

Prediction of Unsaturated Hydraulic Conductivity of Cement-stabilised Laterite Soil under Climate-Induced Wetting and Drying Cycles

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ABSTRACT

Climate change, characterised by rising temperatures and changing precipitation patterns, significantly impacts the geotechnical behaviour of soil. This includes alterations in soil's shear strength, compressibility, and permeability, which in turn affect soil structure and its ability to manage water absorption and retention. Increasing soil moisture can generally reduce permeability by filling finer pores and decreasing pore system connectivity. However, the impact of unsaturated conditions on the soil's permeability is often overlooked in design compared to saturated conditions. Hence, changes in temperature and rainfall patterns may affect water infiltration into the soil, potentially reducing groundwater recharge and increasing flood risks. Johor, Malaysia, has extensive tropical soil coverage (tropical region), which serves as the focus of this study. Hence, the research aims to elucidate how climate change influences both unstabilised and cement-stabilised laterite soils' permeability by conducting the falling head permeability tests to determine saturated hydraulic conductivity (k_{sat}), while unsaturated hydraulic conductivity (k_{unsat}) is derived using GeoStudio (SEEP/W) based on experimental data from soil-water characteristic curve (SWCC) and k_{sat} under varying matric suctions. Results indicate that both saturated and unsaturated conditions significantly affect the permeability coefficient of unstabilised and cement-stabilised laterite soils, with the substantial reduction in permeability largely attributed to the effect of saturation and stabiliser. Thus, predicting unsaturated permeability coefficients in the context of climate change is crucial for effective disaster management, as it will improve infrastructure design, enhance risk assessments, and support community preparedness, ultimately fostering more resilient societies capable of withstanding the challenges of a changing climate.

Keywords: *Climate change; saturated and unsaturated conditions; cement; permeability; disaster management*

INTRODUCTION

SOIL-WATER CHARACTERISTIC CURVE (SWCC)

The soil-water characteristic curve (SWCC) of soil describes the relationship between water content and suction within the soil. Water content quantifies the amount of water present in the soil pores, typically expressed as volumetric water content (θ) in soil science or gravimetric water content (w) in geotechnical engineering (the ratio of water mass to solid mass). Another commonly used term

is the degree of saturation (S_r), indicating the percentage of pore space filled with water. These variables are sometimes normalized relative to residual water content or zero water content, as described by Fredlund and Xing (1994) (Fredlund et al. 1994).

Due to hysteresis, the SWCC can be represented as either a drying (desorption or desaturation) curve or a wetting (sorption or saturation) curve. For simplicity in describing and measuring its features, the drying curve is typically used. A typical SWCC exhibits three distinct stages: the transition zone, the boundary effect zone, and

the residual zone. These stages are illustrated in Figure 1. The inflection point on the curve divides it into two key regions: the air entry value (AEV) suction and the residual conditions (residual suction or residual water content). The AEV indicates the suction at which air starts to enter the soil's largest voids. The suction corresponding to the residual moisture content is termed the residual suction value (RSV) or residual soil suction. Lu (2020) has defined the residual degree of saturation occurs when further increases in suction do not significantly displace more water, following the model proposed by Brooks and Corey (1964). In this research paper, the relationship defined by the SWCC has been utilised to estimate the unsaturated hydraulic conductivity.

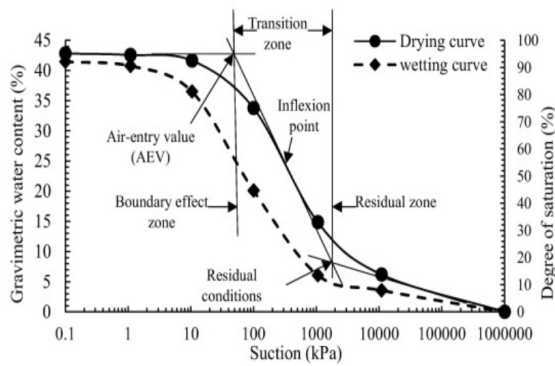


FIGURE 1. Typical SWCC of residual soil (Vanapalli et al. 1996)

The SWCC experimental data collected in the laboratory can be effectively represented by mathematical models. Among these, Equation 1, as proposed by Fredlund and Xing (1994) and incorporating three fitting parameters (a , n , and m), is distinguished by its flexibility and superior fitting accuracy (Leong & Rahardjo, 1998; Rahimi et al. 2015).

$$\theta(\psi) = \frac{\theta_s}{\left[\ln\left(e + \left(\frac{\psi}{a}\right)^n\right) \right]^m} \quad (1)$$

In this context, $\theta(\psi)$ represents the volumetric water content as a function of suction, where ψ denotes suction and e (approximately 2.718) is the base of the natural logarithm. The parameter a describes the suction value at the inflection point, while the parameter n is associated with the rate of change in the desaturation zone. Lastly, the parameter m is related to the asymmetry of the SWCC. In civil engineering practices, mostly matric suction is considered compared to total suction. A correction factor, as presented in Equation 2, has been introduced to adjust Equation 1 so that the water content approaches zero when

suction reaches 1,000,000 kPa. Here, $C(\psi)$ represents the correction factor related to suction, ψ denotes suction, and ψ_r refers to the residual suction.

$$C(\psi) = \left[1 - \frac{\ln\left(1 + \frac{\psi}{\psi_r}\right)}{\ln\left(1 + \frac{1000000}{\psi_r}\right)} \right] \quad (2)$$

SOIL PERMEABILITY

Soil permeability is crucial in various geotechnical applications, such as slope stability and seepage analysis, groundwater flow and contaminant transport, and the settlement and stability of earth structures. The permeability of unsaturated soils influences water infiltration during rainfall events, significantly impacting slope stability. Lower permeability can cause pore water pressures to build up, reducing the soil's shear strength and increasing the risk of slope failures. Generally, the permeability properties indicate the soil's ability to permit the passage of liquids, like water, and measure how quickly water can move through the soil. Permeability can be determined through laboratory tests, such as constant head and falling head tests, as well as in-situ field tests. Several factors influence soil permeability, including porosity and pore size distribution; generally, soils that are more porous with larger pore sizes exhibit higher permeability.

For saturated soil at a specific void ratio (or density), permeability remains nearly constant and can be measured directly or estimated using empirical methods, such as the pore-size distribution function. In contrast, for unsaturated soil, permeability depends on the volumetric water content (θ) or the degree of saturation (S_r). Generally, the permeability of unsaturated soil is determined experimentally, a process that requires significant time and specialised equipment. Alternatively, a model is commonly employed as an indirect method to predict the unsaturated permeability function from the saturated coefficient of permeability (k_{sat}) and the soil-water characteristic curve (SWCC).

Numerous prediction models (indirect method) have been proposed for estimating the permeability of unsaturated soils based on SWCC. In 1986, Mualem classified these prediction models into three categories: statistical, empirical, and macroscopic models (Zhai & Rahardjo, 2015). Among these, the statistical model is considered the most rigorous and yields the most accurate results (Zhai & Rahardjo, 2015). Hence, in Table 1, a brief discussion is provided of the various used methods for estimating the permeability of unsaturated soils.

TABLE 1. Various methods in estimating the permeability of unsaturated soils

Method	Descriptions	Research specimen	References
Experimental laboratory testing	It is a direct measurement of permeability in a laboratory setting. This involves measuring permeability concerning matric suction and volumetric water content.	Silt-sand soil	Nazari et al. (2018)
Modified triaxial equipment	A modified triaxial apparatus can be used to measure the permeability of unsaturated soils, assessing it as a function of matric suction and volumetric water content.	Compacted sand–kaolin	Goh et al. (2015)
Statistical analysis	This method employs a statistical model to derive the permeability function from the saturated coefficient of permeability and the soil-water characteristic curve (SWCC). The concept of SWCC is analogous to the pore-size distribution function, which is closely related to soil permeability.	Fine sand	Zhai & Rahardjo (2015)
Empirical analysis	Empirical models utilise soil texture and porosity to estimate soil permeability. This model employs statistical relationships between soil properties and permeability to predict permeability values.	Silty soil and clayey soil	Suharyatun et al. (2023)
Macroscopic analysis	Macroscopic models are employed to characterize soil behavior on a larger scale, emphasizing the average properties of the soil. These models are valuable for comprehending the overall soil behavior and forecasting its permeability.	Silicate sand and loamy sand	Tsakiroglou & Aggelopoulos (2013)

The coefficient of permeability in unsaturated soils (k_{unsat}) is not constant but varies with the volumetric water content, which is influenced by soil suction (ψ). This suction can either be matric suction or total suction (including matric suction and osmotic suction). Soil suction, a critical factor in the behavior of unsaturated soils, along with another stress state variable, governs their characteristics. Thus, it is recommended to use the term “permeability function for unsaturated soils” to describe the relationship between the coefficient of permeability and soil suction.

Several empirical methods/equations proposed by Burdine (1953), Mualem (1976), van Genuchten (1980), Fredlund and Xing (1994) and Leong and Rahardjo (1998) have been employed to forecast the permeability characteristics of unsaturated soils (Fattah et al. 2014; Gebru 2020; Nazari et al. 2018; Rahimi et al. 2015; Zhai & Rahardjo 2015; Y. Zhang & Schaap 2019). These approaches utilise both the k_{sat} and the SWCC specific to the soil. With advancements in equations defining the SWCC, more accurate predictions of the permeability function have emerged. Hence, in this research, the empirical equation of Fredlund and Xing (1994) has been considered due to extensive use by other researchers (Fredlund et al. 1994).

While a significant number of researchers have investigated soil permeability under unsaturated conditions, the majority of studies have focused on saturated conditions

(Behnood 2018; Mengue et al. 2017; Mousavi & Wong 2016; Samuel et al. 2019; Tsakiroglou & Aggelopoulos 2013; Y. Zhang & Schaap 2019). As a result, the body of research on unsaturated soil permeability remains limited. Furthermore, many of these studies have overlooked the coupling effect of saturation (suction) and bonding (stabiliser) in infrastructure design. Despite this, there are some studies available in the literature that address unsaturated soil permeability (Delage & Cui 2008; Gebru 2020; Goh et al. 2015; Lu & Likos 2006; Pandey et al. 2019; Rahimi et al. 2015; Zhai & Rahardjo 2015). Having considered both saturated and unsaturated conditions, therefore, this research paper examines the effect of suction and stabiliser on the soil's hydraulic conductivity (permeability).

Furthermore, studies that integrate experimental measurements with predictive approaches to estimate unsaturated hydraulic conductivity for cement-stabilised laterite soils are still limited. This knowledge gap restricts the ability to accurately evaluate the long-term hydraulic performance of stabilised subgrades exposed to changing climatic conditions. Therefore, this study seeks to address this gap by investigating the unsaturated hydraulic conductivity of cement-stabilised laterite soil through laboratory testing and predictive analysis under climate-induced wetting and drying conditions, thereby providing a better understanding of its hydraulic response for resilient geotechnical applications.

MATERIALS AND METHODS

RESEARCH MATERIALS

In this study, laterite specimens are obtained from Universiti Teknologi Malaysia in Johor Bahru, Johor, Malaysia. The physical properties of the soil are analysed through several laboratory tests, including wet sieving, particle sieve analysis, and Atterberg limit tests. For the mechanical properties, standard compaction, unconfined compressive strength (UCS), and pressure plate tests are conducted.

Meanwhile, for the soil stabiliser, Ordinary Portland Cement (OPC) CEM I 42.5 N provided by YTL Cement Bhd is employed. This cement is chosen for its high clinker content (95–100%), known to enhance the soil's strength (Joel & Mbapuan, 2016). Furthermore, the higher clinker percentage is anticipated to accelerate the attainment of desired strength levels.

RESEARCH METHODS

The main laboratory testing in this research is the pressure plate extractor. The principle of the pressure plate extractor is based on the method of axis translation. The test is performed using the pressure plate method according to

ASTM D 2325-68. The specimens for determining the Soil-Water Characteristic Curve (SWCC) can be prepared using three methods: slurry, compacted, and undisturbed (Fredlund & Zhang 2018). In this research, the specimens are prepared using the compacted method according to the obtained Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) into the rings with 20 mm height and 50 mm diameter, which is the same ring size used by Roshan et al. (2023). The influence of ring size on the pressure plate results is negligible; therefore, a small circular ring is chosen to reduce the equalisation time (Wen et al. 2015).

Next, the specimens are placed in a thermostatically controlled moisture humidity chamber for seven days, after compacting the calculated amount of soil inside the rings. The humidity chamber has been set to 25°C and 100% humidity, as suggested by Roshan et al. (2023). The specimens are then saturated before the test begins, which starts once they are fully saturated. This research uses a drying path with an air pressure range from 1 kPa to 900 kPa. Specimens are weighed after reaching suction equilibrium at each pressure increment. Finally, the specimens are oven-dried to determine the moisture content for each applied air pressure at the end of the test. Figure 2 provides a step-by-step illustration of the pressure plate test procedure.

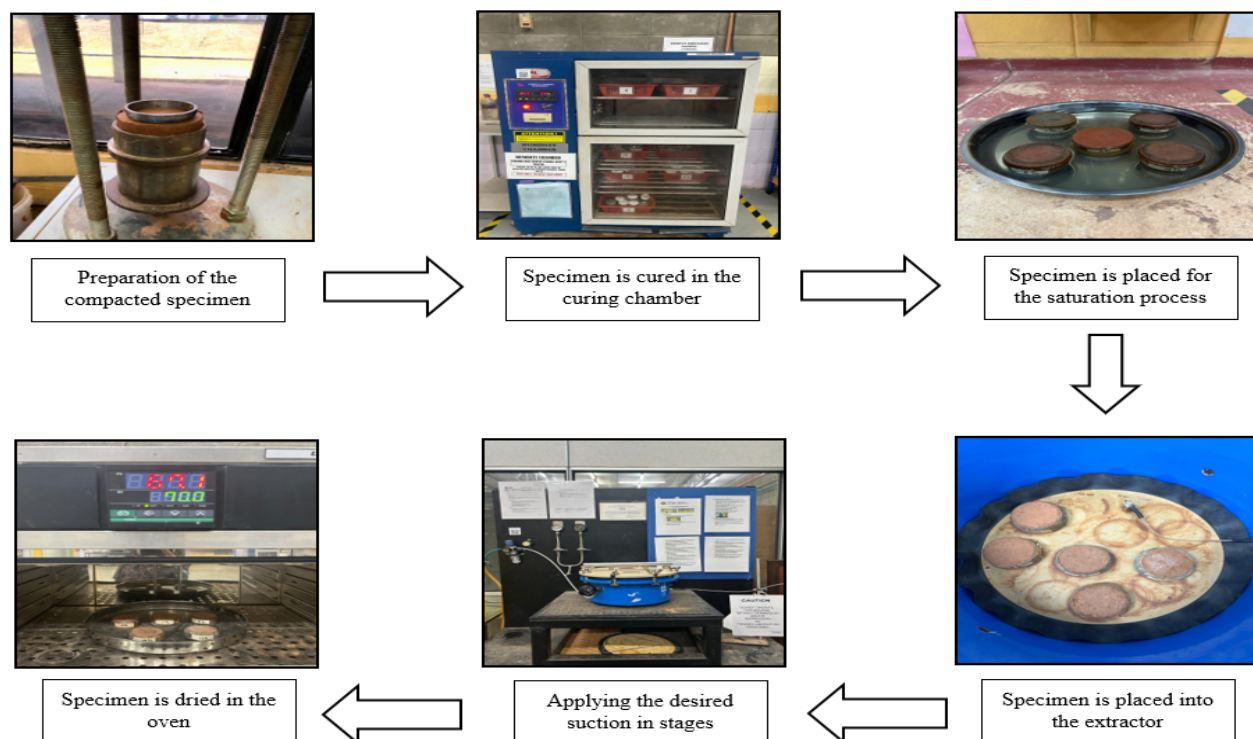


FIGURE 2. Pressure plate extractor testing procedure

SOFTWARE DEVELOPMENT

GeoStudio is an integrated software suite featuring multiple modules for analysing diverse geotechnical issues. It comprises eight main modules that can be utilised either independently or in combination to address a wide spectrum of geotechnical problems, including groundwater flow, slope stability, soil stress-strain behavior, and heat and mass transfer, including unsaturated soils. It enables users to model the behavior of unsaturated soils under different conditions, such as deformation, slope stability, and seepage. The software offers tools for defining the model domain, conducting multiple analyses simultaneously, and interpreting results with advanced visualisation preferences.

SEEP/W module has been extensively employed by various researchers in predicting/estimating the unsaturated soil's hydraulic conductivity including Al Siaede (2019); Rahardjo et al. (2019) and Pereira et al. (2021). It considers the effects of negative pore water pressures (matric suction) on hydraulic conductivity and flow in unsaturated soils. It includes tools to estimate the soil-water characteristic curve (SWCC) and hydraulic conductivity functions necessary for analysing unsaturated flow. These estimation routines enable users to define the hydraulic properties of the soil without the need for extensive laboratory testing. In unsaturated conditions, the SEEP/W module will be implemented which accommodates fluctuations in matric suction resulting from alterations in pore-water pressure, thereby deriving the unsaturated hydraulic conductivity function through automatic estimation based on the experimental data of saturated hydraulic conductivity and volumetric water content.

EMPIRICAL EQUATIONS

To describe how permeability varies with matric suction or volumetric water content, empirical equations are developed. These models/equations are based on laboratory test results and are entirely data driven. Various researchers have summarised the obtained data into functions or curves. These empirical equations are useful in engineering practice when measured data is available to describe the relationship between permeability and suction or degree of saturation. Below are some of the empirical equations commonly used in Table 2.

However, most proposed Soil-Water Characteristic Curve (SWCC) equations consist of two main issues. First, many equations become asymptotic to a horizontal line at low suction ranges, meaning the coefficient of water volume change relative to matric suction approaches zero (Gebru, 2020). Hence, using such equations in numerical modelling for low suction ranges can cause instability and is considered inaccurate. Second, many empirical equations approach an asymptotic horizontal water content line at high suctions, extending toward infinity beyond the residual condition, which is physically unreasonable (Gebru, 2020).

Therefore, these two issues have been addressed in the Fredlund and Xing (1994) equation, which provides a SWCC with a modest gradient in the low suction range. Additionally, by incorporating the correction function $C(\psi)$, the Fredlund and Xing (1994) equation ensures that soil suction approaches 1 GPa at zero water content, which overcoming the limitations of earlier models (Fredlund et al. 1994).

TABLE 2. Various empirical equations developed by various researchers

Functions	Researchers	References
$k = k_s$, for $\psi \leq \psi_{\text{aev}}$	Brooks and Corey (1964)	
$k_r = (\psi/\psi_{\text{aev}})^n$, for $\psi \geq \psi_{\text{aev}}$	Brooks and Corey (1964)	
$K = \bar{\Theta}^n$ where, $\bar{\Theta} = (\theta - \theta_r)/(\theta_s - \theta_r)$	Averjanov (1950)	
$K = K_s (\theta/\theta_s)^n$	Campbell (1973)	(Gebru, 2020)
$K = \exp [-\alpha(\psi - \psi_{\text{aev}})]$, for $\psi_{\text{aev}} \leq \psi \leq \psi_{\text{res}}$	Rijetma (1965)	
$\theta_w = C(\psi) \left(\frac{\theta_s}{\{\ln[\exp(1) + (\frac{\psi}{\alpha})^n]m\}} \right)$	Fredlund and Xing (1994)	

RESULTS AND DISCUSSIONS

SOIL CLASSIFICATION

Based on the results, the soil is classified as very high plasticity sandy silt (MV) according to the British Soil

Classification System (BSCS). It comprises 31% coarse grains and 69% fine grains, aligning with findings from previous researchers. Overall, Table 3 provides a summary of all the primary test results along with the standards that are followed.

TABLE 3. Various properties of unstabilised and cement-stabilised laterite soil

Soil properties		Results	Units	Test standards
Natural water content		40		BS EN ISO 17892-1:2014
Liquid limit		70		
Plastic limit		42		BS EN ISO 17892-12:2018
Plasticity index		28	%	
Gravel		13		
Sand		18		BS EN ISO 17892-4:2016
Silt		61		ISO:13320 (2009)
Clay		8		
Particle density	Laterite	2.74		
	3% cement-stabilised	2.76		
	6% cement-stabilised	2.77	g/cm³	BS EN ISO 17892-3:2015
	9% cement-stabilised	2.83		
	12% cement-stabilised	2.86		
	Optimum moisture content (OMC)	Laterite	28	
3% cement-stabilised		28		
6% cement-stabilised		30	%	
9% cement-stabilised		28		
12% cement-stabilised		33		BS 1377-4:1990
Maximum dry density (MDD)	Laterite	1.39		
	3% cement-stabilised	1.41		
	6% cement-stabilised	1.44	g/cm³	
	9% cement-stabilised	1.45		
	12% cement-stabilised	1.47		
7-days unconfined compressive strength (UCS)	Laterite	201		
	3% cement-stabilised	391		
	6% cement-stabilised	1233	kPa	BS EN ISO 17892-7:2017
	9% cement-stabilised	1738		
	12% cement-stabilised	1900		

SOIL-WATER CHARACTERISTIC CURVE (SWCC)

Table 4 presents the experimental data from the pressure plate extractor for laterite specimens stabilised with 0%, 3%, 6%, 9%, and 12% cement, and cured for 7 days. This curing period aligns with the guidelines set by the Malaysia Public Works Department for soil stabilisation techniques, as related to the curing age for unconfined compressive

strength (UCS) (Malaysia Public Work Department, 2018). As the cement dosages increase, the volumetric water content in the SWCC graph generally decreases. This reduction occurs because the higher cement dosage results in a denser soil structure with reduced total porosity, leading to fewer and smaller voids available for water retention.

TABLE 4. Experimental data points of volumetric water content for unstabilised and cement-stabilised laterite soil

Suction (kPa)	Volumetric water content				
	0%	3%	6%	9%	12%
0.1	0.5134	0.5192	0.5452	0.5661	0.5844
10	0.4943	0.5157	0.5327	0.5574	0.5742
50	0.4803	0.5062	0.5292	0.5561	0.5724
100	0.4663	0.4963	0.5253	0.5554	0.5709
200	0.4441	0.4726	0.5169	0.5526	0.5679
300	0.4339	0.4635	0.5067	0.5421	0.5592

continue...

...cont.

500	0.4184	0.4489	0.4754	0.5149	0.5396
700	0.3840	0.4143	0.4416	0.4808	0.5302
900	0.3361	0.3937	0.4102	0.4365	0.4927

Next, the obtained experimental data of volumetric water content is illustrated in graph image as shown in Figure 3. The volumetric water content decreases as the suction increase, indicating the water retention capacity of cement-stabilised soil generally improves. The increased suction levels result in greater water retention in smaller pores. Cement stabilisation alters the pore structure by enhancing the proportion of micropores capable of retaining water under suction (Roshan et al. 2023).

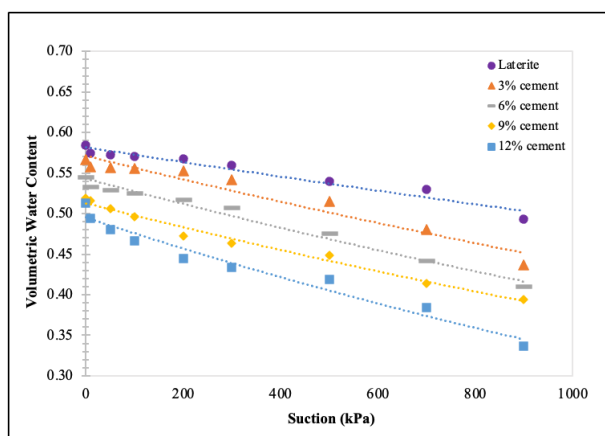


FIGURE 3. Graph of volumetric water content versus suction for unstabilised and cement-stabilised laterite soil

Cement improves the soil's capacity to retain water in smaller pores, leading to a steeper slope in the transition zone of the SWCC curve, as portrayed in Figure 4. Moreover, increasing the cement percentage generally leads to a reduction in volumetric water content in the SWCC graph. This occurs because of the decreased porosity, alterations in water retention behavior, and the effects of chemical shrinkage during hydration, all of which are due to increased suction (Nusit et al. 2017).

The obtained experimental data are then fitted using the Fredlund and Xing (1994) model as per Equation 1. The fitted curves show good agreement with the experimental data for both unstabilised and cement-stabilised soils. Unlike the SWCC of the sandy soil studied by Pujiastuti et al. (2018), the residual portion in Figure 4 spans a wider suction range (Pujiastuti et al. 2018). This can be attributed to the soil type; fine-grained soils like clay and stabilised soils have higher residual suction compared to the coarse soils.

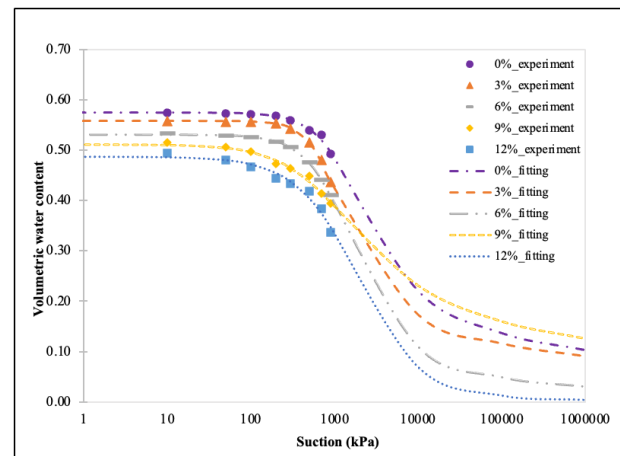


FIGURE 4. SWCC of obtained experimental data and measured/fitting data using Fredlund and Xing (1994) model

This experimental data is then analysed using SWCC solver to determine the fitting parameters for Fredlund and Xing (1994) model. The fitting parameters for the model are detailed in Table 5. The R^2 criteria serve as a measure for assessing the reliability of the linear regression equations obtained. High R^2 values, ranging from 0.9508 to 0.9876 (which is close to 1) suggest that the curves align closely with the measured data.

According to Fredlund and Vanapalli (2002), the residual suction for most soils is approximately 1500 kPa (Fredlund & Vanapalli, 2002). Hence, in this research, a residual suction (Ψ_r) of 1500 kPa is used to determine the correction factor based on Equation 2. This factor is then applied to Equation 1 to adjust the SWCC for zero water content at 1,000,000 kPa suction. Given that zero water content occurs at 1,000,000 kPa and the residual suction for most soils is around 1500 kPa (Fredlund & Rahardjo, 1993), the Fredlund and Xing (1994) model (refer Figure 4) is depicted.

Figure 5 shows the air entry value (AEV) with cement content, derived from the SWCC graph. The AEV of unstabilised soil is 190 kPa, increasing to 250 kPa, 290 kPa, 320 kPa, and 400 kPa for cement contents of 3%, 6%, 9%, and 12%, which is in agreement with findings by Alexander et al. (2020); Eyo et al. (2021); Eyo et al. (2022) and Roshan et al. (2023). The AEV increased with higher cement content, which is most probably due to a decrease in soil pore size with increasing cement content (Chen et al. 2024).

Besides, this AEV increment is attributable to the effect of stabilisation. This rise is due to the reduction in

pore size caused by the addition of cement. Ng and Pang (2000) identified that factors such as initial dry density, initial water content, soil structure, and drying and wetting history affect the SWCC (Ng & Pang, 2000). Thus, the observed increase in AEV with cement content in this study

can be attributed to changes in compaction results (MDD and OMC) and soil structure resulting from cement addition. These results are in line with findings from previous studies (Emery et al. 2020; Thudi, 2006; W. lu Zhang et al. 2018).

TABLE 5. Fitting parameters for Fredlund and Xing (1994) model

Soil type	Fredlund and Xing (1994)					
	Saturated volumetric water content	Fitting parameter related to the air entry value	Fitting parameter related to the maximum slope of the curve	Fitting parameter related to the curvature of the slope	Fitting parameter related to the residual suction of soil	Coefficient of determination
	θ_s	a	n	m	Ψ_r	R^2
Laterite	0.5134	1060.7491	1.7782	0.6932	1500	0.9542
3% cement-stabilised	0.5192	727.1526	2.4131	0.6371	1500	0.9508
6% cement-stabilised	0.5452	1031.4194	1.6802	1.1774	1500	0.9876
9% cement-stabilised	0.5661	566.5236	1.1488	0.6600	1500	0.9788
12% cement-stabilised	0.5844	1787.3324	1.9444	0.9360	1500	0.9542

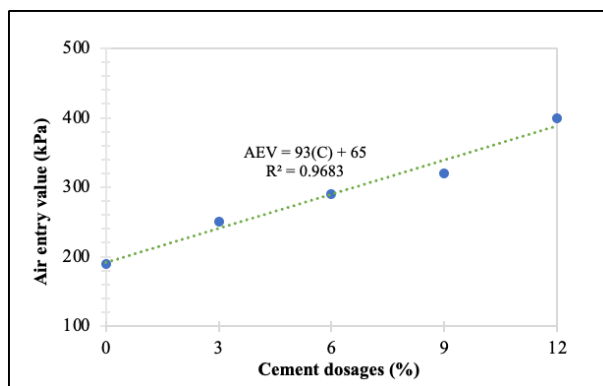


FIGURE 5. Graph of air entry value (kPa) versus cement dosages (%)

SOIL PERMEABILITY COEFFICIENT (SATURATED HYDRAULIC CONDUCTIVITY, K_{SAT})

Hydraulic conductivity refers to the soil's ability to permit water flow when subjected to a hydraulic gradient. Water flux through soil is influenced by the size and concentration of pores. Therefore, reducing the size of the pores is crucial to minimise water infiltration into the soil. This can be achieved through various techniques/methods, including soil compaction and soil stabilisation. In this research, laterite soil is stabilised with cement to enhance mechanical strength and reduce water infiltration, which is important for road infrastructure, slope stability, and ground liner systems.

The saturated permeability of both unstabilised and cement-stabilised laterite is measured through the falling head hydraulic conductivity test, due to the fine-grained nature of the laterite soil. The obtained saturated hydraulic conductivity coefficient (k_{sat}) in Figure 6 indicates a decrease in saturated hydraulic permeability with increased cement dosage, which is in line with research findings by Roshan et al. (2023) and Tran-Nguyen et al. (2023). The k_{sat} increase steadily from 7.89×10^{-10} m/s to 3.16×10^{-10} m/s, 1.76×10^{-10} m/s, 9.68×10^{-11} m/s, and 1.97×10^{-11} m/s, with the addition of 3%, 6%, 9%, and 12%, respectively. It is illustrated that the addition of cement to natural soil increases the bonding forces between soil grains through the production of hydration products (Chen et al. 2024; Consoli et al. 2021; Djelloul et al. 2017; Festugato et al. 2021; Ghadir & Ranjbar, 2018; Horpibulsuk et al. 2012; Imafidon et al. 2021; Joel & Agbede, 2011; Mengue et al. 2017, 2018; Oluremi et al. 2016, 2020; Roshan et al. 2022; Suddeepong et al. 2018; Wahab et al. 2021, 2024). Besides, the figure also demonstrates that water flow from the pores of unstabilised soil is significantly greater compared to cement-stabilised soil. Cement hydration gels reduce pore size and increase the bonding force between soil particles, thereby decreasing hydraulic conductivity (Ecay et al. 2020).

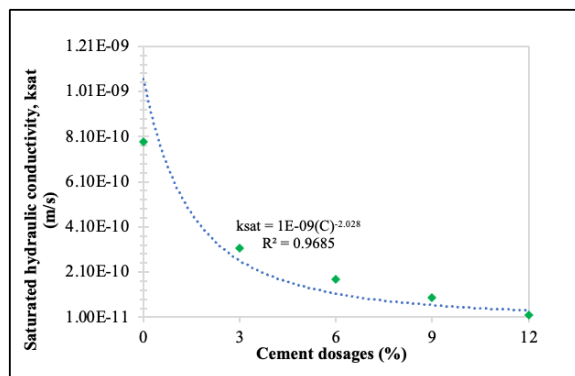


FIGURE 6. Graph of saturated hydraulic conductivity versus cement dosage

SOIL PERMEABILITY COEFFICIENT (UNSATURATED HYDRAULIC CONDUCTIVITY, K_{UNSAT})

As the cement content in a soil mixture increases, the unsaturated hydraulic conductivity (k_{unsat}) typically decreases, as illustrated in Figure 7. This is due to the denser soil structure resulting from higher cement dosage, which reduces both pore size and connectivity. As a result, water encounters greater resistance flowing through the smaller pores. Moreover, cement acts as a binding agent, enhancing particle cohesion and further decreasing the soil's porosity and permeability, leading to reduced hydraulic conductivity (Hassan 2009; Lade & Trads 2014; Razali & Che Malek 2019). The enhanced water retention and suction contribute to the overall stability of cement-stabilised soil, increasing its resilience under varying moisture conditions. In summary, increasing the cement content in soil generally decreases unsaturated hydraulic conductivity. This reduction is due to smaller pore sizes, greater binding, enhanced capillary effects, and structural changes from hydration. Understanding these factors is crucial for assessing the performance of cement-stabilized soils in engineering applications.

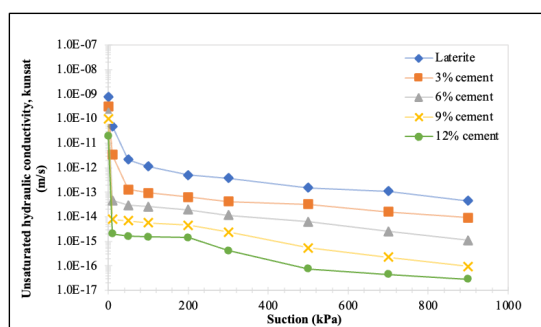


FIGURE 7. Graph of unsaturated hydraulic conductivity versus suction for unstabilised and cement-stabilized laterite soil

CONCLUSIONS

This paper offers a thorough analysis of the saturation and stabiliser's influence on the soil-water characteristic curve (SWCC) and permeability coefficient of laterite soil. The SWCC experimental data are obtained using the pressure plate extractor method along a drying path. These data are then fitted using Fredlund and Xing (1994) empirical models. Meanwhile, the saturated hydraulic conductivity (k_{sat}) is attained from the falling head permeability tests, while the unsaturated hydraulic conductivity (k_{unsat}) is derived using GeoStudio (SEEP/W module) based on the SWCC and k_{sat} experimental data. Based on the completed results, the following conclusions are deduced:

1. Using cement as a stabiliser has enhanced the SWCC of laterite soil. As a result, cement-stabilised laterite soil is suitable to be used in road pavement, railway construction, embankments, and slope stabilisation.
2. The SWCC results from this study can be implemented to calculate unsaturated hydraulic conductivity and to perform numerical modeling for both unstabilised and cement-stabilised lateritic soil.
3. The volumetric water content exhibited a consistent decrease with the addition of cement. Consequently, the SWCC of the stabilised specimens is positioned below that of the unstabilised specimens, indicating a lower water content in the stabilised lateritic soil at equivalent suction levels.
4. The air entry value (AEV) gradually increased from 190 kPa for untreated to 250, 290, 320, and 400 kPa for 3%, 6%, 9%, and 12% cement. This inclination trend indicates that the water infiltration and flow can be delayed and prevented when the laterite soil is stabilised by cement.
5. The observed increase in the air entry value (AEV) with higher cement content is attributed to the reduction in pore size. Thus, greater cement percentage requires more energy/matric suction to initiate the water removal from the soil pores.
6. The empirical models of Fredlund and Xing (1994) are used to fit the experimental data effectively for both unsaturated unstabilized and cement-stabilized lateritic soils. The model proposed by Fredlund and Xing (1994) has effectively fit both unsaturated unstabilised and cement-stabilised laterite soil, as evidenced by an R^2 value approaching 1.

7. GeoStudio (SEEP/W) software can be employed to determine the unsaturated permeability coefficient without extensive laboratory testing, significantly reducing the time required.
8. As cement is introduced, the overall pore size within the soil matrix decreases. This reduction in pore size limits the pathways available for water flow, leading to a lower saturated hydraulic conductivity.
9. With higher cement content, capillary rise and water retention in smaller pores become more pronounced. This effect can reduce the rate at which water moves through the soil, thereby decreasing unsaturated hydraulic conductivity.
10. Saturation is a critical factor in determining soil permeability. In saturated conditions, the pore spaces are fully occupied by water, providing uninterrupted flow paths. Conversely, in unsaturated conditions, the presence of air in the pore spaces disrupts these flow paths, resulting in reduced permeability.
11. The combined impact of saturation and cement stabilization leads to a significant reduction in the permeability coefficient of laterite soils. Saturated conditions ensure continuous flow paths, while cement stabilization decreases pore size and connectivity, resulting in a marked reduction in permeability.
12. Prolonged or intense rainfall may increase the degree of saturation and hydraulic conductivity, while higher temperatures and extended dry periods promote moisture loss, increase matric suction, and alter the unsaturated hydraulic behaviour of the soil.

In summary, predicting unsaturated permeability coefficients in the context of climate change can play a crucial role in enhancing disaster management strategies. This approach involves examining how soil and water interactions are influenced by shifting climate patterns, which is vital for effective risk assessment and mitigation. The unsaturated permeability coefficient is an essential parameter that describes water movement through soil when it is not fully saturated. Practically, incorporating predictions of unsaturated permeability into the design of infrastructure, such as drainage systems, buildings, and roads, can boost their resilience to extreme weather events. For instance, the saturated and unsaturated permeability coefficients results can be used to better understand how water infiltrates the ground. This knowledge allows stormwater management system designers to improve efficiency in their designs. As climate change leads to altered precipitation patterns and higher evaporation rates, forecasting these changes helps in managing water resources and maintaining soil stability both of which are vital during natural disasters like floods or landslides.

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DECLARATION OF COMPETING INTEREST

None.

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