figure 7. Effect of bentonite content and dry density on matric suction under NaCl solution.

3.2.2 Effect of $CaCl_2$ (Divalent Cations)

In contrast, samples treated with $CaCl_2$ display different behaviour. The addition of Ca^{2+} ions strongly aggregates clay particles, leading to a larger, fewer-pore structure that reduces capillary forces, resulting in a decline in ψ_m at low bentonite contents and a slight increase at higher contents, where swelling effects predominate. The stronger electrostatic attraction of divalent cations compresses the diffuse double layer, promoting particle bridging and stabilising soil structure but reducing its water-holding capacity. Hence, ψ_m in $CaCl_2$-treated samples is usually smaller than in NaCl and distilled water.

Bentonite in a saline solution may show different swelling properties because Na+ ions interact with the clay particles. This could result in pore spaces (Figure 1) that differ from those in bentonite soil with distilled water. As with the previous soil samples using distilled water, ψ increases as MDD increases. This may be due to compacted

soil particles, which could improve the soil's water-holding capacity, or to Na^+ ions being drawn into smaller pore spaces, thereby increasing the osmotic effects. As observed in the previous samples (without NaCl) there is still a non-linear trend with a decrease followed by an increase in ψ as the bentonite percentage increases.

However, the introduction of $NaCl$ Seems to moderate the initial decrease, potentially because osmotic effects compensate for the initial increase in pore size. Water content (as discussed above) plays a significant role in how bentonite interacts with the saline solution. At higher water contents, the ψ tends to be lower, likely because there's more water available to facilitate ion exchange and swelling. Thus, a larger volume of the soil mixture is affected. Figure 8 shows the water retention behaviour of soil wetted with CaCl2. Different trends have been observed for $CaCl_2$ compared with NaCl. Samples wetted with 12% NaCl. The initial water content increases linearly. As bentonite concentration increases, the opposite occurs.

Suction values increase as the bentonite content increases to 5% , the trend reverses at 7% bentonite content, in contrast to samples wetted with water (Figure 8). But the trend line is more linear in the case of 25% initial water content at the $1.6g/cc$ MDD. But at 16% with 5% bentonite content, suction values do not change. The presence of Ca^{2+} ions in the $CaCl_2$ the solution leads to a different behavior compared to Na^+ ions from $NaCl$. Divalent cations can induce flocculation of clay particles, resulting in a more aggregated soil structure with larger but fewer pores. Soil aggregation can initially reduce matric suction by reducing capillary forces in larger pores. The trends in the graphs typically show an increase in ψ with increasing bentonite content, but the presence of Ca^{2+} ions may result in a more complex relationship.

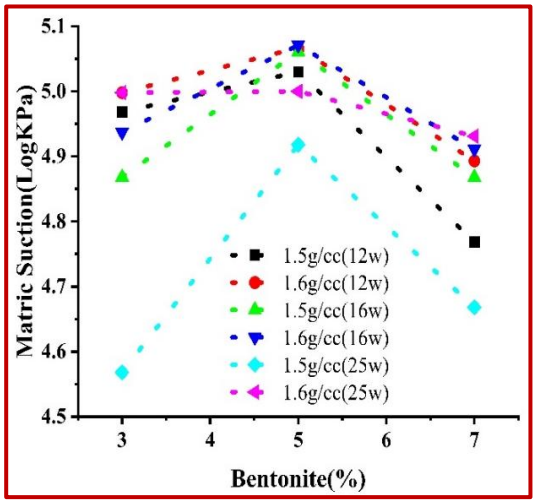


Figure 8. Effect of bentonite content and dry density on matric suction under $CaCl_2$ solution.

Initially, the ψ may not increase as sharply, or may even decrease, compared with distilled water due to flocculation. At a certain bentonite content, bentonite swelling increases and becomes more dominant. Higher MDD has been associated with higher ψs across different solutions. With $CaCl_2$ effect of dry density may be more pronounced due to the stronger interparticle forces caused by divalent cations. The swelling is a crucial characteristic of bentonite, and in the presence of Ca^{+2}, The swelling may be less than with Na^+due to the flocculation effect. However, as bentonite content increases, ψ increases because the soil matrix can hold more water. The flocculated

structure induced by $CaCl_2$ might be more stable than the dispersed structure typically formed in $NaCl$ solutions. The flocculation of bentonite affects the soil's mechanical properties, such as compressibility and shear strength.

Unlike $NaCl$, which tends to disperse clay particles and maintain higher ψ due to the swelling, $CaCl_2$ can lead to a reduction in ψ at lower bentonite contents due to flocculation. The effects of $CaCl_2$ are more noticeable in the lower range of bentonite content, while at higher contents, the ψ tends to follow an increasing trend, similar to the patterns observed with distilled water and $NaCl$, although typically at a lower magnitude of ψ.

3.3 Total Suction Behavior and Osmotic Contributions

Total suction (ψ_t) follows trends similar to matric suction but reflects the combined effects of matric and osmotic components. Under distilled-water conditions, ψ_t shows a characteristic "V-shaped" response with increasing bentonite content, with a minimum around 5%, corresponding to the transition from dispersion-dominated to swelling-dominated behavior.

In NaCl-treated samples, ψ_t increases more consistently with bentonite content because swelling and osmotic suction act together. Dissolved salts elevate osmotic potential, contributing significantly to total suction, particularly at higher bentonite contents.

In $CaCl_2$-treated samples, ψ_t initially increases because $CaCl_2$ is hygroscopic, but it subsequently decreases beyond a critical bentonite content. The $CaCl_2$ behavior reflects a balance between osmotic suction enhancement and microstructural coarsening from flocculation, which reduces capillary retention. The peak observed around 5% bentonite indicates an optimal balance between these competing mechanisms.

Figure 8 shows total suction at different initial water percentages and bentonite contents, as used in the earlier equation. For 1.6g/cm^3 MDD, suction follows a complex pattern: decreasing, slightly increasing, then decreasing, and finally increasing (Figure 9).

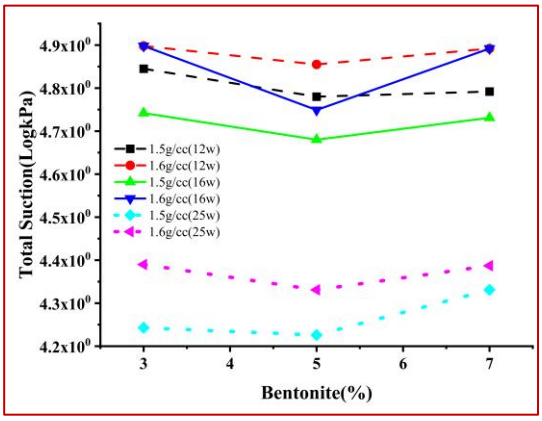


Figure 9. Effect of bentonite content and initial water content on total suction under distilled water

3.4 Effect of Initial Water Content

Initial water content controls suction, including saturation and capillarity. Lower water content (12%) increases suction because of stronger capillary forces and lower pore saturation. Increasing water content (16% and 25%) lowers suction because of pore saturation and reduced capillary forces.

At higher water content, the effect of bentonite content is less pronounced, suggesting the system is near saturation, and that bentonite swelling does not substantially affect suction—the swelling behaviour of chemically treated samples

results from ionic interactions that affect water-holding capacity. Figure 10 shows total suction using NaCl solution for the above water contents; a clear trend is observed at 16% water content compared to the other water contents.

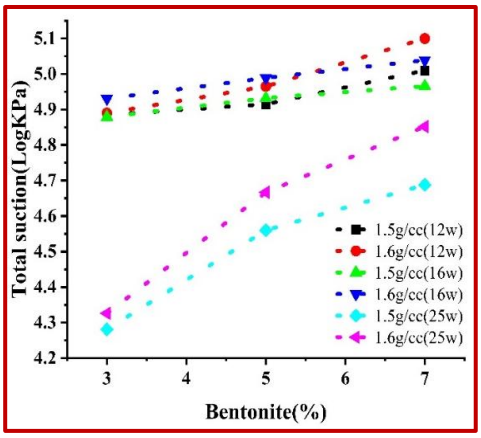


Figure 10. Effect of bentonite content and initial water content on total suction under NaCl solution

Figure 11 depicts the relationship of the total suction of samples wetted with $CaCl_2$. Calcium ions significantly impact the soil's physical and chemical behaviour. Total suction decreases as bentonite content increases up to 7% across all initial water contents and at both high and low MDD. For both MDDs, total suction increases as bentonite content rises, peaks at around 6% bentonite, and then decreases (Figure 11). The initial increase could be due to the hygroscopic nature $CaCl_2$, which initially draws water from the environment, increasing total suction. The peak represents the point at which the bentonite's ability to swell and retain water is maximised.

After the peak, the decrease in total suction may indicate that the system has reached a saturation point where additional bentonite does not significantly contribute to increased water retention, or it could indicate that the structure of the soil-bentonite matrix is altered by the presence of calcium, which may lead to flocculation and aggregation, thus reducing the overall suction. Figure 11 shows a continuous increase in total suction with the addition of bentonite at lower MDD, peaking at around 5% bentonite, then decreasing at higher MDD. The difference in trends for the two MDDs might suggest that the effect of $CaCl_2$ is more pronounced at higher densities, possibly due to more effective ion exchange and flocculation at higher MDD, which could enhance the soil's structure and water retention ability up to a certain point, after which the system becomes oversaturated.

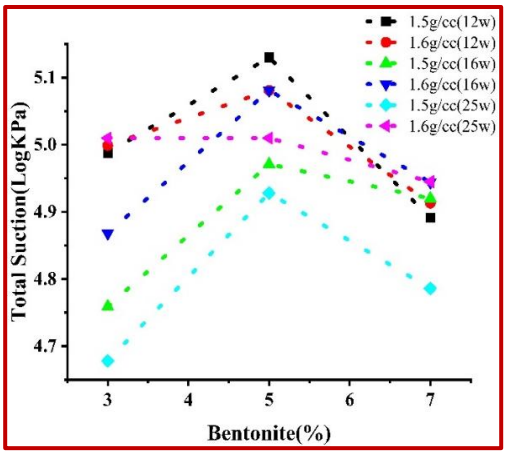


Figure 11. Effect of bentonite content and initial water content on total suction under $CaCl_2$ solution.

With 25% For the initial water content, the total suction is lower than in the other graphs, reflecting the higher initial saturation (Figure 11). For the lower MDD, the suction first increases, then decreases, indicating a trend similar to the other water contents but with an earlier saturation point. For the higher MDD, the suction increases slightly throughout, suggesting that the soil-bentonite mixture at higher density can still utilise the added water for further hydration and swelling, despite the high initial water content.

Chemicals like $CaCl_2$ and NaCl affect the water retention capacity of laterite-bentonite mixes, as shown in the experiment. Salt solutions, especially Ca2+ ions, had a greater impact than Na^+ ions. Consequently, the water retention capacity decreased. One possible remedy was to add bentonite to the mixture. Adding bentonite would affect the suction properties somewhat, regardless of the water saturation level. Bentonite's additive effect is minimal once the mixture is fully incorporated. In a bentonite-laterite mixture, $CaCl_2$ has a more noticeable effect than NaCl at lower suction ranges.

3.5 WP4C /Chilled Mirror dew point

The WP4C water-retention curves in Figure 12 show a progressive reduction in equilibrium water content with increasing suction across all laterite-bentonite mixtures, reflecting the gradual removal of pore water from the soil matrix as drying conditions intensify. At a given suction level, specimens with higher bentonite content consistently retained more water, indicating the enhanced water-holding capacity associated with bentonite's larger specific surface area and swelling characteristics. Furthermore, mixtures compacted at a dry density of 1.6 g/cc exhibited higher equilibrium water contents than those compacted at 1.5 g/cc, highlighting the contribution of denser packing and a greater proportion of fine pores to water retention. The influence of pore-fluid chemistry was also evident, with deionised water specimens generally exhibiting the highest water-retention capacity, followed by NaCl-treated samples, while $CaCl_2$-treated specimens displayed the lowest equilibrium water contents across the investigated suction range. The pore structure can be attributed to the different effects of monovalent and divalent cations on clay particle interactions. Na^+ ions promote diffuse double-layer expansion and facilitate water adsorption, whereas Ca^{2+} ions compress the diffuse double layer and induce particle aggregation, thereby reducing the amount of water retained within the soil structure. The separation of the water-retention curves becomes increasingly pronounced at higher

suction levels, suggesting that hydro-chemical effects are more significant under unsaturated conditions where adsorbed water dominates the retention mechanism, indicating that both bentonite content and ionic valence play critical roles in controlling the water-retention behavior of laterite-bentonite barrier materials and consequently influence their long-term hydraulic performance under chemically aggressive environments.

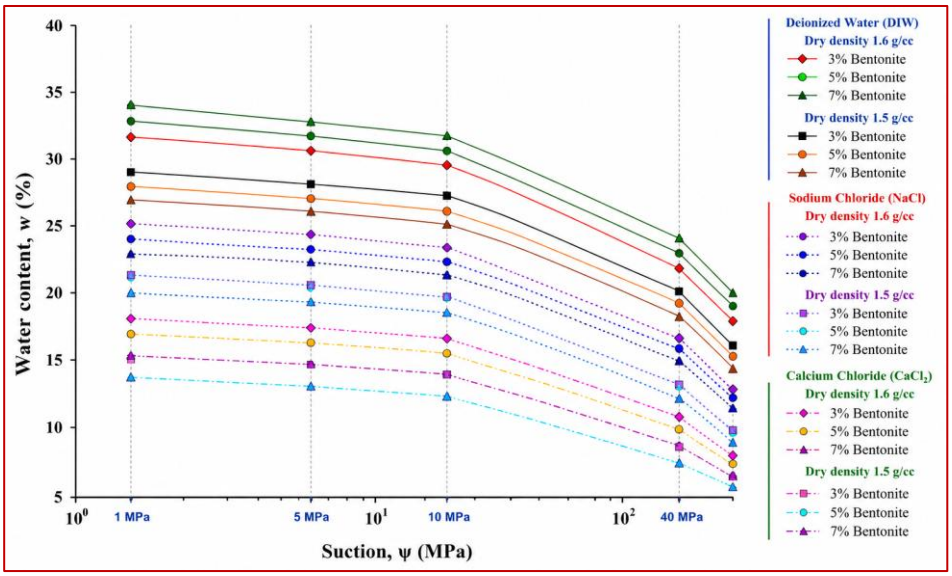


Figure 12 Water-retention behavior of compacted laterite-bentonite mixtures under different pore-fluid chemistries.

Note: Results obtained from WP4C measurements under deionised water, NaCl, and $CaCl_2$ environments, showing the influence of bentonite content, dry density, and pore-fluid chemistry on equilibrium

3.6 Microstructural Interpretation (SEM and MIP Integration)

Microstructural analysis confirms the hydro-chemical control of suction behavior.

- Distilled water produces dispersed structures with larger pores and higher retention.
- NaCl induces partial aggregation, resulting in a relatively uniform pore structure.
- $CaCl_2$ induces strong flocculation, dense clusters, and reduced microporosity.

The structural variations explain the contrasting suction responses under different ionic environments. MIP results further confirm that:

- Bentonite addition shifts pore size distribution from macropores to micropores
- Ca^{2+} promotes flocculation and aggregation, resulting in pore-size redistribution toward a more macropore-dominated/coarser pore structure and reduced microporosity.
- Na^{+} maintains a balanced pore structure

These observations demonstrate that ionic valence governs pore evolution, which in turn controls suction behavior.

Using DIW, NaCl, and $CaCl_2$ as treatments shows how different cation valencies and ionic strengths affect microstructural characteristics. $CaCl_2$ generates substantial aggregation and reduced permeability; NaCl induces limited stabilisation and structure; and DIW promotes maximum particle swelling and dispersion (Figure 13).

Because of its hydrophilic properties, bentonite typically exhibits swelling behavior when combined with laterite in a DIW-containing mixture. Because DIW saturates the interlayer gaps, bentonite particles can expand, increasing

their volume and changing the microstructure. Incorporating DIW into the bentonite-laterite matrix enhances ion mobility. The bentonite and laterite components interact more effectively in a saturated environment because cation exchange occurs more readily [46].

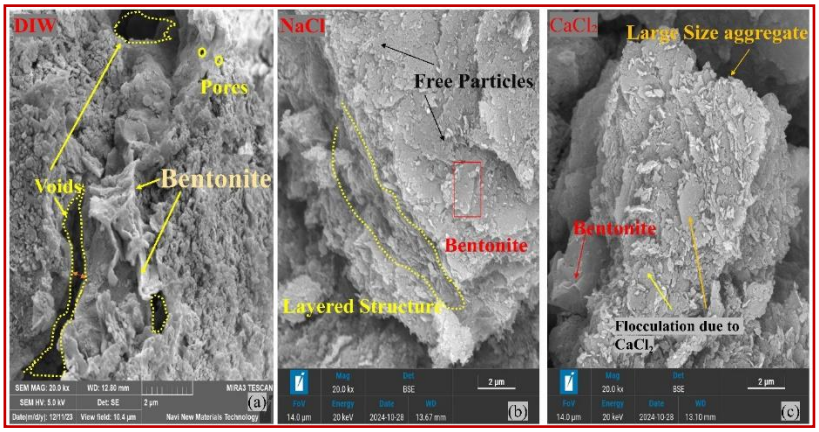


Figure 13. Microstructural Comparison of samples treated with (a)DIW (b) NaCl (c) $CaCl_2$

DIW alters the particle arrangement in the mixture. Bentonite swelling produces a denser structure, which inhibits hydraulic conductivity by increasing interfacial adhesion among particles. Adding deionised water alters the microstructure of bentonite-laterite. Strength, mechanical stability, hydraulic conductivity, and cation exchange capacity are all enhanced. Water treatment significantly alters the morphology observed in scanning electron micrographs of DIW-treated materials. Compared with the untreated surface, the treated surface appears rougher and more porous at low magnification. This transformation results from the reaction between water and bentonite. SEM images show that the compact structure pulls apart, creating matrix holes as the bentonite swells with water. The gaps result from bentonite expanding upon water absorption, as shown by the varying scales.

Water is an ideal medium for bentonite compared to other chemicals. At higher magnification, the bentonite flakes are shown stacked (Figure 14a). Partially exfoliated, separated flakes indicate that water treatment enhances delamination of bentonite layers. Delamination increases surface area, opens internal cavities, and improves water retention. If the material could be made more porous, it could hold more water and be used in high-moisture environments. Introducing weak areas through gaps and layers could compromise mechanical strength, even if the structure is enhanced. Because bentonite reacted with water, the samples treated with DIW transformed from compact to porous, layered structures. Mechanical and physical behaviors, such as the ability to absorb and retain water, can be influenced by structural changes under varying situations.

Calcium chloride ($CaCl_2$) affects the microstructure of bentonite and profoundly impacts soil physical and chemical properties. $CaCl_2$ provides Ca^{2+} ions with a larger charge valence than monovalent ions (such as sodium ions). Solids and ions undergo ion exchange, with Ca^{2+} ions occupying the interlayer spaces of bentonite, thereby decreasing the clay's swelling potential. In fact, a study found that increasing the concentration of $CaCl_2$ reduces the swelling ratio of bentonite due to charge screening. Divalent ions (such as Ca^{2+}) attract the clay layers more strongly,

thereby decreasing their interlayer spacing. The Ca^{2+} ions in bentonite promote stronger bonding between montmorillonite platelets, leading to a denser mass and lower water content.

Figure14b illustrates how $CaCl_2$ impacts the microstructure of bentonite clay, and thus its suction capacity. The photos show that $CaCl_2$ alters the particle structure, forming a denser structure. Although clay particles are aggregated, the first picture shows spaces and microcracks (at lower magnification). Water can flow through the early structure with minor modifications. The second and third photos demonstrate the effect of $CaCl_2$ on interparticle bonding and pore filling. This denser structure impacts the suction of treated bentonite. Higher suction in untreated or less compacted clays was due to less compact particles and more water stored in pores. Treatment with $CaCl_2$ increases particle flocculation and decreases interparticle distances, but also reduces pore space for moisture storage and, hence, suction [47].

This reduced porosity diminishes moisture flow and water retention capacity under varying environmental conditions. Furthermore, $CaCl_2$ treatment substitutes calcium ions with sodium ions in clays. Ion exchange facilitates particle flocculation and stabilises the microstructure, thereby improving moisture retention and reducing equilibrium suction. Microscopic images reveal a denser structure with smaller pores and improved particle cohesion, thus reducing suction. Suction decrease minimises volume change due to moisture variation in geotechnical applications; thus, clay can be stabilised under variable moisture conditions. $CaCl_2$-treated bentonite has a more stable structure and density, reducing suction and therefore making it an excellent material for low-permeability and dimensional-stability applications, such as containment system liners and barriers.

Scanning electron microscopy (SEM) images (Figure 14c) reveal the effects of NaCl treatment on bentonite texture and layered arrangement. At higher magnification, these images show a layered structure in the clay matrix, demonstrating NaCl's effects on bentonite's structure. In the first set of photos, at 2.00 kx, a compact structure with cracks is observed; the details reveal discrete layers, perhaps due to NaCl-induced changes in compactness and flake formation.

At a higher magnification (20.0 kx), "Flakes and Layers of Bentonite" showcases intricate formations resembling fine flakes. Ionic interactions in NaCl weaken van der Waals forces, increasing interlayer separation and reducing cohesion. This morphological alteration significantly affects bentonite's water absorption and cation-exchange capacity. As the concentration of NaCl increases, bentonite's swelling capacity diminishes because sodium ions (Na^+) occupy the interlayer gaps, substantially decreasing the maximum swelling ratio. Consequently, this results in particle agglomeration rather than expansion. The reduced swelling potential leads to tighter packing, thereby limiting water movement and further swelling.

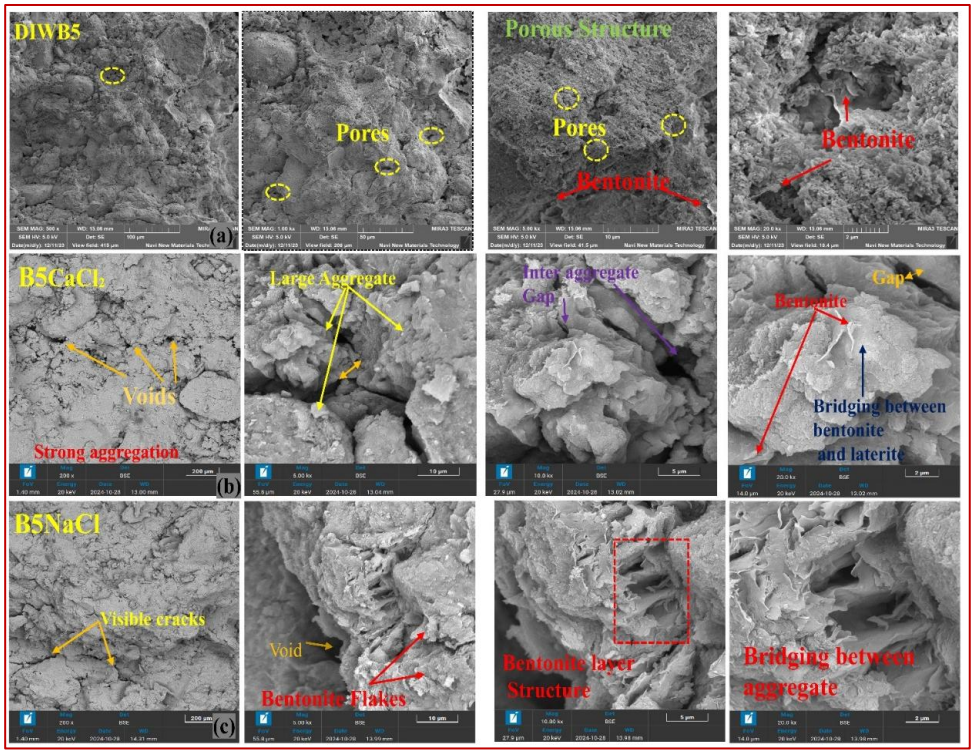


Figure 14. SEM features of Laterite-bentonite using Different Chemicals

Swelling, ion exchange, and permeability are important issues in geotechnical engineering and environmental remediation. Understanding these differences is essential. More free particles are visible in the $CaCl_2$-treated sample than in the NaCl-treated samples, indicating the divalent ion effect.

SEM images indicated larger aggregates in $CaCl_2$-treated samples than in NaCl-treated samples (Figure15(a-b)). The microstructure of the aggregate exhibits distinct features in the presence of NaCl and $CaCl_2$. Sodium ions (Na^+) enter the interlayer spaces of bentonite, decreasing the negative charge on the clay particles and reducing swelling. Ca^{2+} ions cause clay particles to stick together, forming cemented masses that reduce water retention. Salts reduce the bentonite diffuse double layer and osmotic potential, which affect water absorption and retention.

Flocculation by $CaCl_2$ improves bentonite's mechanical properties, increasing its resistance to erosion and leaching. This is important for landfill liners and cut-off barriers. $CaCl_2$ increases the stability and density of the microstructure of bentonite-laterite combinations via Ca^{2+} bridging. As shown in the SEM images in Figure 15, the sample treated with $CaCl_2$ is denser than the samples treated with NaCl.

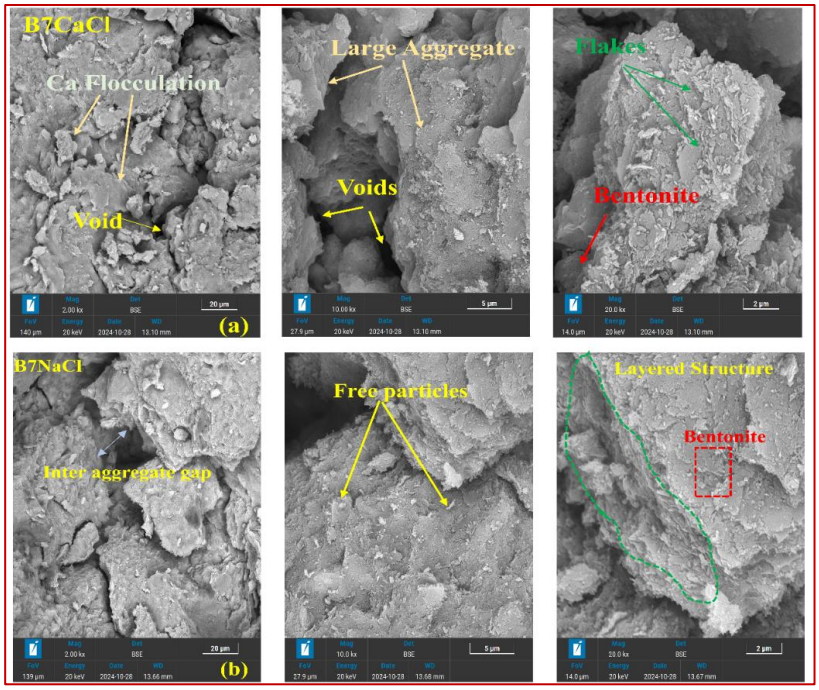


Figure 15. SEM comparison of laterite-bentonite microstructures treated with (a) $CaCl_2$ and (b) NaCl, highlighting differences in particle aggregation and pore development

Soil performance depends on composition and structure. Suction is created by the interconnected voids and pores in the soil. The presence of bentonite and salt creates intricate microstructures that hold water. Suction was higher in $CaCl_2$-treated samples than in NaCl or DIW-treated samples. DIW-treated samples were affected by bentonite, according to Mercury Intrusion Porosimetry (MIP) tests. Bentonite-laterite clumping decreased porosity, as shown in SEM images. However, NaCl-treated samples were multilayered.

4 Conceptual illustrations:

The conceptual framework shows the hydro-chemo-microstructural mechanisms that drive the evolution of suction and barrier performance of laterite-bentonite mixtures under various pore-fluid conditions (Fig. 16). Deionised water helps hydrate bentonite, disperse particles, expand the diffuse double layer, and facilitate better water adsorption, while Na^+ causes monovalent-ion interaction, keeping particles relatively dispersed and allowing a fine pore structure and better capillary retention. Calcium ions provide greater electrostatic screening, diffuse double-layer compression, ion bridging, and flocculation and aggregation effects, leading to pore-size redistribution towards a more macropore-dominated/coarser structure and lower microporosity and water retention. Higher bentonite content increases water-holding capacity and pore-size refinement over time; higher dry density reduces pore size and increases suction. A critical bentonite content at 5% is identified as a transition zone between dispersion-dominated and swelling-dominated structural responses, and the range of 5-7% is identified as a potential formulation window. Thus, particle interaction is governed by ionic valence; particle arrangement controls pore-size redistribution; pore structure influences water retention and matric suction; and a combination of hydro-chemical and microstructural responses governs the hydraulic integrity and durability of laterite-bentonite engineered barriers.

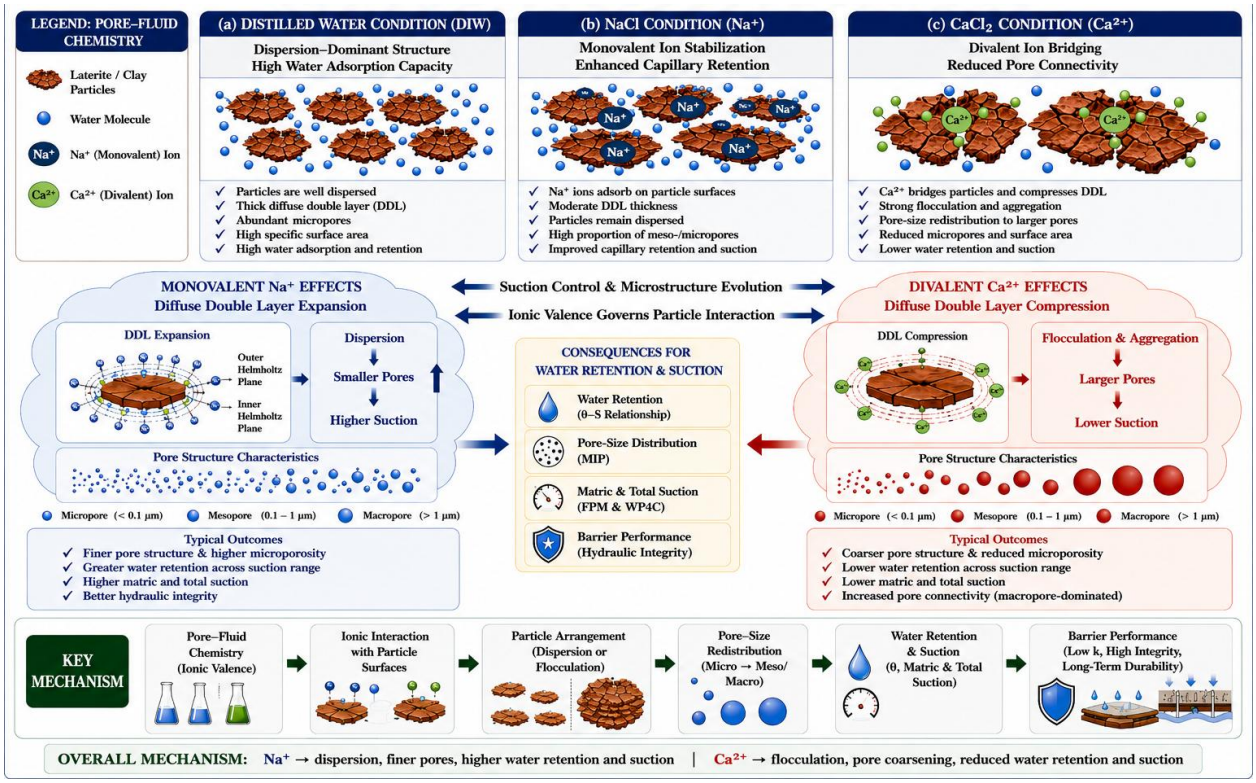


Figure 16. Hydro-chemical processes governing suction and microstructure in laterite-bentonite mixes

5 Engineering and Sustainability Implications

The results have implications for designing and evaluating laterite-bentonite (LB) engineered barriers for environmental containment. The coupled effects of bentonite content, dry density and pore fluid chemistry on barrier performance are illustrated by suction, water retention, MIP and SEM results. The threshold is found to be approximately 5% bentonite, and the interval 5-7% bentonite may be suitable to formulate enhanced water retention and suction characteristics of bentonites.

Suction generally increased with increasing dry density (from 15 to 16 g/cm³), which is generally believed to be due to pore constriction during compaction control in barrier construction. Pore-fluid chemistry is also very important, however. In addition to promoting dispersion, Na^+ also causes pore-size redistribution towards a more macropore-dominated/coarser structure, and towards reduced microporosity, due to its flocculation and aggregation nature. These chemical and microstructural changes can significantly alter the material's water retention and suction and should be considered when assessing barrier performance at a specific site.

From a sustainability standpoint, performance-based optimisation of bentonite dosage and compaction (rather than maximising bentonite content) is supported. Using laterite as the main matrix and optimising the bentonite fraction can reduce unnecessary use of swelling clay while achieving the desired hydraulic performance. It applies to landfill liners, cover systems, contaminated-site barriers and other barriers in the urban environment.

The study shows potential for resource-efficiency and durability benefits but does not quantify life-cycle impacts, carbon emissions or economic performance. Further research is needed to combine LCA, cost analysis and

long-term field exposure in order to quantify the environmental and economic performance of optimized LB barriers.

6 Conclusion

This study investigated the coupling effects of bentonite content, dry density, and pore fluid chemistry on the evolution of suction and microstructures in compacted laterite-bentonite mixtures. Main conclusions are as follows:

1) A nonlinear bentonite-content response was found, where there was an approximate threshold of 5% bentonite content associated with a change in the predominant microstructural and suction response. At lower concentrations, dispersion and pore restructuring play a greater role and, at higher bentonite concentrations, pore refinement and swelling play a greater role.
2) The dry density may be an important control on the suction; higher density compaction will result in higher suction, usually because of an increase in pore constriction and change in the capillary pore network. This effect depends on bentonite content and should be considered in mixture composition.
3) Pore-fluid chemistry significantly alters the values of suction and water retention. Particle interactions under Na^{+}-dominated and Ca^{2+}-dominated conditions differ, showing that ionic valence is an environmental factor that significantly influences the hydrochemical behaviour of laterite-bentonite barriers. These interpretations should be considered alongside the measured suction and MIP/SEM results.
4) Using suction, MIP and SEM observations, a hydro-chemo-microstructural pathway is established that connects the chemistry of pore fluids and interactions between clay particles with pore-size redistribution and, ultimately, suction and water-retention behavior. This provides a mechanistic explanation for the different hydro-mechanical responses of identical laterite-bentonite formulations in different chemical environments.
5) The identified threshold has repercussions for the potential for resource-efficient barrier design. The results indicate that bentonite dosage should be optimised based on hydraulic performance, compaction conditions, and chemical exposure, not added arbitrarily. Although these optimisations might reduce unnecessary use of swelling clay in lateritic barrier matrices, environmental, economic, and life-cycle evaluations are needed to determine quantitative sustainability benefits.

Overall, the results explain the mechanism for designing more chemically resistant laterite-bentonite containment materials for landfill, contaminated-site, and other environmental infrastructure uses within sustainable urban development. Future research should assess various mixed and natural pore chemistries, wetting/drying cycles, long-term chemical exposure and field-scale conditions, as well as environmental and life-cycle assessments, to understand the sustainability performance of these barrier systems as a whole and evaluate the sustainability of optimised barrier formulations.

Acknowledgements: The authors are grateful to the College of Environment and Civil Engineering and State Key Laboratory of Geohazards Prevention and Geoenvironmental Protection (SKLGP), Chengdu University of Technology, Chengdu, Sichuan, P.R. China, for funding this research. The authors also extend their appreciation to the Deanship of Scientific Research at Northern Border University, Arar, KSA, for funding this research work through the project number NBU-FFR-2026-3879-11.

International Review Board statement: Not applicable.

Informed consent statement: Not applicable.

Data availability statement: The datasets generated and/or analysed during the current study are not publicly available due to confidential data, but are available from the corresponding author on reasonable request.

Competing interests: The authors declare no competing interests.

Funding: The authors also extend their appreciation to the Deanship of Scientific Research at Northern Border University, Arar, KSA, for funding this research work through the project number NBU-FFR-2026-3879-11.

Author Contributions: Haroon Ahmed: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Visualization, Writing - original draft. **Wei Meng:** Funding acquisition, Methodology, Project administration, Supervision, Visualization, Writing-review & editing. **Adnan Altaf:** Formal analysis, Validation, Visualization, Writing-review & editing. **Muhammad Awais Hussain:** Validation, Resources, Visualization, Writing-review & editing. **Muhammad Akbar,** Validation, Funding acquisition, Visualization, Writing-review & editing. **Haroon Ahmed and Ayed Eid Alluqmani,** Funding acquisition, Resources, Visualization, Writing-review & editing. **Masamba Pinto,** Funding acquisition, Resources, Visualization, Writing-review & editing.

AI Declaration: AI was used for grammar and language improvement only.

References

1. Wan, Y., et al., *Studies on Hydration Swelling and Bound Water Type of Sodium- and Polymer-Modified Calcium Bentonite.* Advances in Polymer Technology, 2020. **2020**(1): p. 9361795.
2. Schanz, T. and S. Tripathy, *Swelling pressure of a divalent-rich bentonite: Diffuse double-layer theory revisited.* Water Resources Research, 2009. **45**(5).
3. Ortiz-Ramos, U., et al., *Impact of chemical, textural and swelling properties of bentonite on the adsorption of trimethoprim and chlorphenamine from water.* Applied Clay Science, 2026. **284**: p. 108143.
4. Wang, J. and S. Vanapalli, *A framework for estimating the matric suction in unsaturated soils using multiple artificial intelligence techniques.* International Journal for Numerical and Analytical Methods in Geomechanics, 2024. **48**(11): p. 2854-2879.
5. Mu, Q.-y., et al., *Water retention curves of a deformable lean clay under various stress ratios: Emphasizing the pore shape effects.* Computers and Geotechnics, 2025. **186**: p. 107403.
6. Fu, J., et al., *Water Retention Model of Unsaturated Soil Considering Capillarity and Adsorption in a Wide Suction Range.* International Journal of Geomechanics, 2026. **26**(3): p. 04025363.
7. Jalal, F.E., X. Li, and K. Onyelowe, *Swelling reduction in bentonite due to saline solutions via fractal modeling.* Scientific Reports, 2025. **15**(1): p. 27628.
8. Zheng, C. and Y. Yuan, *Study on the effect of water content on physical properties of bentonite.* PloS one, 2025. **20**(1): p. e0303522.

9. Pham, T.A., M. Sutman, and S. Nadimi, *Capillary-based nonisothermal suction stress and nonlinear shear strength criteria for unsaturated compacted soils.* International Journal of Geomechanics, 2025. **25**(5): p. 04025061.
10. Wang, D., M. Li, and Z. Wang, *Hydro-mechanical coupling and microstructural evolution mechanism of expansive soil under full suction range.* Scientific Reports, 2026. **16**(1): p. 8347.
11. Al-Moadhen, M.M., H.M. Hussein, and N.S. Atia, *Stress-Dependent Soil Water Characteristic Curves of Compacted Sand–Gypsum Mixtures.* Journal of Engineering, 2026. **2026**(1): p. 7149663.
12. Chi, Z.-C., et al., *Effect of hydration on mechanical properties and microstructure of expansive soil.* Environmental Earth Sciences, 2023. **82**(6): p. 133.
13. Bao, X., et al., *Study on mechanical and hydraulic behavior of compacted clay under pore water saline and matric suction conditions.* Transportation Geotechnics, 2025. **54**: p. 101636.
14. Zhang, C., Y. He, and J. Li, *Influence of osmotic suction on the hydro-mechanical behavior and micro-structure of compacted red clay in contaminated sites.* Environmental Earth Sciences, 2026. **85**(12): p. 256.
15. Lu, P.-H., et al., *Chemical effects on the hydro-mechanical behavior of compacted bentonite: a review.* Environmental Earth Sciences, 2025. **84**(18): p. 514.
16. Nayak, B.P., et al., *Experimental investigations on thermo-hydro-mechanical properties of compacted bentonite-based backfill materials.* Bulletin of Engineering Geology and the Environment, 2025. **84**(8): p. 392.
17. Daniels, K., et al., *Bentonite homogenisation and swelling: the effect of salinity.* Applied Clay Science, 2024. **247**: p. 107200.
18. Kim, J., et al., *A unified van Genuchten-type water retention model for compacted bentonite.* Engineering Geology, 2026: p. 108590.
19. Hou, C.-l., X.-y. Ma, and X. Kang, *Effects of salt and pH on microstructure and physico-mechanical behaviors of clay sediments : A references review.* Marine Georesources & Geotechnology, 2024. **42**(6): p. 736-766.
20. Cheng, H., et al., *Experimental study and model prediction of the influence of different factors on the mechanical properties of saline clay.* Scientific Reports, 2025. **15**(1): p. 3490.
21. Wang, T., M. Wu, and Z.-Y. Yin, *Hydro-mechanical analysis of soil-structure interfaces considering surface roughness using a coupled CFD-DEM approach.* Powder Technology, 2026: p. 122485.
22. Liu, R., et al., *A novel theoretical approach to calculate critical normalized roughness Rcr at the soil-structure interface.* Computers and Geotechnics, 2025. **179**: p. 107033.
23. Francisca, F.M., et al., *Contaminant transport and fluid flow in soils.* Horizons in Earth Research. Nova Science Publishers, New York, 2012: p. 179-214.
24. Ruan, R., et al., *The role of soil pore structure on nitrate release from soil organic matter and applied fertilizer under three fertilization regimes.* Soil and Tillage Research, 2025. **248**: p. 106396.
25. Almuaythir, S., M.S.I. Zaini, and M. Hasan, *Shear strength, compressibility, and consolidation behaviour of expansive clay soil stabilized with lime and silica fume.* Scientific Reports, 2025. **15**(1): p. 26185.
26. Omo-Okoro, P., et al., *Soil pollution and its interrelation with interfacial chemistry.* Molecules, 2025. **30**(12): p. 2636.

27. Ma, C., et al., *Monovalent cation–anion pairing governs scaling and particulate fouling in saline water distribution systems: evidence from K^+-salt dosing.* Journal of Environmental Chemical Engineering, 2026: p. 122088.
28. Wani, T.I., et al., *Bentonite swelling behavior under physicochemical controls: A critical review on thermal–electrolytic conditions and mineralogical determinants for nuclear waste management.* Journal of Environmental Chemical Engineering, 2025: p. 120290.
29. Zhang, Y., L. Li, and B. Hu, *Experimental investigation and predictive model of entire suction range for undisturbed granite residual soil.* Scientific Reports, 2026.
30. Di Donna, A. and L. Laloui, *Response of soil subjected to thermal cyclic loading: experimental and constitutive study.* Engineering Geology, 2015. **190**: p. 65-76.
31. Hardenberg, M. and C. Vrettos, *Dynamic stiffness and damping of four compacted clays at different consistencies from resonant column tests.* Soil Dynamics and Earthquake Engineering, 2025. **196**: p. 109436.
32. Guo, H., et al., *Numerical simulation study on the force of overwintering foundation support structure of unsaturated seasonal permafrost under indoor experiments.* Royal Society Open Science, 2024. **11**(11): p. 240992.
33. Wang, L., et al., *A closed-form equation for effective stress of unsaturated saline clay considering capillary and osmosis effects.* International Journal of Geomechanics, 2024. **24**(6): p. 04024086.
34. Shan, X., et al., *Analysis of Factors and Mechanisms Influencing the Matric Suction and Water-Holding Capacity of Carbonate Saline Soil.* Water, 2025. **17**(4): p. 469.
35. Slatter, E., et al., *Investigation of suction generation in apparatus employing osmotic methods*, in *Unsaturated soils for Asia*. 2020, CRC Press. p. 297-302.
36. Niu, G., et al., *Investigation into the shear strength of a weakly expansive soil over a wide suction range.* Acta Geotechnica, 2024. **19**(5): p. 3059-3073.
37. Lin, G., et al., *Experimental investigation of chemical effects on the swelling properties and shear strength of expansive clay.* International Journal of Geomechanics, 2025. **25**(1): p. 04024329.
38. Washburn, E.W., *The dynamics of capillary flow.* Physical review, 1921. **17**(3): p. 273.
39. Palatnik, L., P. Cheremskoj, and M.Y. Fuks, *Pores in films.* 1982.
40. Hu, K., et al., *From micropores to macropores: Investigating pore characteristics of Longmaxi shale in the Sichuan Basin.* Energy & Fuels, 2024. **38**(5): p. 3961-3981.
41. Kodikara, J., S. Barbour, and D. Fredlund. *Changes in clay structure and behaviour due to wetting and drying*. in *Proceedings 8th Australia New Zealand conference on geomechanics: consolidating knowledge*. 1999. Australian Geomechanics Society.
42. Ning, W., et al., *Investigation of key morphological parameters of pores in different grades of asphalt mixture based on CT scanning technology.* Construction and Building Materials, 2024. **434**: p. 136770.
43. Zhang, J., et al., *Hydromechanical behaviour of expansive soils with different suctions and suction histories.* Canadian Geotechnical Journal, 2016. **53**(1): p. 1-13.
44. He, Y., K.-n. Zhang, and D.-y. Wu, *Experimental and modeling study of soil water retention curves of compacted bentonite considering salt solution effects.* Geofluids, 2019. **2019**(1): p. 4508603.
45. He, Y., et al., *Influence of pore fluid concentration on water retention properties of compacted GMZ01 bentonite.* Applied clay science, 2016. **129**: p. 131-141.

46. Thankam, N.S., V. Rekha, and U. Shankar, *Use of lateritic soil amended with bentonite as landfill liner.* Rasayan J Chem, 2017. **10**(4): p. 1431-1438.
47. Dehshiri, E., et al., *Impact of filter cake water chemistry on bentonite functionality and pellet quality in magnetite pelletizing.* Materials Chemistry and Physics, 2026: p. 132773.