Jurnal Teknologi

Full Paper

IMPACT OF PHYSICAL CHARACTERISTICS AND MINERALOGY OF CLAY ON SWELLING BEHAVIOR

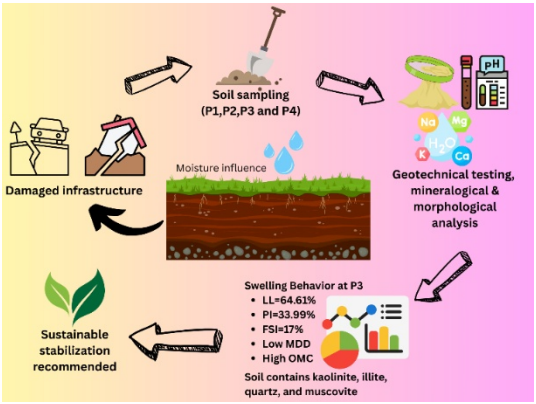
Bibi Zafirah Zaki[a], Nik Norsyahariati Nik Daud[a]*, Zulfarahim Hibadullah[b]

[a]Department of Civil Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia.
[b]Department of Civil Engineering, Politeknik Kota Bharu, 16450 Ketereh, Kelantan, Malaysia.

Article history
Received
20th August 2025
Received in revised form
18th November 2025
Accepted
1st December 2025
Published
1st November 2026

*Corresponding author
niknor@upm.edu.my

Graphical abstract



Abstract

Expansive soils, known for their considerable changes in volume resulting from moisture variations, present major challenges to geotechnical engineering, particularly in semi-arid environments. This study presents a detailed investigation into the geotechnical behavior, mineralogical composition, and morphological features of expansive soils sampled from a paddy field. Four subsurface samples (P1–P4) were extracted at a uniform depth of 1.3 meters. Post-collection, the samples were oven-dried and passed through a 0.425 mm sieve to standardize the material for testing. XRD analysis identified kaolinite, illite, quartz, and muscovite as dominant mineral constituents. XRF showed major components were silicon dioxide (51.93%), iron oxide (20.87%) and aluminum oxide (18.03%), indicating clay presence. SEM analysis revealed a porous microstructure with irregular, platy clay particles forming interconnected networks, affecting water absorption. Sample P3 exhibited the highest expansive potential, with a liquid limit of 64.61%, a plasticity index of 33.99%, and a free swell index of 17%. A low maximum dry density (1.175 g/cm³) and specific gravity (2.26) in P3 suggest a fine-grained matrix with a high proportion of clay minerals. P4 had high optimum moisture content (29%) due to silt-clay and coarse particles. Soils shrinkage 10.49-11.42% upon drying. Swelling potential varied from 10% (P2) to 17% (P3), likely due to differences in clay minerals. The findings underscore the role of mineralogy and moisture sensitivity in the swelling behavior of expansive soils and highlight the need for sustainable stabilization strategies employing environmentally benign additives.

Keywords: Expansive soil, swelling, shrinking, geotechnical properties, mineralogical and morphological characteristics

Abstrak

Tanah ekspansif yang terkenal dengan perubahan besar dalam isipadunya yang terhasil daripada variasi lembapan, memberikan cabaran utama kepada kejuruteraan geoteknik, terutamanya dalam persekitaran separa gersang. Kajian ini membentangkan penyiasatan terperinci tentang tingkah laku geoteknik, komposisi mineralogi, dan ciri morfologi tanah ekspansif yang diambil daripada sawah padi. Empat sampel bawah permukaan (P1–P4) telah diekstrak pada kedalaman seragam 1.3 meter. Selepas pengumpulan, sampel telah dikeringkan dengan ketuhar dan melalui penapis 0.425 mm untuk menyeragamkan bahan untuk ujian. Analisis XRD mengenal pasti kaolinit, illit, kuarza, dan muscovit

DOI: https://doi.org/10.11113/jurnalteknologi.v88.25465

sebagai juzuk mineral yang dominan. XRF menunjukkan komponen utama ialah silikon dioksida (51.93%), oksida besi (20.87%) dan aluminium oksida (18.03%), menunjukkan kehadiran tanah liat. Analisis SEM mendedahkan struktur mikro berliang dengan zarah tanah liat yang tidak teratur membentuk rangkaian yang saling berkaitan, menjejaskan penyerapan air. Sampel P3 mempamerkan potensi ekspansif tertinggi, dengan had cecair sebanyak 64.61%, indeks keplastikan sebanyak 33.99%, dan indeks bengkak bebas sebanyak 17%. Ketumpatan kering maksimum yang rendah (1.175 g/cm³) dan graviti tentu (2.26) dalam P3 mencadangkan matriks berbutir halus dengan perkadaran mineral tanah liat yang tinggi. P4 mempunyai kandungan lembapan optimum yang tinggi (29%) disebabkan oleh tanah liat kelodak dan zarah kasar. Tanah mengecut 10.49-11.42% semasa pengeringan. Potensi bengkak berbeza-beza daripada 10% (P2) hingga 17% (P3), berkemungkinan disebabkan oleh perbezaan dalam mineral tanah liat. Penemuan ini menggariskan peranan mineralogi dan kepekaan lembapan dalam tingkah laku pembengkakan tanah yang luas dan menyerlahkan keperluan untuk strategi penstabilan mampan menggunakan bahan tambahan jinak alam sekitar.

***Kata kunci*:** Tanah ekspansif, Bengkak, Mengecut, Sifat geoteknik, Ciri-ciri mineral dan morfologi

©2026 Penerbit UTM Press. All rights reserved

1.0 INTRODUCTION

Expansive soils, known as swell-and-shrink soils which exhibit notable volume instability in response to moisture fluctuations or partial saturation, a phenomenon attributed to their high content of specific clay minerals or active chemical processes [1]. The potential for a soil to shrink or swell is influenced by a combination of factors. These include the soil's initial moisture content, its internal structure, void ratio, overburden stresses, and the existence of type and quantity of clay minerals [2]. Commonly found in semiarid regions, these soils often cause severe structural damage, particularly affecting foundations and pavements due to their expansive nature [3].

Expansive soils are a major geotechnical challenge, especially in paddy fields. Their tendency to shrink and swell with moisture changes, combined with low strength, causes significant damage to infrastructure. This is often exacerbated by a failure to properly assess the soil's swelling potential [4,5]. Additionally, the differential movement caused by swelling and shrinking can undermine the stability of both shallow and deep foundations, potentially cause structural damage or lead to costly repairs [6,7]. To address these issues effectively, understanding the geotechnical properties of expansive soils in paddy fields is crucial. Proper identification and classification of these soils are essential for designing engineering solutions that account for their unique shrink-swell characteristics, ensuring sustainable soil infrastructure [8,9].

Early detection of reactive or expansive soils during the initial stages of a site investigation is of paramount importance to ensure proper geotechnical planning and risk mitigation. This process often involves physical tests such as Atterberg limits, potential volume change, and free swell index tests [9]. Swelling potential can also be estimated indirectly using factors like plasticity, clay particle size distribution, and activity parameters [8]. A classification summary, as outlined in Table 1 [3] provides a classification for expansive soils according to their swell potential and correlating it with index properties such as liquid limit, plasticity index, and shrinkage. By determining the liquid limit, plasticity index, and shrinkage of a soil sample, these table could be used to estimate its swell potential. Asuri and Keshavamurthy [6] suggested two key approaches for identifying expandable clay structures in such soils: inferential testing and mineral identification. The inferential evaluation of soil properties involves a combination of direct and indirect methodologies. Direct methods, such as those for determining liquid limits and particle size distribution, provide fundamental data. In contrast, indirect techniques like the free swell tests and oedometer test are utilized to assess soil behaviour. Furthermore, advanced analytical tools, including X-ray diffraction (XRD), differential thermal analysis (DTA), dye adsorption, and scanning electron microscopy (SEM), are critical for the precise identification of mineralogical components, which directly informs our understanding of the soil's composition and performance.

Table 1 The classification of expansive soil

Swell potential	Liquid limit (%)	Plasticity index (%)	Shrinkage (%)
Low	20 - 35	< 18	> 15
Medium	35 - 50	15 - 28	10 - 15
High	50 - 70	25 - 41	7 - 12
Very high	> 70	> 35	< 11

DOI: https://doi.org/10.11113/jurnalteknologi.v88.25465

The potential for soil to swell varies depending on its mineral composition. Some minerals, like montmorillonite, illite, nontronite, chlorite, and vermiculite, increase swelling. Conversely, minerals like quartz and calcite reduce swelling. More clay in the soil also leads to greater swelling and better water absorption. Evaluation of swelling in expansive soils mainly focuses on clay minerals, particularly kaolinite, illite, and montmorillonite. Smectites, which are related to minerals like quartz and kaolinite, are common, while as a highly prevalent mineral in the Earth's crust, kaolinite can be formed through either primary geological processes or the secondary alteration of other minerals [7, 10-17]. The structure of kaolinite consists of stacked layers, with each layer containing a sheet of silica and a sheet of alumina. Between these sheets, there is a shared layer of oxygen atoms. Kaolin and halloysite clays are formed from the chemical weathering of alumina-silicates. To create minerals like kaolin, a low ratio of silica to alumina is necessary. Kaolinite is the lowest expansive of the three common clay minerals due to its structure containing stable potassium (K+) ions [5]. This mineral also possesses strong interlayer forces that enable it to resist expansion when exposed to moisture [18,19].

The illite mineral consists of alternating layers of alumina and silica. It exhibits greater swelling and shrinkage compared to kaolinite due to its higher capacity to absorb water. Montmorillonite has a similar layered structure as illite. Illite also contains K+ ions in its interlayer spaces, which further decreases its expansiveness [5]. Additionally, illite possesses a significantly lower cation exchange capacity compared to montmorillonite [20]. The phenomenon is attributed to the constrained interlayer space and the fixed coordination of small potassium ions (K+) within the ditrigonal cavities of the tetrahedral sheet's surface structure [21]. Therefore, the expansiveness of clay minerals varies significantly, with montmorillonite being the most expansive due to its weak interlayer bonding and high cation exchange capacity. This is followed by illite, which has limited expandability due to potassium ions binding its layers, and finally kaolinite, which is non-expansive due to strong hydrogen bonding between its 1:1 layer [5], where it shows the mineral expansiveness order is Montmorillonite > Illite > Kaolinite. As the predominant silica polymorph in natural environments, quartz constitutes a prevalent mineralogical component across a diverse of magmatic, metamorphic, and sedimentary lithologies. Furthermore, quartz serves as a significant economic source of silica raw material. Quartz is among the pure minerals, yet even minor impurities and defects can hold significant relevance and provide valuable insights, especially about the mineral's origin. The mineral like quartz with the chemical formula of SiO_2, occurring in two natural forms. The most common and significant variety of quartz is trigonal, low-temperature alpha-quartz, a form that remains stable at the Earth's surface [22].

The objectives of this study are 1) To characterize the physical properties, mineralogical and morphological characteristics of the expansive soil. 2) To examine the relationship between the swelling behavior of expansive soil and its physical, mineralogical, and morphological characteristics. 3) To evaluate the impact of moisture content and plasticity on the expansive behavior of the soil.

2.0 MATERIALS AND METHODS

Samples collection

Soil samples in this study were sourced from a paddy field situated in Ladang Merdeka Mulong, Kota Bharu, Kelantan, which is in the northeastern part of Peninsular Malaysia as shown in Figure 1. Geological map showing that the collected soil samples involved in this study included a mixture of clay, silt, sand, and gravel, which are typical components of expansive soils.

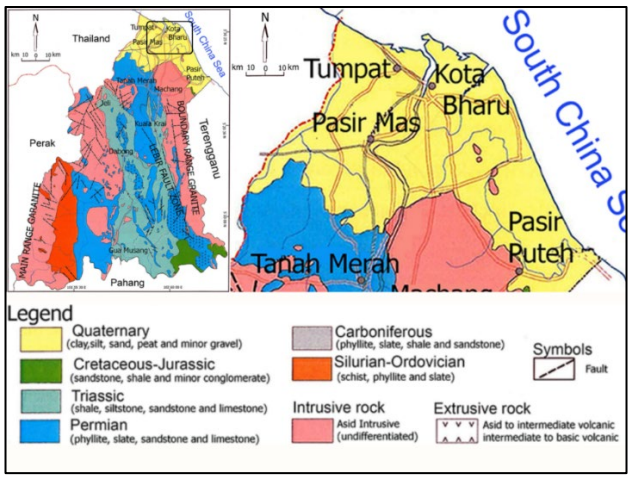


Figure 1 Geological map of Kota Bharu, Kelantan, Malaysia

According to Rezaee et al. [23], the area of paddy soil being classified as expansive soil which can undergo significant volume changes when subjected to moisture fluctuations. Disturbed soil samples were taken at 1.3 meters from the ground surface in accordance with BS 5930:1999.



Figure 2 Map of sampling points

DOI: https://doi.org/10.11113/jurnalteknologi.v88.25465

Samples preparation

The collected soil samples were dried in an oven for 24 hours at 110°C to remove their moisture content, following the procedure outlined in BS 1377:1990. This step ensures that the results from subsequent tests are not influenced by moisture variability. After drying, the soil samples were sieving using a 0.425 mm sieve as shown in Figure 3 to remove any large particles and ensure uniformity for geotechnical tests. All four soil samples (P1, P2, P3 and P4) exhibit a general light brown to tan color, though sample at P1 appears to have a slightly darker or more yellowish while sample at P4 appears a light grey color. Texturally, samples at P1, P2 and P3 are composed of fine particles which is silty or clayey composition with a relatively uniform appearance, whereas sample P4 appears as a clay which cohesive, massive or cracked mass with very fine particles.



Figure 3 Sample of soils at different sampling points

Testing program

X-ray Fluorescence (XRF)

X-ray Fluorescence (XRF) was executed to measure the elemental composition of the soil. XRF helps to quantify the concentration of various elements by using Shimadzu EDX-720. The soil samples were oven-dried and then were ground using a grinding machine for two minutes to achieve a fine powder. The powdered material was passed through a 0.075 mm sieve to ensure homogeneity and minimize particle size effects for the XRF analysis.

X-ray Diffraction (XRD)

X-ray Diffraction (XRD) analysis was carried out with a Rigaku SmartLab X-ray Diffractometer to precisely characterize the mineral composition, chemical composition, and crystalline structure of the soil samples. The soil samples underwent X-ray Diffraction (XRD) analysis utilizing a Cu-Ka radiation source. The experimental conditions included an operating voltage of 40 kV and a current of 100 mA. Data was collected over a 2θ range from 5° to 45°, with the diffraction intensity patterns recorded in counts. The diffractometer generated a mineral diffraction pattern where each mineral phase was identified by the angles and intensities of the refracted X-ray beams which corresponding to specific 2θ spacings [25]. The four sampling points are located seemingly in a uniform environment such as the same field, similar topography, no significant human disturbance variations. This could be assumed that their underlying mineralogy wouldn't drastically differ.

Field Emission Scanning Electron Microscopy (FESEM)

FESEM-EDX was implemented to study the microstructure and surface morphology of the soil particles at high resolution. FESEM allows for the observation of fine details such as particle size, shape, and aggregation, while EDX provides elemental composition analysis at the microscopic scale by using the FEI Nova NanoSEM 230 and Oxford Instruments Max 20. FESEM analysis was used to provide detailed microstructural images of the soil, while the coupled EDX system enabled localized elemental analysis. According to Selvakumar et al. [24], soil samples were mounted on FESEM stubs and then sputter-coated with a thin layer of gold. This was done to improve electrical conductivity and prevent charging artifacts during scanning electron microscopy.

Physical and Chemical Properties

In accordance with British Standard Method (BS 1377:1990), various tests were performed on the soils. These tests including particle size distribution, Atterberg limits, moisture content, linear shrinkage, and pH test, were used to evaluate the soil's geotechnical behavior. Particle size distribution was conducted to determine the relative proportions of sand, silt, and clay in the soil by using the Endecotts EFL 2000 Sieve Shaker Machine. The Atterberg limits were carried out to assess the plasticity of soil, specifically its liquid limit and plastic limit which help to predict the shrinkage and swelling characteristics. The Casagrande method was used to determine the liquid limit, which is the moisture content where a soil transitions from plastic to a liquid consistency under standardized test conditions. Defined as the moisture content at which a soil ceases to act plastically, the plastic limit represents the transition point between the plastic state and the semi-solid state of the soil. In the plastic range, the soil was rolled into thin threads without crumbling. The moisture content of soil was carried out to measure the amount of water present in the soil which influences the compaction and shear strength. It could be attributed to the ratio of the weight of water in the soil sample to the weight of the dry soil sample. It is typically expressed as a percentage. The weight of water in the soil sample was determined by undergone oven-dried at 110°C for 24 hours. The linear shrinkage was conducted to quantify the amount the soil shrinks when dried which indicates its potential for volume changes due to moisture fluctuation. It could be related to the decrease in one dimension which usually length of a soil sample dries from a wet state to a dry state. It is usually expressed as a percentage. A pH test was performed to determine the soil's level of acidity or alkalinity. This is an important step because a soil's pH

DOI: https://doi.org/10.11113/jurnalteknologi.v88.25465

value can have a significant effect on its overall chemical stability.

Swell Test

Free swell index was conducted as accordance to ASTM D5890-11 which determines the tendency of swelling in soil. Prepared two representative 10g samples of dry soil which pass through a 0.425 mm sieve. Individual soil samples are carefully introduced into separate 100 ml graduated cylinders. One cylinder is subsequently filled to a 100 ml volumetric mark with distilled water, while the second is filled to identical mark using kerosene. Both cylinders are allowed to stand undisturbed for 24 hours. After this period, the final volumes of the soil in both cylinders are recorded. The FSI is calculated as the percentage difference between the final volume of the soil in distilled water and the final volume of the soil in kerosene, using the final volume in kerosene as the reference volume.

3.0 RESULTS AND DISCUSSION

This section presents the results and analysis. It includes physical properties, chemical properties, mineralogical and morphological characteristics as well as the swelling behavior of expansive soils.

Soil Chemical Composition

According to XRF analysis, the chemical composition of the soil is presented in Table 2. The chemical composition of the soil reveals a soil predominantly composed of silicon dioxide (SiO_2) at 51.93%, alongside significant iron oxide (Fe_2O_3) at 20.87% and aluminum oxide (Al_2O_3) at 18.03%, indicative of potential clay mineral presence. The high Fe_2O_3 occurs because of the white cementing materials (iron oxide colloids) serving as a strong adhesive. They attached to soil particles, strengthened their bonds, and promoted the creation of soil aggregates and microscopic pore structures [26]. The notable potassium oxide (K_2O) content of 5.44% may point towards minerals like illite, while the titanium dioxide (TiO_2) at 2.51% is likely a product of weathering. The very low calcium oxide (CaO) content of 0.16% implies a deficiency in calcium-based minerals. Based on the criteria for pozzolans (ASTM C618), the sum of SiO_2, Al_2O_3, and Fe_2O_3 is 90.83%, which is significantly greater than the required 70%. This suggests that the soil has the potential for pozzolanic activity.

Table 2 Chemical compositions of soil

Compound	Composition (%)
Silicon dioxide (SiO_2)	51.93
Iron oxide (Fe_2O_3)	20.87
Aluminium oxide (Al_2O_3)	18.03
Potassium oxide (K_2O)	5.44
Titanium dioxide (TiO_2)	2.51
Calcium oxide (CaO)	0.16

Soil Mineralogical

In this study, XRD analysis was conducted to analyze minerals in the soil structures. According to the results shown in Figure 4, the 2θ range from 5° to 45° suggests that the soil samples were in a single-phase condition, with peaks appearing at various 2θ angles which are kaolinite (2θ = 12.4°, 19.9°, 35.05°), illite (2θ = 8.85°, 25.05°), quartz (2θ = 26.65°, 36.55°, 39.45°, 40.35°, 42.45°). The diffractogram of the soil shown in Figure 4 indicates that the mineral composition includes kaolinite, illite, quartz, and muscovite. Among these, the most dominant mineral found in the soil is quartz. The XRD pattern of soil shows it primarily characterized by distinct peaks of quartz which significant reflections are observed at 2θ angles around 26.65° (d = 3.35 Å), 36.55° (d = 2.46 Å) 39.45° (d = 2.28 Å), 40.35° (d = 2.24 Å) and 42.45° (d = 2.13 Å). The prevalence of quartz indicates mechanical stability and less plasticity, but it does not affect the swelling-sensitive clays. However, the XRD results of the soil showed a slightly decreased trend in intensity of peaks. Among the clay minerals, quartz exhibits the highest relative percentage at 45.8969%, whereas illite has the lowest relative percentage at 0.00029%. Besides, the clay mineral component of the soil is composed of kaolinite at a relative percentage of 33.7313% and muscovite at 1.9554%.

Kaolinite, illite, quartz, and muscovite are particularly important among the different minerals present in soils because of their distinct properties and behaviors. This finding aligns with the mineralogical compositions reported in similar soils by Lew [27]. However, it is crucial to distinguish that while both studies identify kaolinite, it is a non-expansive 1:1 clay mineral. The significant swelling potential in such contexts is typically attributed to the presence of expansive 2:1 clay mineral like montmorillonite (smectite) which may exist as discrete particles or within mixed-layer structures. The inclusion of illite within the soil composition has the potential to enhance its plasticity and improve its capacity for water retention. The increased levels of quartz in soil could be different mechanical properties where potentially resulting in a higher friction angle and a decrease in plasticity [28-30]. The swelling behavior is primarily driven by the soil's composition, which includes various mixed-layer clay minerals specifically illite-smectite, illite-montmorillonite, kaolinite-montmorillonite, and montmorillonite-calcian [31]. Illite have a strong swelling potential because they can absorb water.

DOI: https://doi.org/10.11113/jurnalteknologi.v88.25465

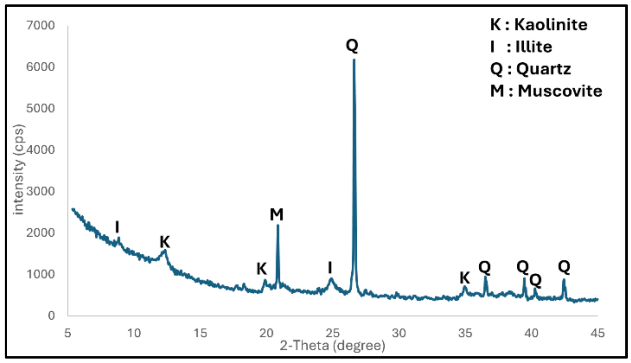


Figure 4 X-ray diffractogram pattern of soil

Morphological soil

To evaluate the alterations in morphology and elemental composition of the examined soils, FESEM tests were performed on the soil samples. FESEM analysis in Figure 5 demonstrated the soil microstructure at a magnification of 30,000 times. The image shows a highly aggregated and porous arrangement of soil particles. The dominant feature is the presence of numerous platy or flaky particles, characteristic of clay minerals. These particles are irregularly shaped and appear to be stacked and interconnected, forming complex pore networks. There is a noticeable variation in particle size, with smaller particles often appearing to fill the spaces between larger ones. The flaky, platy morphology strongly suggests the presence of some minerals such as kaolinite and illite which are common in many soil types. Specifically, analysis of the scanning electron microscopy (SEM) image indicates that the soil exhibits a microstructure containing both dispersed and flocculated particles, characterized by a heterogenous distribution of irregular shapes and sizes. This is because of the presence of certain pores that can be seen as a result of oxide formation [30]. Furthermore, the arrangement of particles and pores facilitates water absorption, directly explaining the observed volumetric changes.

The Energy Dispersive X-ray Spectroscopy (EDX) analysis shown in Figure 6 detailed the distribution of elemental composition in the soil. The spectrum is dominated by a major oxygen (O) peak, confirming its role as the most abundant element. The quantitative analysis identified the primary elemental composition as Oxygen (51.99%), Silicon (19.88%), Aluminum (13.84%), Iron (6.65%), Carbon (5.99%) and Potassium (1.66%). The predominance of O, Si, Al, and Fe is a clear indicator of a mineral assemblage rich in silicates and oxides such as quartz and kaolinite. Selvakumar et al. [24] also reported that expansive soils possess a high swelling potential, and swollen clay particles frequently exhibit characteristics akin to dispersive materials. When fully saturated, these soils are prone to significant volumetric increase over time where behavior is attributed to their high surface area and extensive interparticle spaces.

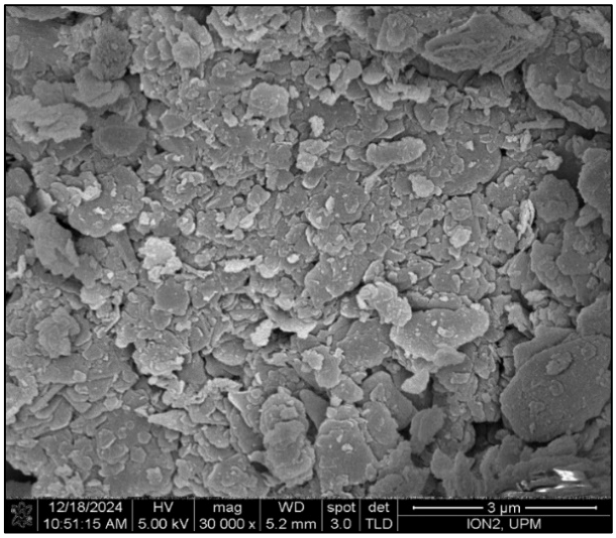


Figure 5 SEM image of soil

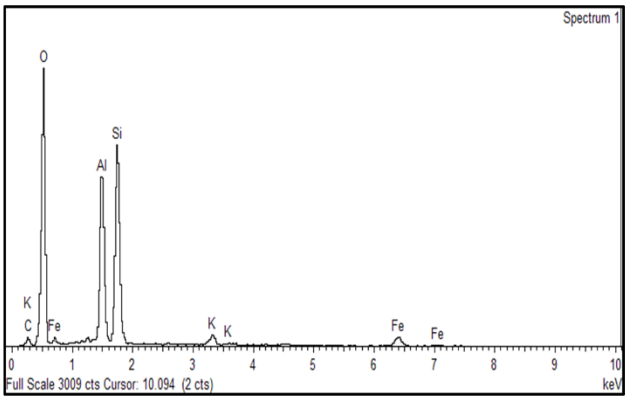


Figure 6 EDX analysis spectrum of soil

Physical and Chemical Properties

The PI and LL values of soil samples plot above the U-line (Figure 7) indicates that the soil is likely a clay. This means it has a high clay content and exhibits high plasticity and cohesion. All samples are classified as clays (CL or CH). Based on the Unified Soil Classification System (USCS), the soils were categorized as clay with low plasticity (CL) at P1 and clay with high plasticity (CH) at P2, P3, and P4.

Figure 8 illustrates the particle size distribution curves for soil samples gathered from four distinct sampling locations (P1, P2, P3, and P4). The geotechnical properties and chemical properties of the soil were summarized in Table 4.

DOI: https://doi.org/10.11113/jurnalteknologi.v88.25465

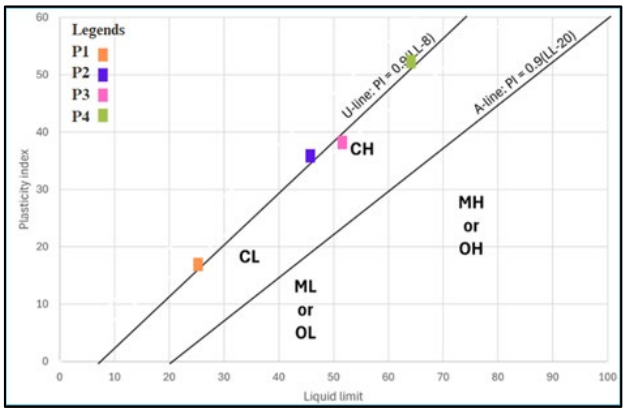


Figure 7 Plasticity chart of soils at different sampling points

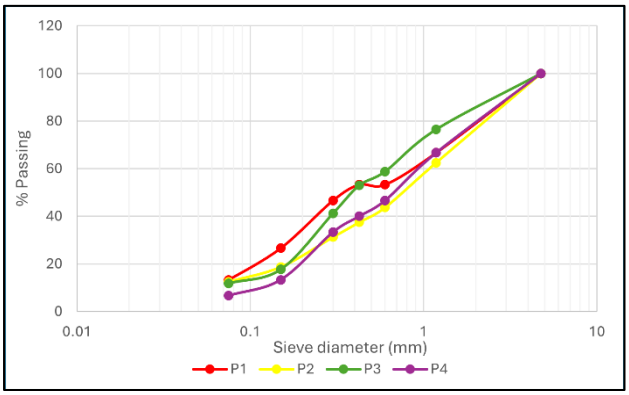


Figure 8 Particle size distribution at different sampling points

However, Adajar and Valbuena [33] also found that the criteria for expansive soils as defined by the National Structural Code of the Philippines (NSCP) as summarized in Table 3. Therefore, based on these three criteria from the NSCP, the sampling point which appears to most consistently meet the conditions for being classified as expansive, as it passes all three criteria.

Table 3 The classification of soil

Properties	Sampling points			
	P1	P2	P3	P4
Percent passing No. 200 sieve (%) (>10%)	Pass	Pass	Pass	Pass
Liquid limit (%) (>50%)	Fail	Pass	Pass	Fail
Plasticity index (%) (15%)	Fail	Fail	Pass	Pass

The geotechnical properties of the soils at different sampling points are shown in Table 4. Specifically, the moisture content ranged from 29.52% to 39.98%, indicating a slight increase across the sampling points. P4 demonstrated the highest moisture content, which is 39.98% followed by P2 which is 33.84%. P2 and P4 might experience more expansive behavior which makes the soil tendency to swell. The soil samples typically exhibit higher moisture retention, which plays a crucial role in their volume changes. However, these results can be associated with the requirement of water for hydration and the purposes of compaction [34].

Table 4 Geotechnical properties of soils at different sampling points

Soil Properties	Sampling Points			
	P1	P2	P3	P4
Gravel	6.67	6.25	5.88	0
Sand	73.33	81.25	82.35	86.67
Fine material (Clay, Silt)	20	12.5	11.76	13.33
Liquid limit (%)	26.69	50.47	64.61	47.75
Plastic limit (%)	17.49	35.73	30.62	22.73
Plasticity index (%)	9.2	14.74	33.99	25.02
Moisture content (%)	29.52	33.84	29.72	39.98
Linear shrinkage (%)	11.42	10.96	11.19	10.49
Free swell index	13	10	17	11
Specific gravity	2.59	2.54	2.26	2.40
Soil classification, USCS	CL	CH	CH	CH
pH	6.75	5.62	3.65	4.07
Maximum dry density (g/cc)	1.275	1.23	1.175	1.175
Optimum moisture content (%)	18	27	23	29

The Atterberg limits are crucial for the classification of soil throughout a wide category. The result of liquid limit shows a slightly increased trend, ranging from 26.69% to 64.61% are presented in Figure 9. It can be seen P3 shows the high plasticity soil, which is 64.61% compared to other sampling points. Mehta and Sachan [35] established that a high liquid limit is a direct indicator of significant swell potential in clay-rich soils. The increased montmorillonite content enhances its ability to retain water and strengthens the cohesive forces between the particles. Also, similar results were found by Butt et al., [36] and Adetoro and Faluyi [37] which the increase could be resulted from highest in water absorption capacity. The plastic limit ranged from 17.49% to 35.73%. The soil at P2 obtained the highest value, which is 35.73%. The higher plasticity and cohesion at P2 account for this behavior. The high liquid and plastic limits result from the presence of expanding clay minerals including smectite, hydrous mica, and chlorite [38]. Besides, the plasticity index results ranged from 9.20% to 33.99%. Higher in plasticity index value particularly at P3 which is 33.99% is likely to indicate more expansive soil conditions. As stated by Holtz and Gibbs [3] in Table 1, it showed that the plasticity index from 25% to 41% attributed to the high in swell potential.

DOI: https://doi.org/10.11113/jurnalteknologi.v88.25465

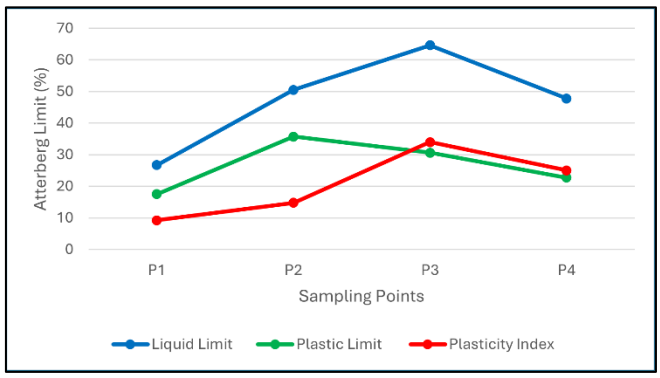


Figure 9 Atterberg limits values of soils in different sampling points

Linear shrinkage ranged from 10.49% to 11.42%. This test directly measures the soil's potential for contraction as water content decreases, a property governed by the type and amount of active clay minerals present. The lower shrinkage value of 10.49% at P4 suggests a comparatively lower content of clay minerals such as illite. This implies a reduced tendency for significant volume changes in response to moisture variations. Free swell index values exhibited ranging from 10% to 17%. High value in free swell index, which is 17% at P3 indicates significant expansiveness where it could lead to severe swelling when hydrated. Comparatively, lower in the free swell index, which is 10% at P2, suggests soils with reduced swelling potential where it might be safer for construction purposes. The variation in free swell index values across the sampling locations is directly linked to differences in their clay mineralogy and composition.

The specific gravity values in Table 4 range from 2.26 to 2.59. The specific gravity was the highest value, which is 2.59 at P1. The behavior at location P1 is governed by its substantial clay mineral content, specifically kaolinite, illite, quartz and muscovite, as quantified by XRD. Furthermore, the specific gravity is potentially influenced by the density and compositional characteristics of the constituent minerals. As delineated in Table 4, the observed pH values for the samples range from 3.65 to 6.75. The pH value shows a slight decreased trend which indicated the acidic conditions. The soil at P3, which is 3.65, obtained the most acidic compared to other sampling points. This highly acidic soil promotes shrink-swell behavior. The soil's acidic properties are likely a result of its elevated clay content, which frequently leads to a more acidic environment.

Figure 10 presented the maximum dry density obtained the decreasing trend from 1.275 g/cm^3 to 1.175 g/cm^3. The result of maximum dry density at P3 and P4 showed the lowest value in specific gravity. Jha and Sivapullaiah [39] stated that the maximum dry density is likely influenced by two main factors such as the soil's particle size distribution and its specific gravity. Another study by Oguche et al. [40] reported that the observed results could be a consequence of the low specific gravity inherent to the expansive soil. Moreover, the optimum moisture content of the expansive soil was found to fall within the range of 18% to 29%. However, the optimum moisture content of expansive soil was found to be the highest value at P4 which is 29%. The high OMC is likely due to the composition and nature of the clay minerals present within the 13.33% fines fraction. Even a small percentage of expansive clay minerals such as illite can dominate the soil's water-holding behavior.

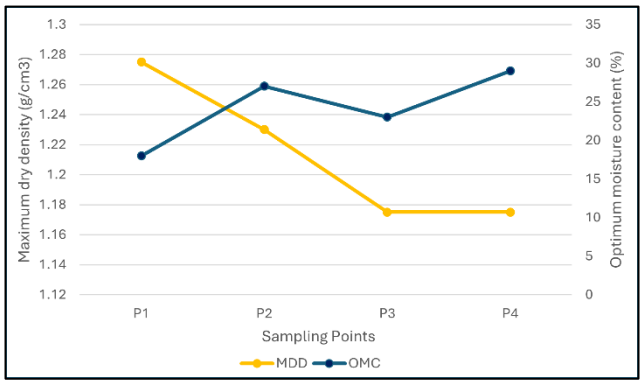


Figure 10 Compaction properties of soils in different sampling points

The XRD analysis confirms that the soil is predominantly composed of quartz (45.9%), which is non-plastic and high sand fraction reported in the particle size distribution. The geotechnical properties are ultimately governed by the clay mineral. Although the presence of low illite, a 2:1 clay mineral is one of the factor explaining the soil's elevated plasticity (Liquid Limit up to 64.61%, PI up to 33.99%) and its classification as CH. The capacity of illite to absorb water and its potential presence in mixed-layer structures such as illite-smectite directly account for the significant free swell index (up to 17% at P3) and the high moisture contents (up to 39.98%). This is further confirmed by the XRF data, which shows a high K_2O content (5.44%), a key chemical indicator for illite. The acidic pH conditions (as low as 3.65), likely a result of weathering processes that release ions from these clay minerals, can further enhance the clay's activity and swell potential. Therefore, geotechnical behavior is not a simple function of clay content but is precisely controlled by the specific mineralogy, where the interplay between high quartz and low illite dictates the soil's stability and its tendency to volume change.

4.0 CONCLUSION

The aims in this study were to study geotechnical properties, mineralogical and morphological characteristics of expansive soil as well as the relationship to confirm swell behavior.

The comprehensive conclusions are outlined below:

1) The characterization confirms that the soil, particularly at location P3 possesses the physical properties (high LL, PI, FSI) that classify the soil as highly expansive. The mineralogy (kaolinite, illite, quartz, and muscovite) defines the soil's inherent

DOI: https://doi.org/10.11113/jurnalteknologi.v88.25465

potential to swell and exhibit plasticity. These minerals create the morphology (platy, porous structure) that facilitates water absorption.
2) The mineralogy of expansive soil defines the potential to swell, the physical properties (high LL, PI) provide diagnostic evidence of this potential, and the morphology (porous, platy structure) facilitates the physical process of swelling and the presence of minerals in expansive soil such as kaolinite, illite, quartz and muscovite.
3) High plasticity verifies a strong potential for soil expansion and an increasing moisture content results in the release of swelling pressure, manifesting as the expansive behavior.

The study effectively identified the physical and mineralogical properties of expansive soils, emphasizing significant swelling behavior at P3, attributed to its high plasticity, moisture levels, and mineral composition. These findings align with the objectives of the study. Further research will also be conducted to focus on the sustainable approaches which use eco-friendly stabilizers. The potential for combining agricultural waste products or industrial by-products like saw dust ash (SDA) as soil stabilization techniques should be explored to make soil improvement more sustainable.

Acknowledgement

We wish to acknowledge the financial support funded by Universiti Putra Malaysia through the Geran Putra Inisiatif (GPI) (Grant No.: 9795100). We are grateful to the Faculty of Engineering, Universiti Putra Malaysia, Selangor, and Politeknik Kota Bharu, Kelantan for providing laboratory facilities. We also express our sincere appreciation to the academic and technical staff at both institutions for their invaluable assistance and guidance.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Data availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Ethics declaration

Formal ethical approval was not obtained for this study. However, the authors confirm that the research was conducted in accordance with established ethical principles and good research practices, with due consideration given to participant rights, informed consent, confidentiality, and responsible data handling.

References

[1] Kalantari, B. (2012). Foundations on expansive soil: a review. Research Journal of Applied Sciences, Engineering and Technology, 4(18), 3231-3237.
[2] Bell, F. G., & Culshaw, M. G. (2001). Problems soils: a review from a British perspective. In Problematic Soils: Proceedings of the Symposium Held at Nottingham Trent University on 8 November 2001 (pp. 1-35). Thomas Telford Publishing.
[3] Holtz, W. G., & Gibbs, H. J. (1956). Engineering properties of expansive clays. Transactions of the American Society of Civil Engineers, 121(1), 641-663. https://doi.org/10.1061/TACEAT.0007324
[4] Kumar, S. P., Prasad, L. D., Sivanarayana, C., & Prasad, D. S. V. (2019). A study on stabilization of expansive soil by using agricultural by-products. International Journal of Civil Engineering (IJCE).
[5] Zamin, B., Nasir, H., Mehmood, K., Iqbal, Q., Farooq, A., & Tufail, M. (2021). An experimental study on the geotechnical, mineralogical, and swelling behavior of KPK expansive soils. Advances in civil engineering, 2021(1), 8493091. https://doi.org/10.1155/2021/8493091
[6] Asuri, S., & Keshavamurthy, P. (2016). Expansive soil characterisation: an appraisal. Indian National Academy of Engineering, 1, 29-33. https://doi.org/10.1007/s41403-016-0001-9
[7] Reddy, P. S., Mohanty, B., & Rao, B. H. (2020). Influence of clay content and montmorillonite content on swelling behavior of expansive soils. International Journal of Geosynthetics and Ground Engineering, 6, 1-12. https://doi.org/10.1007/s40891-020-0186-6
[8] Der Merwe, V. (1964). The prediction of heave from the plasticity index and the percentage clay fraction. The Civil Engineer in South Africa, 6(6), 103.
[9] Ikeagwuani, C. C., & Nwonu, D. C. (2019). Emerging trends in expansive soil stabilisation: A review. Journal of Rock Mechanics and Geotechnical Engineering, 11(2), 423-440. https://doi.org/10.1016/j.jrmge.2018.08.013
[10] Jefferson, I., & Jones, L. D. (2012). Expansive soils. ICE Manual of Geotechnical Engineering Vol 1: Geotechnical Engineering Principles, Problematic Soils and Site Investigation (ICE Manuals), 413-441.
[11] Aqeel, A. (2016). Investigation of expansive soils in Obhor Sabkha, Jeddah-Saudi Arabia. Arabian Journal of Geosciences, 9, 1-14. https://doi.org/10.1007/s12517-016-2341-x
[12] Hakami, B. A., & Seif, E. S. S. A. (2019). Expansive potentiality of sabkha soils of Rabigh Lagoon, Saudi Arabia: a case study. Arabian Journal of Geosciences, 12, 1-14. https://doi.org/10.1007/s12517-019-4271-x
[13] Sarkar, B., Rusmin, R., Ugochukwu, U. C., Mukhopadhyay, R., & Manjaiah, K. M. (2019). Modified clay minerals for environmental applications. In Modified clay and zeolite nanocomposite materials (pp. 113-127). Elsevier. https://doi.org/10.1016/B978-0-12-814617-0.00003-7
[14] Biswas, B., Juhasz, A. L., Mahmudur Rahman, M., & Naidu, R. (2020). Modified clays alter diversity and respiration profile of microorganisms in long-term hydrocarbon and metal co-contaminated soil. Microbial Biotechnology, 13(2), 522-534. https://doi.org/10.1111/1751-7915.13510
[15] Ombaka, O. (2016). Characterization and classification of clay minerals for potential applications in Rugi Ward, Kenya. African Journal of Environmental Science and Technology, 10(11), 415-431. https://doi.org/10.5897/AJEST2016.2184
[16] Gaudin, A., Ansan, V., Lorand, J. P., & Pont, S. (2020). Genesis of a florencite-bearing kaolin deposit on ordovician schists at Saint-Aubin-des-Châteaux, Armorican Massif, France. Ore Geology Reviews, 120, 103445. https://doi.org/10.1016/j.oregeorev.2020.103445
[17] Karakaya, M. C., Karakaya, N., Temel, A., & Yavuz, F. (2021). Mineralogical and geochemical properties and genesis of kaolin and alunite deposits SE of Aksaray (Central Turkey). Applied Geochemistry, 124, 104830. https://doi.org/10.1016/j.apgeochem.2020.104830
[18] Hernández, A. C., Sánchez-Espejo, R., Meléndez, W., González, G., López-Galindo, A., & Viseras, C. (2019). Characterization of Venezuelan kaolins as health care

DOI: https://doi.org/10.11113/jurnalteknologi.v88.25465

ingredients. Applied Clay Science, 175, 30-39. https://doi.org/10.1016/j.clay.2019.01.003
[19] Akisanmi, P. (2022). Classification of clay minerals. Mineralogy, 3-9. https://doi.org/10.5772/intechopen.103841
[20] Kahr, G., & Madsen, F. T. (1995). Determination of the cation exchange capacity and the surface area of bentonite, illite and kaolinite by methylene blue adsorption. Applied clay science, 9(5), 327-336. https://doi.org/10.1016/0169-1317(94)00028-O
[21] Bergaya, F., Lagaly, G., & Vayer, M. (2013). Cation and anion exchange. In Developments in Clay Science (Vol. 5, pp. 333-359). Elsevier. https://doi.org/10.1016/B978-0-08-098259-5.00013-5
[22] Götze, J., Pan, Y., & Müller, A. (2021). Mineralogy and Mineral Chemistry of quartz: A review. Mineralogical Magazine, 85(5), 639-664. https://doi.org/10.1180/mgm.2021.72
[23] Rezaee, L., Moosavi, A. A., Davatgar, N., & Sepaskhah, A. R. (2020). Shrinkage-swelling characteristics and plasticity indices of paddy soils: spatial variability and their influential parameters. Archives of Agronomy and Soil Science, 66(14), 2005-2025. https://doi.org/10.1080/03650340.2019.1706169
[24] Selvakumar, S., Soundara, B., Raj, N., & Kulanthaivel, P. (2024). Microstructural investigation on the expansive soils for sustainable stabilization purposes. Discover Soil, 1(1), 8. https://doi.org/10.1007/s44378-024-00009-0
[25] Lew, B. (2010). Structure damage due to expansive soils: A case study. Electronic Journal of Geotechnical Engineering, 15, 1317-1324.
[26] Zhang, X. W., Kong, L. W., Cui, X. L., & Yin, S. (2016). Occurrence characteristics of free iron oxides in soil microstructure: evidence from XRD, SEM and EDS. Bulletin of Engineering Geology and the Environment, 75(4), 1493-1503.
[27] Ng, C. W. W., Owusu, S. T., Zhou, C., & Chiu, A. C. F. (2020). Effects of sesquioxide content on stress-dependent water retention behaviour of weathered soils. Engineering geology, 266, 105455.
[28] Burnett, A. D. (1995). A quantitative X-ray diffraction technique for analyzing sedimentary rocks and soils. Journal of testing and evaluation, 23(2), 111-118. https://doi.org/10.1520/JTE10902J
[29] Sridharan, A., & Prakash, K. (2000). Classification procedures for expansive soils. Proceedings of the Institution of Civil Engineers-Geotechnical Engineering, 143(4), 235-240. https://doi.org/10.1680/geng.2000.143.4.235
[30] Lin, B., Cerato, A. B., Madden, A. S., & Elwood Madden, M. E. (2013). Effect of fly ash on the behavior of expansive soils: microscopic analysis. Environmental & Engineering Geoscience, 19(1), 85-94. https://doi.org/10.2113/gseegeosci.19.1.85
[31] Tahasildar, J., Rao, B. H., & Shukla, S. K. (2017). Mineralogical compositions of some Indian expansive soils and their influence on swelling properties. International Journal of Geosynthetics and Ground Engineering, 3, 1-10. https://doi.org/10.1007/s40891-016-0081-3
[32] Adetola, S., Oyejide, A., Emmanuel, E., Adejinle, S., & Aiyegbabe, J. (2024). Microstructural Analysis of blended Guinea-Corn Stalk and Saw-Dust Ash for Cement Mixture of Interlocking Concrete Block. In 2024 International Conference on Science, Engineering and Business for Driving Sustainable Development Goals (SEB4SDG) (pp. 1-6). IEEE. https://doi.org/10.1109/SEB4SDG60871.2024.10629948
[33] Adajar, M. A., & Valbuena, K. (2021). Optimization of the strength properties of expansive soil stabilized with agricultural wastes. GEOMATE Journal, 21(88), 35-41. https://doi.org/10.21660/2021.88.gxi253
[34] Ogunribido, T. H. T. (2012). Geotechnical properties of saw dust ash stabilized southwestern Nigeria lateritic soils. Environmental Research, Engineering and Management, 60(2), 29-33. https://doi.org/10.5755/j01.erem.60.2.986
[35] Mehta, B., & Sachan, A. (2017). Effect of mineralogical properties of expansive soil on its mechanical behavior. Geotechnical and Geological Engineering, 35, 2923-2934. https://doi.org/10.1007/s10706-017-0289-6
[36] Butt, W. A., Gupta, K., & Jha, J. N. (2016). Strength behavior of clayey soil stabilized with saw dust ash. International Journal of Geo-Engineering, 7, 1-9. https://doi.org/10.1186/s40703-016-0032-9
[37] Adetoro, A. E., & Faluyi, O. S. (2015). Potentials of Non-Cementitious Additives for Stabilization of Oye Local Government Area Soils, Ekiti State, Nigeria. International Journal of Scientific Research in Knowledge, 3(11), 288-296. https://doi.org/10.12983/ijsrk-2015-p0288-0296
[38] Ito, M., & Azam, S. (2009). Engineering characteristics of a glacio-lacustrine clay deposit in a semi-arid climate. Bulletin of Engineering Geology and The Environment, 68, 551-557. https://doi.org/10.1007/s10064-009-0229-7
[39] Jha, A. K., & Sivapullaiah, P. V. (2018). Potential of fly ash to suppress the susceptible behavior of lime-treated gypseous soil. Soils and Foundations, 58(3), 654-665. https://doi.org/10.1016/j.sandf.2018.02.024
[40] Oguche, J. O., Adeyeri, J. B., Amu, O. O., & Joseph, O. F. (2022). Stabilization of Expansive Clay Soils Using Saw Dust Ash. Journal of Innovation Science and Technology, 2(1).