https://doi.org/10.32762/eygec.2025.37

SOIL WATER RETENTION CURVES AND THEIR IMPLICATIONS FOR GEOTECHNICAL ENGINEERING AND CORROSION OF BURIED INFRASTRUCTURE

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ABSTRACT

Understanding the soil-water interaction and its implications for engineering applications is essential for a wide range of fields, including geotechnical engineering and infrastructure corrosion. The soil water retention curve (SWRC), which describes the relationship between soil water content and suction, is a critical parameter for these applications. This study compares the SWRCs of different soil types, including sand, loam, and sandy loam, under both remoulded and undisturbed conditions, using two widely employed methods: the filter paper method and the modified evaporation method (Hyprop). Additionally, the research explores the impact of soil moisture on corrosion rates, particularly in kaolinite clay-sand mixtures, by examining the relationship between the Air Entry Value (AEV), Air Transition Point (ATP), and the moisture content. Remoulded and undisturbed samples were analysed for their SWRCs, with compacted samples prepared according to the Standard Proctor test (ASTM D698). The results reveal that the SWRCs for compacted soils showed minimal differences between the two methods, while undisturbed samples exhibited variations likely due to differences in dry densities. Furthermore, the study investigates how the fine structure of kaolinite clay influences moisture retention and corrosion behaviour, with steel coupons exposed to the kaolinite-sand mixture under optimal moisture conditions. The corrosion rates, assessed by weight loss method and SEM-EDX were linked to the moisture content and ATP, revealing that higher fine particle content in the soil led to increased moisture retention and enhanced corrosion risk for buried metal infrastructure. These findings highlight the importance of understanding SWRCs in both soil engineering and corrosion management, emphasizing the role of soil texture and moisture content in influencing soil behaviour and material degradation

Keywords: SWRCs, air transition point, weight loss, SEM-EDX.

INTRODUCTION

Soil suction is fundamental in understanding the mechanical behaviour of unsaturated soils. The functions of unsaturated soil and its hydraulic characteristics can be determined using Soil Water Characteristic Curves (SWCCs). These curves are particularly valuable in agricultural engineering for evaluating soil water storage, field capacity, and aggregate stability, and in geotechnical engineering to estimate slope stability and volume changes (collapse or swelling) due to rainfall. They also help assess the performance of pile foundations and buried pipelines susceptible to corrosion. (He et al., 2025; Rajkai et al., 2004 The SWRCs is describe correlation between soil suction (h) and volumetric soil water content (θ) (van Genuchten & Pachepsky, 2011). Multiple direct and indirect methods exist to measure SWRC. A key direct method is the axis-translation technique, which maintains pore-water pressure by artificially increasing atmospheric pressure. This controls negative pore pressure and defines matric suction as the difference (ua - uw). It is limited by the air-entry value of ceramic disks, typically up to 1500 kPa (Fredlund et al., n.d.-a). The filter paper (FP) method, developed by agronomists and soil scientists, involves placing a dry filter paper in contact with soil, allowing moisture exchange until equilibrium is reached. The filter paper's water content is then measured gravimetrically and converted to matric suction using a calibration curve per ASTM D 5298. This method covers a range up to 1500 kPa, making it suitable for fine-grained soils (Shwan, 2024) (Bicalho et al., n.d.; Collis-George, 1967; Khan et al., 2022a). For total suction, several indirect methods are used, such as relative humidity sensors, psychrometers, chilled mirror hygrometers, and the non-contact filter paper method. These estimate suction by correlating measured parameters like dew point or relative humidity. In the non-contact FP method, a dry filter paper is suspended above soil in an airtight chamber to achieve water vapor equilibrium. The air gap allows only vapor exchange, enabling total suction measurement. The filter paper's water content is then matched to suction using a calibration curve (Fredlund et al., n.d.-b). At equilibrium, the water content of the filter paper is quickly measured and linked to suction through a pre-calibrated curve. (KRAHN & FREDLUND, 1972).

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Soil suction can be measured through various approaches, each with distinct characteristics. (Ridley & Borland, 1993). This study investigates how SWRC transition points, particularly air-entry value and residual suction, affect corrosion in buried metals. By varying moisture content in kaolinite clay across saturated, transition, and residual zones, soil suction is correlated with electrochemical corrosion behaviour using mass loss data and SEM-EDX analysis.

MATERIALS AND EXPERIMENTAL METHODS

The kaolinite clay used in this study the Polwhite B China Clay from Imerys Kaolinite company is a premium, medium-sized particle derived from a deposit in the Southwest of England.

Table 1 *Physio-chemical properties of KC*

Properties	Value
Brightness ISO	82.5±1.0
Moisture (%)	1.5
pH	5.4
Specific Gravity	2.609
Water Soluble Salt Content (%)	0.15
Oil Absorption (g/100g)	38
SiO_2 (%)	47
Al_2O_3 (%)	37

The Kaolinite was mixed with silica sand at five different compositions (10%, 15%, 20%, 25%, and 30% KC by weight). The properties are shown in Table 1. The optimum moisture content was determined as per ASTM D 698, soil-water retention property were determined using both filter paper and Hyprop methods, the Whatman 42 ashless filter paper were used as per ASTM D 5298-03.(International & indexed by mero, 2010), the grain size distribution of the Kaolinite clay and Silica sand is shown in figure 1. with the resulting data modeled using the van Genuchten-Mualem VG (van Genuchten, 1980). in Equation 1.

$$\theta = \theta_{r^+} + \frac{\theta_s{}^+\theta_r}{[1+(\alpha|h|)^n]^m} \quad (1)$$

Where "θ" is the water content (L3 L-3), θ_r and θ_s are residual and saturated water content, α is the inverse of air entry value (L^{-1}), n and m are the curve fitting parameters, where m=1-1/n. The grain size distribution curve of kaolinite sand mixture is shown in Figure 1. The air entry value (AEV), described as the pressure head at which air initially starts to replace water in the largest soil pores, was determined from Van Genuchten model parameters α (AEV ≈ $1/\alpha$) [1]. For the electrochemical characterization the steel coupons (60mm*60mm*0.5mm) specimen were used. Ensuring the surface consistency of the steel coupons were sequentially grounded using sandpapers from 80 #, 240 #, 350 #, 400 #, 600 #, 800 #, 1000 # to 1200 #, grits. All steel coupons were thoroughly cleaned by ultrasonic cleaning in acetone and ethanol to remove surface contaminants and then air dried. Specimens were subsequently embedded in kaolinite and silica sand mixtures with varying kaolinite content (10, 15, 20, 25, 30% by dry weight of silica sand) was compacted to their respective optimum moisture content as per ASTM D698. (Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens, 2003) For the accuracy and reliability of the results each mixture contains two steel coupons specimen placed horizontally into the mixture. The prepared Steel coupons and their chemical composition are listed in Table 2.

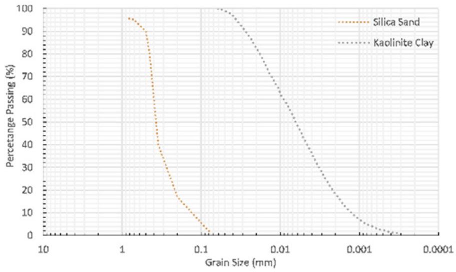

Figure 1 *Grain Size distribution curve of kaolinite and Silica sand*

Table 2 *Physio-chemical properties of KC*

Chemical Properties	Value (wt%)
C	0.025
P	0.03
S	0.02
Mn	0.25
Cr	17.58
Si	0.4
Ni	10.09
Fe	Bal

Following the corrosion testing period, the steel coupons were extracted from the kaolinite-silica sand mixture (10-30% kaolinite by weight) To systematically evaluate the corrosion damage, surface morphology analysis was performed using scanning electron microscopy (SEM) and Energy-dispersive spectroscopy (EDS) was subsequently conducted to quantify elemental distributions, with particular attention to iron oxidation products and potential clay-mineral interactions at the interface. This combined microstructural and compositional analysis revealed the corrosion mechanisms specific to the kaolinite-sand in controlled Laboratory environment.

The specimens were first gently brushed to remove the soil particles and were cleaned with ethanol to remove corrosion residues. After drying, they were immediately weighed using 4-digit analytical balance to determine the mass loss.

RESULT AND DISCUSSION

The SWRCs of kaolinite-silica sand mixtures (10-30% KC) obtained via FP and Hyprop methods showed consistent results. Increasing kaolinite content led to systematic changes in hydraulic properties shown in Figure 2. The measured air entry value (AEV) progressively increases from 1.731, 8.660, 17.886, 26.41, and 36.184 kPa in the boundary zone. The air transition point, where moisture retention shifts from capillary to adsorption, showed moisture content rising from 6.22% to 13.62%, moving toward the residual zone. These moisture shifts promote corrosion in steel, influenced by soil type. Furthermore, the results, as presented in Figure 3, demonstrate that steel specimens embedded in soil with 10% kaolinite content (KC) experienced a higher corrosion rate compared to those in 15%, 20%, 25%, and 30% KC. It indicates that while kaolinite content increases the corrosion resistance of the soil-steel system. The improvement may be attributed to the finer particle size and higher retention. The micromorphology and element content of corrosion product is evaluated by using Scanning Electron Microscopy equipped with Energy Dispersive X-ray analysis shown in Figure 4. The corrosion products formed small, densely packed agglomerates on the specimen, without significant voids.

The EDS analysis revealed that the formed corrosion residues predominantly consisted of ferrous (Fe), oxygen (O), and Silicon (Si). The reddish-brown corrosion products observed on the specimen were strongly suggesting the formation of ferric oxide (Fe_3O_3), as the dominant phase. Which is consistent with the characteristic coloration of this oxide. The presence of Si in the corrosion layer indicates incorporation from the 10% kaolinite clay ($Al_2Si_2O_5(OH)_4$) and 90% silica sand (SiO2) mixture elucidated the specific role of the clay-sand mixture in the corrosion mechanism.

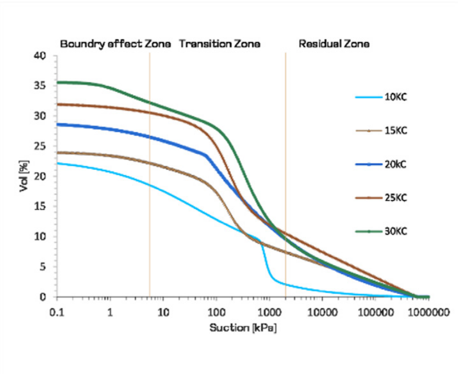

Figure 2 *SWRCs of Kaolinite sand mixture*

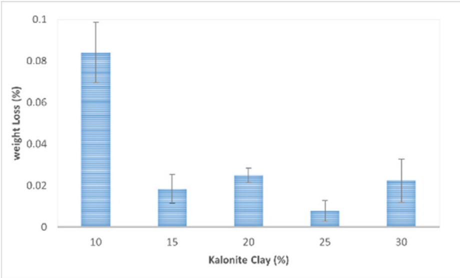

Figure 3 *Weight loss of steel specimen at varying KC percentage*

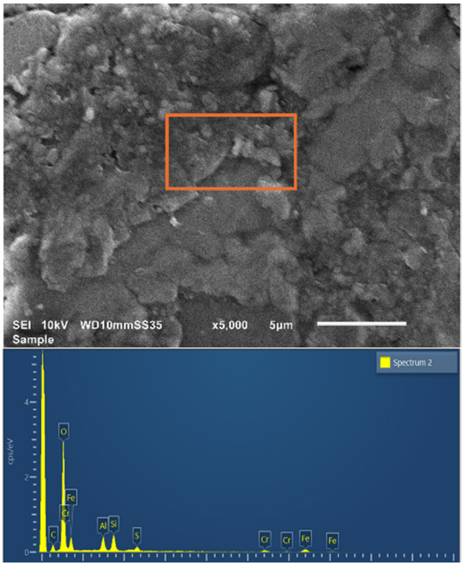

Figure 4 *Microstructure and element content of steel specimen*

CONCLUSION

This study systematically correlates kaolinite clay content (10-30% KC) in silica sand mixtures with evolving hydraulic properties and corrosion behaviour. SWRC analysis revealed a direct relationship between KC content and hydraulic parameters such as air entry values increased from 1.731 kPa (10% KC) to 36.184 kPa (30% KC), while the transition from capillary to adsorption-dominated moisture retention shifted from 6.22% to 13.62% water content. These hydraulic transitions create distinct electrochemical environments, with 10% KC mixtures exhibiting the most aggressive corrosion conditions. Microstructural characterization identified dense, void-free agglomerates of Fe_2O_3 as the primary corrosion product, with Si incorporation from the clay-sand matrix fundamentally modifying the oxide layer's protective properties. The inverse relationship between KC content and corrosion

rate demonstrates how soil composition directly governs steel degradation mechanisms, providing critical design parameters for infrastructure in clay-sand environments.

ACKNOWLEDGMENTS

The Author would like to Acknowledge the financial support provided by Higher Education Commission of Pakistan under (AHPB) Batch IV program. Special thanks are also extended to the BGGG-GBMS for the conference funding. The author would like to sincerely thanks Mr. Filip Van Boxstael, Mr. Maarten Volckaert, Mr. Pol Gryson, and Mr. Asif Ali for their expertise and valuable technical assistance and support during the laboratory work.

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