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Soil Water Characteristics Curves (SWCC) of Residual Soils Stabilized using Emerging and Novel Bioinspired Technique

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ABSTRACT

The development of unsaturated soil mechanics stemmed from the inadequacies of classical soil mechanics in addressing the partial pore spaces found in real-world soil systems. However, assessing soil parameters under partial saturation is resource-intensive. To streamline this, the Soil-Water Characteristic Curve (SWCC) theory was introduced. Widely applied across geotechnical engineering, water resources, and agriculture, SWCC predicts parameters of unsaturated soil systems. In geotechnical engineering, SWCC is vital for designing systems near the Earth's surface, like slopes, clay liners and foundations. Furthermore, most of conventional soil improvement techniques pose a lot of environmental concerns. thus, emergence of green construction materials widely known as bio mediated and bioinspired soil improvement techniques like Enzymatic induced calcite precipitation (EICP). EICP, an emerging eco-friendly as it employs use of simply chemical compound that reduces carbon footprints, bioinspired technique as it mimics natural forming process, was applied to stabilize tropical soil for SWCC determination. SWCC parameters were derived by subjecting EICP-treated soils at varying concentration of cementation solutions (0 – 1.00 M) using pressure plate method. Results revealed that saturated water content θs, retention water content θr, and air entry value Ψa increased with higher cementation solution concentration. The values of θs, θr, and Ψa improved from of 0.663, 0.23405, and 3.4832 at 0 concentration of cementation solution to 0.701, 0.22864, and 7.7086, respectively upon treatment with 1.00 M cementation solution. Finally, it has been demonstrated EICP is capable of improving the SWCC parameters of residual soil, thus the EICP technique can be exploited in stabilization of residual for construction of compacted clay liner.

Keywords:
Soil water characteristics curve (SWCC); Enzymatic induced calcite precipitation (EICP); Soil stabilization

1. Introduction

The conceptual framework of unsaturated soil mechanics has been established for almost 30 years in order to address the problems associated with classical soil mechanics. In classical soil

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mechanics, laboratory experiments, analysis of geotechnical engineering structures, and studying the behaviour of soil were all based on the assumptions that soil systems are fully saturated [1]. The assumptions that soils are fully saturated in classical soil mechanics led inaccurate prediction of soil behaviour that could potentially compromise the integrity and safety of structures and soil systems [2]. Therefore. Unsaturated soil mechanics has become essential tool for determining behaviour of soils that are partially saturated, especially soil systems that situated in the vadose zone [3].

In comparison with the classical saturated soil mechanics, laboratory evaluations of soil parameters in unsaturated soil mechanics are expensive and labour intensive. However, the use of soil water characteristics curve make the analysis in unsaturated soil mechanics simpler and practicable [4]. Soil water characteristic curve or soil water retention curve (SWRC) is central in understanding and predicting behaviours of unsaturated soil systems. SWCC is a model for assessing and determining hydro-mechanical properties of unsaturated soils [5]. The concept of SWCC has been applied in the field of geotechnical engineering, water resources engineering, irrigation engineering, and agricultural science [6].

In geotechnical engineering, SWCC has been applied in the analysis and design of slope stability [7,8], seepage and infiltration in dams [9], compacted soil liners in landfills [10,11], capillary barrier systems [12], and bearing capacity of foundations [13]. SWCC is also important studying the existence and movement of soil water in predicting the hydrological cycle characteristics and runoff generation mechanism. Zhang *et al.,* [14] emphasis the significance of using SWCC as a tool for estimating hydrological parameters of runoff in pervious and impervious surfaces. SWCC measure the relationship between matric suction and volumetric water content of soils which are mostly applied to systems that are situated near ground surface or vadose zone [6]. Thus, the concept of SWCC is highly recommended in the study of the behaviour of both natural and stabilized unsaturated soils [6,15].

As stated above, SWCC are applied to near ground surface soil systems, therefore its values are likely to be influenced by parameters related to the soil [5] and environmental factors [15]. The parameters that are found to influence the shape SWCC as identified by [5] were soil structure, soil type, initial water content, void ratio, mineralogy, pore sizes and distribution, clay content, and amount of organic matter. The environmental factors that affect SWCC were identified by [15] are temperature, physicochemical factors such as pH, surface conductance and chemical stabilizers. Eyo *et al.,* [6] had also compiled the lists of various factors such as chemical stabilizers, soils types and suction measurements technique on the SWCC parameters. Based on their report, most (about two-third) of the studies investigated the effect of lime, while only one-sixth determined the influence of cement on SWCC parameters of various soil types.

Considering the adverse effect linked to cement production, such as carbon dioxide emissions, and the potential harm caused by chemical additives like acrylamide, epoxy resins, conventional methods of soil improvement are seen as environmental threats [16]. Consequently, research efforts are currently directed toward embracing eco-friendly and sustainable materials for soil improvement [17]. Among these advancements, enzymatic induced calcite precipitation (EICP) stands out as an emerging, inventive, and environmentally friendly bio-inspired approach for enhancing soil quality [18-20]. The technique involves decomposing urea via the application of urease enzyme to produce calcium carbonate ($CaCO_3$) in the presence of Ca^{2+} ion [21]. EICP technique has finds many applications in geotechnical engineering. The technique was applied in enhancing shear strength property of sandy soil [22], improvement of shear strength of compacted clay liner [23], erosion control [24], retention of heavy metals [25]. However, literature search, has shown a few or no record on the use of EICP technique for stabilizing residual soil in the field unsaturated soil mechanics. Therefore, this research is aim at investigating, the effect varying the concentration of cementation solution on the SWCC of residual soil stabilized via enzymatic induced calcite precipitation (EICP) technique.

2. Materials and Methods

2.1 Materials

2.1.1 Soils

This study was performed on natural and EICP stabilized residual tropical soil sampled at about 1.5 m deep from a location (1o33’35’’ N, 103o38’38’’E) at Universiti Teknologi Malaysia – Johor Campus. The sampling location has typical tropical rainforest climatic condition and the area is under lain by granite geologic formation. The sampled soil has reddish brown colour and was found to be dominated by kaolinite clay mineral.

2.1.2 EICP solution

The solution was prepared by first dissolving two chemical compounds, urea (CO(NH2)2), and calcium chloride (CaCl2) in distilled de-ionized water. Subsequently, free urease enzyme sourced from jack bean (Canavalia ensiformis) was then added to the dissolved mixture of urea-calcium chloride in order to catalysed the decomposition of urea into ammonia and carbon dioxide. The EICP solution, known as cementation solution were prepared at 0, 0.25, 0.5, 0.75 and 1.00 M equimolar concentration of CO(NH2)2 and CaCl2. The same procedure for the preparation of EICP solution was reported by [19].

2.2 Methods

2.2.1 Soil characterization and compaction test

Laboratory tests that include particle size distribution (PSD), Atterberg limits (Liquid Limit LL, Plastic Limit PL, and Linear Shrinkage SL) and specific gravity were performed on the natural residual soil in order to determine its index properties as well as classify the soil in accordance with the British Soil Classification System (BSCS). All the tests conducted for soil characterization were conducted based on the procedure enshrined in [26]. The compaction test performed on the natural residual soil was based on British Standard Light (BSL) as described in [27]. The index properties of the soil determined from the characterization tests and the result of compaction test are tabulated in the Table 1 below. As illustrated in the table, the original soil sample comprises 58% fines, approximately 24.16% gravel, and 17.16% sand fractions. The liquid limit, plastic limit, linear shrinkage limit, and plasticity index of the natural soil are recorded at 79, 30, 16, and 49, respectively. According to the British Standard Classification System (BSCS), the soil is categorized as sandy silts with very high plasticity (MVS). Additionally, a visual examination indicates that the soil possesses a fine-grained texture and exhibits a reddish-brown coloration.

Table 1
Index Properties of the Natural Soil

Property	Quantity
Natural Moisture Content (%)	32.72
Percentage Passing 63 µm Sieve (%)	58.00
Gravel Fraction (%)	16
Sand Fraction (%)	26
Silt Fraction (%)	52
Clay Fraction (%)	6
Liquid Limit (%)	79
Plastic Limit (%)	30
Plasticity Index (%)	49
Linear Shrinkage (%)	16
Specific Gravity	2.63
Loss on Ignition (LOI) (%)	12.28
BSCS Classification	MV (Silty Sand of Very High Plasticity)
Colour	Reddish Brown
Clay Minerals	Kaolinite
Maximum Dry Density (MDD) (Mg/m3)	1.48
Optimum Moisture Content (OMC) (%)	28

2.2.2 EICP treatment of the residual soil

The residual soils were treated with EICP solutions that are prepared at different molarity of urea-$CaCl_2$ of 0, 0.25, 0.50, 0.75 and 1.00 M. The EICP solutions were first prepared following the procedure described in section 2.1.2. The EICP solutions equivalent to water content at optimum moisture content were mixed with the dry residual soil and then compacted in a Proctor mould. SWCC samples (50 mm diameter and 20 mm height) were extruded from the compacted soil using static compaction machine. The SWCC were wrapped in polythene bags, and then cured for 3 days in humidity chamber operating under 25±2 ^{o}C.

2.2.3 Pressure plate test

Cured samples were immersed in distilled water for 24 hours to achieve saturation. Extractor plates were also saturated similarly. Saturated specimens were then placed in the extractor's plates and subjected to varying matric suctions from 1 to 1500 kPa. For each suction level, tests continued until sample outflow ceased (usually around 24 hours). The specimens were then removed, weighed to find gravimetric water content, and this was repeated until 1500 kPa suction. The test setup is shown in Figure 1. Finally, the specimens were dried at 105°C to determine dry weights for calculating volumetric water contents.

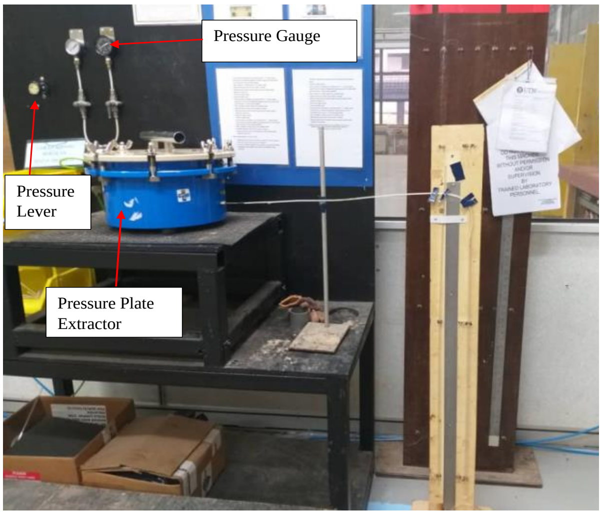


Fig. 1. SWCC Experimental Setup

3. Results and Discussion

3.1 Effect of EICP Treatment on Soil Water Characteristics Curve (SWCC)

Figure 2 shows the measured soil water characteristic curve (SWCC) for various EICP treated soils obtained by plotting volumetric water content against matric suction. As can be seen in the figure, SWCC plots of EICP treated residual soils were higher than that of untreated soil. The plots were also seen to become higher with the increase in the concentration of cementation solution. As explained by [28], soils with large particles and void spaces is plotted at lower position than those with smaller void spaces. In other words, soils with higher fine contents or less void spaces are plotted at higher position than those with less fine content or large number of void spaces [29]. Therefore, SWCC graph of untreated soil sample is plotted at lower position, followed by plots of 0.25 M, 0.50, 0.75 and 1.00 M in increasing order. Furthermore, some previous studies conducted by [30,31] reported similar trend of results. They all found that, SWCC graphs of specimen with higher fine content were plotted higher than those with less fine content.

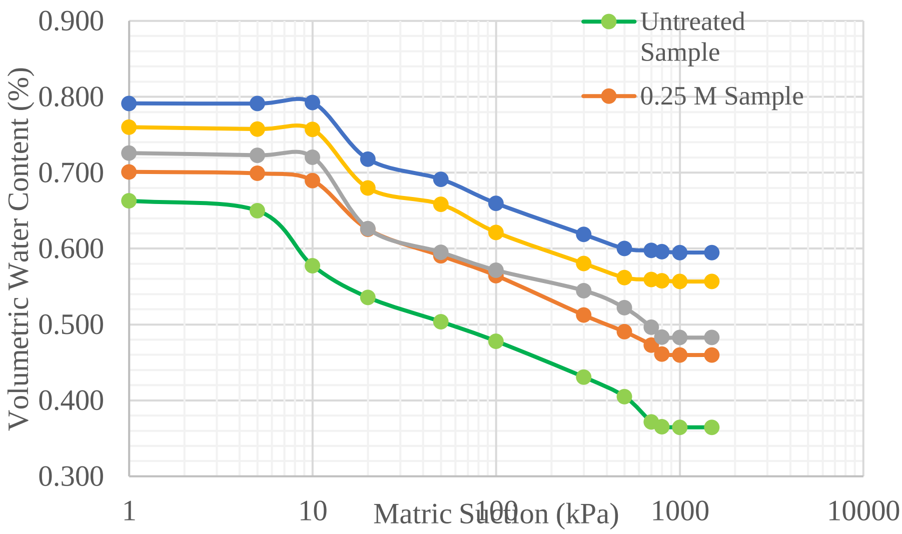
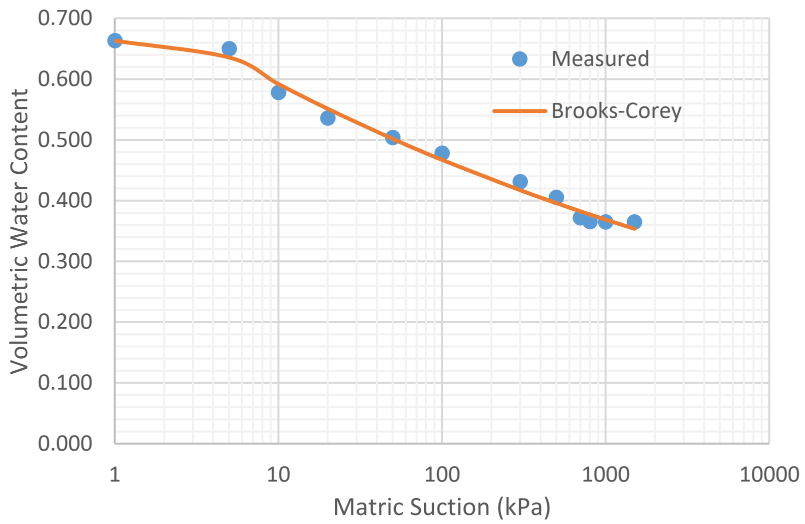


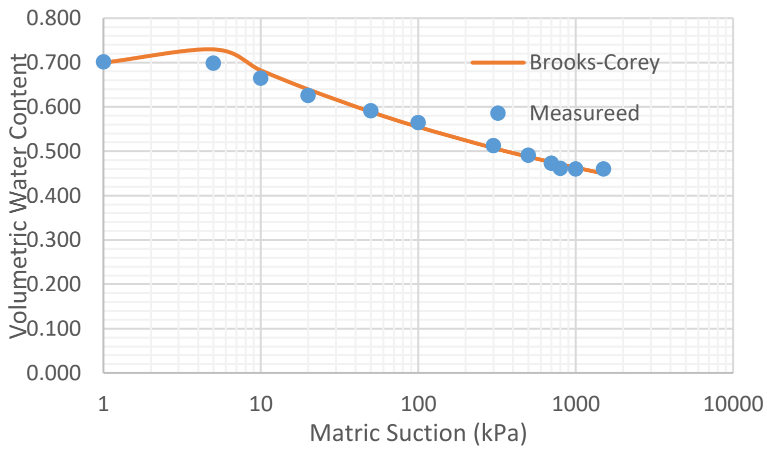
Fig. 2. Measured SWCC for Various EICP Treated Residual Soil

3.2 Brooks-Corey Model of Soil Water Characteristics Curve Parameters of EICP Treated Soils

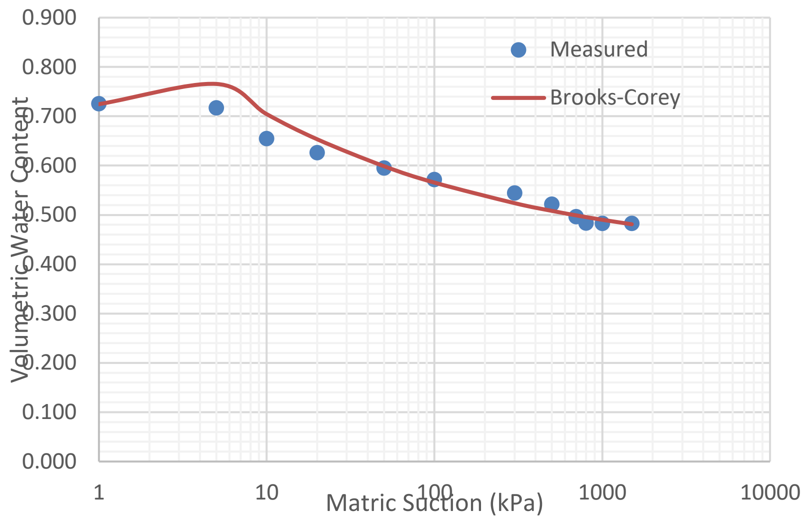
Various models are employed in practice to determine best fit of SWCC based on the laboratory measured values and also obtained fitting parameters. The most common models normally used for fitting SWCC plots include [32-34]. In this study "SWRC Fit" – a nonlinear web interface program written by [35] and accessed at https://seki.webmasters.gr.jp/swrc/ was adopted to determine the SWCC curve fitting parameters based on Brooks-Corey model. Figure 3(a-e) showed SWCC plots of the untreated and EICP treated residual soils at various concentration of cementation solution.



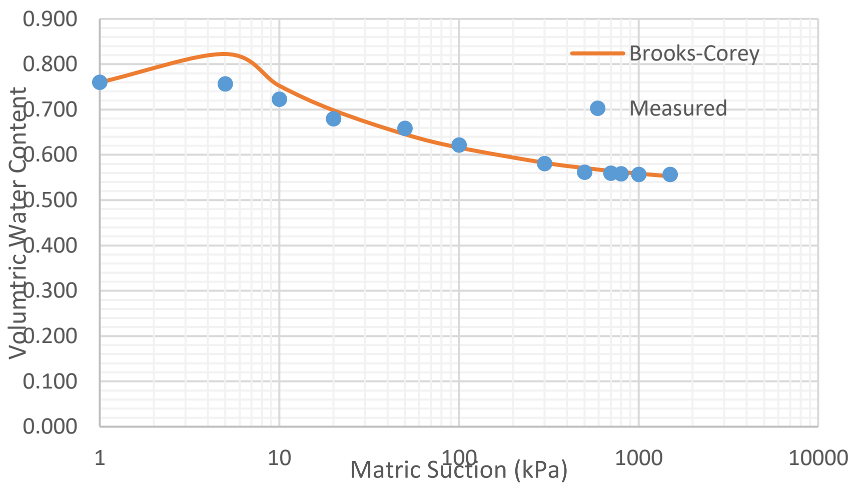
(a): Untreated



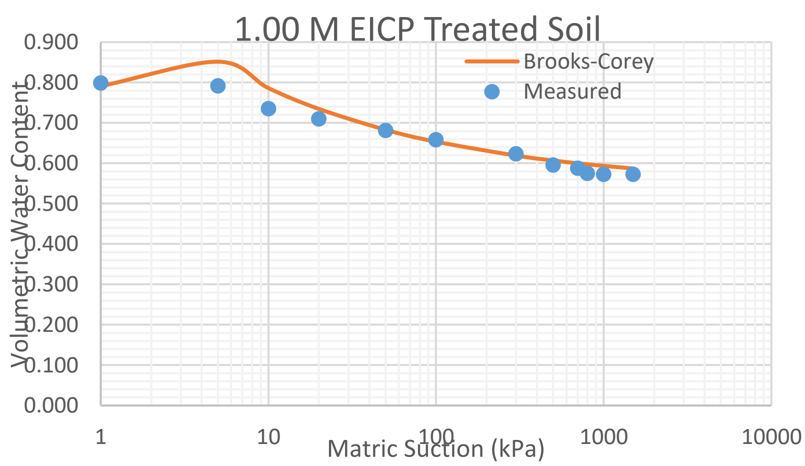
(b): 0.25 M EICP Treated Soil



(c): 0.50 M EICP Treated Soil



(d): 0.75 M EICP Treated Soil



(e): 1.00 M EICP Treated Soil

Fig. 3. SWCC Plots of Untreated and EICP Treated Soils at various Concentration

The fitting parameters for the Soil-Water Characteristic Curve (SWCC), namely the fully saturated volumetric water content (θs), the retention water content (θr), and the air entry value (Ψa), have been summarized in Table 2. Table 2 illustrates a consistent upward trend in the values of θs, θr, and Ψa as the concentration of the cementation solution increases. For example, untreated residual soils exhibited θs, θr, and Ψa values of 0.663, 0.23405, and 3.4832, respectively but following treatment with an EICP solution containing 0.25 M cementation, the corresponding values rose to 0.701, 0.22864, and 7.7086, respectively. The most pronounced increments in θs, θr, and Ψa were observed in soils treated with a 1.0 M EICP solution. The heightened values of θs, θr, and Ψa are attributed to the formation of cementitious matter (calcium carbonates) within the residual soil's matrix. Previous research has established that the creation of $CaCO_3$ particles due to EICP treatment leads to a reduction in pore spaces within the soil matrix [36], thus yielding an increase in θs, θr, and Ψa values. The findings presented in [37], demonstrate that the existence of $CaCO_3$ resulting from Microbially Induced Calcium Carbonate Precipitation (MICP) contributes to an increase in the saturated and retention water contents. They attributed the increase in saturated and retention water content to the formation of $CaCO_3$. Likewise, the detected rise in saturated and water retention capacity in soils treated with EICP in this study can be attributed to the formation of calcite precipitates. This increase signifies enhanced soil stability, thus reinforcing its structural integrity.

Regarding the rise in air entry values associated with the increase in cementation solution or, in an indirect sense, the precipitation of $CaCO_3$ in this study, a similar pattern of findings was observed in the research conducted by [38]. They investigated the influence of cement dosage on the Soil-Water Characteristic Curve (SWCC) of clay soil and arrived at analogous results.

Table 2
SWCC Fitting Parameters

Molarity of Cementation solution (M)	Measure SWCC Parameters		
	θ_s (%)	θ_r (%)	Ψ_a (kPa)
Untreated Soil	0.663	1E-10	3.3134
0.25	0.700	0.22864	7.7086
0.50	0.726	0.40044	7.8442
0.75	0.760	0.51684	9.1918
1.00	0.799	0.54423	9.4356

4. Conclusion

The impact of enzymatic induced calcite precipitation (EICP) bio cementation on the parameters of soil water characteristic curves (SWCC) in residual soils was examined. Five samples with different cementation concentrations – 0, 0.25, 0.50, 0.75, and 1.00 M urea-$CaCl_2$—were prepared and subjected to SWCC tests using a pressure plate apparatus. The results demonstrated that the presence of $CaCO_3$ resulting from EICP treatment significantly influenced the SWCC of the residual soil. Specifically, the formation of $CaCO_3$ led to heightened levels of saturated and retention water content, along with improvements in air entry values. Eventually, it has been proven that EICP has the ability to enhance the SWCC parameters of residual soil. Therefore, the utilization of the EICP technique can be employed in stabilizing residual soil for the construction of a compacted clay liner. Thus, it is imperative if research will be conducted on the use of EICP technique to improve hydraulic conductivity of residual soils for solid waste containment systems.

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References

[1] Fredlund, Delwyn G. "Unsaturated soil mechanics in engineering practice." *Journal of geotechnical and geoenvironmental engineering* 132, no. 3 (2006): 286-321. https://doi.org/10.1061/(ASCE)1090-0241(2006)132:3(286)

[2] Fredlund, Delwyn G. "Use of Unsaturated Soil Mechanics For Environmental Protection And Sustainability."

[3] Osinubi, K. J., and A. A. Bello. "Soil-water characteristics curves for reddish brown tropical soil." *Electron J Geotech Eng* 16, no. Bund. A (2011): 1-25.

[4] Aldaood, Abdulrahman, Marwen Bouasker, and Muzahim Al-Mukhtar. "Soil–water characteristic curve of lime treated gypseous soil." *Applied Clay Science* 102 (2014): 128-138. https://doi.org/10.1016/j.clay.2014.09.024

[5] Onyelowe, Kennedy C., Farid Fazel Mojtahedi, Sadra Azizi, Hisham A. Mahdi, Evangelin Ramani Sujatha, Ahmed M. Ebid, Ali Golaghaei Darzi, and Frank I. Aneke. "Innovative overview of SWRC application in modeling geotechnical engineering problems." *Designs* 6, no. 5 (2022): 69. https://doi.org/10.3390/designs6050069

[6] Eyo, Eyo Umo, Samson Ng'ambi, and Samuel Jonah Abbey. "An overview of soil–water characteristic curves of stabilised soils and their influential factors." *Journal of King Saud University-Engineering Sciences* 34, no. 1 (2022): 31-45. https://doi.org/10.1016/j.jksues.2020.07.013

[7] Peranić, Josip, Željko Arbanas, Sabatino Cuomo, and Matej Maček. "Soil-water characteristic curve of residual soil from a flysch rock mass." *Geofluids* 2018 (2018). https://doi.org/10.1155/2018/6297819

[8] Li, Dian-Qing, Lin Wang, Zi-Jun Cao, and Xiao-Hui Qi. "Reliability analysis of unsaturated slope stability considering SWCC model selection and parameter uncertainties." *Engineering Geology* 260 (2019): 105207. https://doi.org/10.1016/j.enggeo.2019.105207

[9] Thieu, N. T. M., M. D. Fredlund, D. G. Fredlund, and V. Q. Hung. "Seepage modeling in a saturated/unsaturated soil system." In *Proceedings of the international conference on management of the land and water resources, Hanoi, Vietnam*, pp. 20-22. 2001.

[10] Albrecht, Brian A., and Craig H. Benson. "Effect of desiccation on compacted natural clays." *Journal of Geotechnical and Geoenvironmental Engineering* 127, no. 1 (2001): 67-75. https://doi.org/10.1061/(ASCE)1090-0241(2001)127:1(67)

[11] Bahmani, Omid, and Mansure Bayram. "Investigating the hydraulic conductivity and soil characteristics under compaction and soil texture and performances as landfill liner." *Arabian Journal of Geosciences* 11, no. 16 (2018): 453. https://doi.org/10.1007/s12517-018-3817-7

[12] Tan, Sheng Hua, Shi Wei Wong, Du Jia Chin, Min Lee Lee, Ying Hui Ong, Siaw Yah Chong, and Azman Kassim. "Soil column infiltration tests on biomediated capillary barrier systems for mitigating rainfall-induced landslides." *Environmental earth sciences* 77 (2018): 1-13. https://doi.org/10.1007/s12665-018-7770-2

[13] Al-Hashemi, Hamzah M. Beakawi. "Estimation of SWCC for unsaturated soils and its application to design of shallow foundations." In *In Proceedings Of The 3rd World Congress On Civil, Structural, And Environmental Engineering (CSEE'18)*, pp. 1-18. 2018. https://doi.org/10.11159/icgre18.131

[14] Zhang, Pingnan, Gang Chen, Jinning Wu, Chuanhai Wang, Shiwei Zheng, Yue Yu, Youlin Li, and Xiaoning Li. "The Application and Improvement of Soil–Water Characteristic Curves through In Situ Monitoring Data in the Plains." *Water* 14, no. 24 (2022): 4012. https://doi.org/10.3390/w14244012

[15] Lin, Botao, and Amy B. Cerato. "Investigation on soil–water characteristic curves of untreated and stabilized highly clayey expansive soils." *Geotechnical and Geological Engineering* 30 (2012): 803-812. https://doi.org/10.1007/s10706-012-9499-0

[16] Karol, Reuben H. *Chemical grouting and soil stabilization, revised and expanded*. Crc Press, 2003. https://doi.org/10.1201/9780203911815

[17] DeJong, Jason T., Brina M. Mortensen, Brian C. Martinez, and Douglas C. Nelson. "Bio-mediated soil improvement." *Ecological engineering* 36, no. 2 (2010): 197-210. https://doi.org/10.1016/j.ecoleng.2008.12.029

[18] Rosa, Domenico, Lorenzo Verdirame, Irene Bavasso, Maria Paola Bracciale, and Luca Di Palma. "Soil Biocementation via Enzyme Induced Carbonate Precipitation (EICP) Method Employing Soybeans as a Source of Cheap Enzyme." *Chemical Engineering Transactions* 99 (2023): 157-162.

[19] Zango, Muttaqa Uba, Khairul Anuar Kassim, Kamarudin Ahmad, and Abubakar Sadiq Muhammed. "Improvement of strength behaviour of residual soil via enzymatically induced calcite precipitation." *International Journal of Geosynthetics and Ground Engineering* 7 (2021): 1-15. https://doi.org/10.1007/s40891-021-00323-5

[20] Zango, Muttaqa Uba, Khairul Anuar Kassim, Radzuan Sa'ari, Mohd Fadhli Abd Rashid, Abubakar Sadiq Muhammed, Kamarudin Ahmad, and Jodin Makinda. "Use of digital image technique to study leachate penetration in biocemented residual soil." *Materials Today: Proceedings* 48 (2022): 734-740. https://doi.org/10.1016/j.matpr.2021.02.211

[21] Almajed, Abdullah, Hamed Khodadadi Tirkolaei, and Edward Kavazanjian Jr. "Baseline investigation on enzyme-induced calcium carbonate precipitation." *Journal of Geotechnical and Geoenvironmental Engineering* 144, no. 11 (2018): 04018081. https://doi.org/10.1061/(ASCE)GT.1943-5606.0001973

[22] Muhammed, Abubakar Sadiq, Khairul Anuar Kassim, Muttaqa U. Zango, Kamarudin Ahmad, and Jodin Makinda. "Enhancing the strength of sandy soil through enzyme-induced calcite precipitation." *International Journal of Geosynthetics and Ground Engineering* 7, no. 2 (2021): 45. https://doi.org/10.1007/s40891-021-00289-4

[23] Zango, M. U., K. A. Kassim, A. S. Muhammed, K. Ahmad, and J. Makinda. "Effect of biocementation via enzymatic induced calcium carbonate precipitation (EICP) on the shear strength of compacted clay liner." In *IOP Conference Series: Materials Science and Engineering*, vol. 1153, no. 1, p. 012008. IOP Publishing, 2021. https://doi.org/10.1088/1757-899X/1153/1/012008

[24] Ossai, Rashidatu, Lucas Rivera, and Paola Bandini. "Experimental study to determine an EICP application method feasible for field treatment for soil erosion control." In *Geo-Congress 2020*, pp. 205-213. Reston, VA: American Society of Civil Engineers, 2020. https://doi.org/10.1061/9780784482834.023

[25] Moghal, Arif Ali Baig, Mohammed Abdul Lateef, Syed Abu Sayeed Mohammed, Kehinde Lemboye, Bhaskar CS Chittoori, and Abdullah Almajed. "Efficacy of enzymatically induced calcium carbonate precipitation in the retention of heavy metal ions." *Sustainability* 12, no. 17 (2020): 7019. https://doi.org/10.3390/su12177019

[26] British Standards Institution. *British standard methods of test for soils for civil engineering purposes*. British Standards Institution, (1990): 1–49.

[27] Standard, British. "BS 1377-4-1990, Methods of test for Soils for civil engineering purposes-Part4: Compaction-related tests." *London: UK: British Standard institute* (1990): 1–53

[28] Miller, Carol J., Nazli Yesiller, K. Yaldo, and S. Merayyan. "Impact of soil type and compaction conditions on soil water characteristic." *Journal of Geotechnical and Geoenvironmental Engineering* 128, no. 9 (2002): 733-742. https://doi.org/10.1061/(ASCE)1090-0241(2002)128:9(733)

[29] Yamusa, Yamusa Bello, Kamarudin Ahmad, Norhan Abd Rahman, Nor Zurairahetty Yunus, and Ahmad Rashida. "Volumetric shrinkage of compacted soil liner for sustainable waste landfill." *Chemical engineering transactions* 63 (2018): 613-618.

[30] Yamusa, Yamusa Bello, Muhammad Azril Hezmi, Kamarudin Ahmad, and Khairul Anuar Kassim. "Using soil water characteristic curve in computing unsaturated hydraulic conductivity of compacted tropical soil." *ARPN Journal of Engineering and Applied Sciences* 13, no. 17 (2018): 4765-4770.

[31] Osinubi, Kolawole J., and Agapitus Ahamefule Amadi. "Variations in soil water characteristic curves of lateritic soil treated with bentonite." In *Experimental and Applied Modeling of Unsaturated Soils*, pp. 88-95. 2010. https://doi.org/10.1061/41103(376)12

[32] Brooks, R. H. "Hydraulic properties of porous." *Media, In Hydrol. Pap.* 3 (1964): 1-27.

[33] Van Genuchten, M. Th. "A closed-form equation for predicting the hydraulic conductivity of unsaturated soils." *Soil science society of America journal* 44, no. 5 (1980): 892-898. https://doi.org/10.2136/sssaj1980.03615995004400050002x

[34] Fredlund, Delwyn G., and Anqing Xing. "Equations for the soil-water characteristic curve." *Canadian geotechnical journal* 31, no. 4 (1994): 521-532. https://doi.org/10.1139/t94-061

[35] Seki, Katsutoshi. "SWRC fit–a nonlinear fitting program with a water retention curve for soils having unimodal and bimodal pore structure." *Hydrology and Earth System Sciences Discussions* 4, no. 1 (2007): 407-437. https://doi.org/10.5194/hessd-4-407-2007

[36] Almajed, Abdullah, Husain Abbas, Mohamed Arab, Abdullah Alsabhan, Wagdi Hamid, and Yousef Al-Salloum. "Enzyme-Induced Carbonate Precipitation (EICP)-Based methods for ecofriendly stabilization of different types of natural sands." *Journal of Cleaner Production* 274 (2020): 122627. https://doi.org/10.1016/j.jclepro.2020.122627

[37] Tan, Sheng Hua, Shi Wei Wong, Du Jia Chin, Min Lee Lee, Ying Hui Ong, Siaw Yah Chong, and Azman Kassim. "Soil column infiltration tests on biomediated capillary barrier systems for mitigating rainfall-induced landslides." *Environmental earth sciences* 77 (2018): 1-13. https://doi.org/10.1007/s12665-018-7770-2

[38] Hoyos, L. R., H. R. Thudi, and A. J. Puppala. "Soil-water retention properties of cement treated clay." In *Problematic Soils and Rocks and In Situ Characterization*, pp. 1-8. 2007. https://doi.org/10.1061/40906(225)4