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Application of industrial by-product waste as soil stabilising backfill material using a multi-layering method

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Abstract
Peat soil presents significant challenges for construction due to its inherent weak properties, including high water content, limited permeability, low shear Strength, low specific gravity, and acidity. Despite the potential of Mg-rich synthetic gypsum (MRSG) to improve soil properties, research on its use for stabilising severely poor peat soils is limited. This study addresses this gap by investigating the efficacy of MRSG in peat soil stabilisation using a novel multi-layering backfill approach. The methodology includes soil classification of peat soil. And, to understand the mechanical and chemical changes of stabilized peat soil, the unconfined compressive Strength (UCS) testing and microstructural analysis using SEM, EDX, and XRD before and after stabilisation are studied. Peat samples were treated with MRSG through backfilling method in 5, 7, and 9 layers and evaluated the strength increment after curing periods of 7, 28, and 60 days. Results demonstrate that MRSG significantly enhanced the compressive strength, increasing it to 210.33 kPa as early as 7 days for 9 layers of backfill incomparable with the untreated soil strength of 51.87 kPa. The new cementitious product in the soil known as ettringite was observed from SEM analysis and confirmed by the EDX and XRD analysis. By recycling industrial byproducts, this environmentally friendly method encourages sustainability and lessens dependency on raw resources, which is important for infrastructure construction and other projects in areas rich in peat.

Keywords Peat soil · Soil stabilisation · Multi-layer soil backfill · Mg-rich synthetic gypsum (MRSG) · Unconfined compressive strength

1 Introduction

Peatland is Malaysia's largest wetland ecosystem, covering around 2.5 million hectares and about 7.5% of the country's surface area [1]. Peat is mostly found in Malaysia's hilly and coastal areas, with large deposits in Kuantan, Pontian, Batu Pahat, Pekan, and Perak. Peat soil, generated over centuries from degraded organic components, is highly organic and contains degraded plant elements that are often black or dark brown [2].

Regarding the engineering characteristics, peat soil has various weak properties, including low specific gravity [3], high moisture content [4], and high organic and fibre content [5], these characteristics lead to a notable low shear strength [6], low unconfined compressive Strength (UCS) [7], and high compressibility [8], all of which reduce its ability to sustain construction loads.

Massive development in areas with difficult peat characteristics demands the adoption of effective soil stabilisation techniques. Soil stabilisation is critical to maintain the infrastructure's structural integrity in these scenarios.

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Numerous peat stabilisation approaches involving mechanical, chemical, and electrical stabilisation methods are now being used to enhance engineering qualities and make peatland viable for use [9].

Examples of mechanical solutions include peat removal and replacement, a frequent strategy for addressing peat soil's poor qualities. This approach uses drainage to lower the groundwater table, exposing the peat to air oxygen. This exposure affects the peatland's overall hydrological system, altering the breakdown process from anaerobic to aerobic. As a result, large volumes of carbon dioxide (CO2) are emitted into the atmosphere, worsening the greenhouse effect and contributing to climate change [9].

Chemical soil stabilisation, on the other hand, entails adding various chemical agents to improve soil qualities [10]. These chemicals include Ordinary Portland Cement (OPC), lime, bitumen, and tar [11], which interact with the soil to increase its Strength, minimise compressibility, and enhance its overall stability [12]. Despite physical removal, chemical stabilisation tries to change the soil's internal structure and qualities, rendering it more suited for construction while minimising disturbance to the natural hydrological system [13]. Paul et al. [14] studied cement stabilisation of peat soil, finding that cement treatment improved mechanical, chemical, and microstructural properties. It reduced organic material effects, acidity and increased electrical conductivity. Tests (FESEM, EDX, XRD, FTIR) showed a denser structure, formation of strength compounds like CSH and ettringite, and new strength-enhancing gels.

Regarding electrical stabilisation approaches, Wahab et al. [15] investigated the chemical stabilisation of peat soil using electrokinetic stabilisation (EKS) to enhance engineering qualities. EKS was applied to peat samples from Johor, Malaysia, at voltage gradients of 110 and 150 V for 3 and 6 h, respectively. The results revealed considerable enhancements: shear Strength rose from 11.66 to 70 kPa, moisture content dropped from 613.989% to 270.294%, liquid Limit rose from 159.261% to 217.603%, and shear wave velocity rose from 68.5 to 110.5 m/s. Nevertheless, according to Mekonnen et al. [16], electrical stabilising techniques are energy intensive.

As a result, there is an urgent need for more durable and efficient stabilising strategies. Considering rising sustainability concerns, there is a growing interest in employing numerous industrial by-products to stabilise problematic and weak soil. This can significantly improve the soil's characteristics, provide environmental advantages, and align with sustainability goals [17].

Fatima et al. [18] used Plaster of Paris Kiln Dust (PKD) to stabilise dispersive soils in Pakistan. They reported a considerable drop in dispersion potential and a significant improvement in unconfined compression strength after applying variable quantities of PKD (0.5% to 3%) under different curing durations. In another research, Hassan et al. [19] investigated fine marble dust (FMD) to prevent erosion in sodium-rich clays, revealing lower dispersion potential and better soil stability. Several experiments have been conducted with varying FMD ratios and cure durations. The results showed that 30% FMD for KC soil and 20% for HC soil considerably reduced dispersion potential and salt concentration, resulting in increased soil stability. XRD and SEM measurements indicated enhanced resistance caused by flocculation and cementing material development.

Another research conducted by Hassan et al. [20] explored the usage of potassium-rich ash (KRA) to improve dispersibility and reduce internal erosion in sodium-rich clays. Traditional calcium treatments are expensive and detrimental to the environment, necessitating the development of a sustainable alternative. Tests revealed that after 28 days of curing, 15% KRA for QS clay and 10% KRA for PBS clay significantly decreased dispersion and erosion by exchanging Na for K. The findings showed that KRA increased soil stability via flocculation, agglomeration, and electrostatic mechanisms.

Also, Hassan et al. [21] used potassium-rich wood ash (KRWA) to stabilise dispersive clay. Testing KRWA content up to 35% over 60 days revealed that 10% KRWA successfully lowers dispersion and salt concentration by 82% and 57%, respectively, in just 28 days. This treatment enhances soil workability by lowering plasticity by 56%, increasing load-bearing capacity by 575%, and lowering compressibility by 60%. Physiochemical investigations reveal quick ion exchange, agglomeration, and flocculation, followed by pozzolanic activity forming cementitious gels. X-ray diffraction (XRD) and scanning electron microscopy (SEM) demonstrate the creation of denser microstructures.

Additionally, Hassan et al. [22] investigated assessing geosynthetics' behaviour in cohesive soil, particularly how soil plasticity index (PI) impacts reinforced soil mechanics. Investigating three cohesive soils reinforced with various geosynthetics (woven/non-woven geotextile, composite, and geogrid) through triaxial compression and direct shear tests revealed that woven geotextile (GTW) enhanced shear Strength due to superior interface friction and tensile properties. Three layers of GTW increased stiffness, cohesion, and shear strength parameters, highlighting performance variations based on the soil plasticity index.

Accordingly, this study builds upon previous investigations on sustainable, friendly methods for stabilising weak soil via industrial waste to improve soil qualities for building applications, as in recent studies. Specifically, this study examines using Mg-rich synthetic gypsum (MRSG) to stabilise peat soil. Unlike conventional approaches reviewed in recent studies, which often rely on mixing the stabilisers uniformly with the treated soil, our study presents a novel methodology that employs MRSG in a multi-layer soil backfill process.

Despite the potential for MRSG to improve soil properties, particularly in severely poor peat soils, more research is still needed on its use in soil stabilisation. Accordingly, the aim of this study revolves around the effectiveness and innovation of using MRSG in a multi-layer soil backfill technique to stabilise peat soil. Hence, the study's objectives are: 1. To determine the physicochemical and mechanical characteristics of untreated peat soil collected from Gebeng. 2. To analyse the effect of compressive Strength on untreated and treated Peat with Mg-rich synthetic gypsum using the soil layering method. 3. To interpret the microstructural improvements of treated and untreated peat with different curing periods.

2 Materials

2.1 Soil sample

The sample was collected from an industrial area in Gebeng, Pahang state, at 3°59′57.8"N 103°21′33.0" E. Such sampling is often carried out using test pit excavation at short depths. In this scenario, peat samples were obtained with a shovel, hoe, and trowel on a smaller scale. The soil samples were kept in airtight containers to avoid bacterial and algal development and preserve their properties. Air contact was reduced by thoroughly filling the sample containers before closing them.

The engineering characteristics of the used peat soil were determined in the Soil Mechanics and Geotechnics Laboratory at Universiti Malaysia Pahang. Before testing, the damp sample was air-dried for a day and baked for 24 hours at 105 °C. The tests conducted to study the peat characteristics included natural moisture content [23], particle size distribution [24], Atterberg limits [25], specific gravity [26], compaction [27], loss on ignition (LOI) [27], and pH [28].

Furthermore, peat samples were visually classified according to their appearance and content. When pressed, the samples emitted dark brownish water and contained degraded plant elements, including tree roots and wood remnants. According to visual inspection and the Von Post Scale, the Gebeng site's peat soil was classified as H3, signifying very minimally degraded peat. Furthermore, the Radforth System defined peat soil as fine-fibrous (category 11), distinguished by combining woody and non-woody materials in fine-fibrous Peatpeat. Table 1 summarises the peat soil properties and classification.

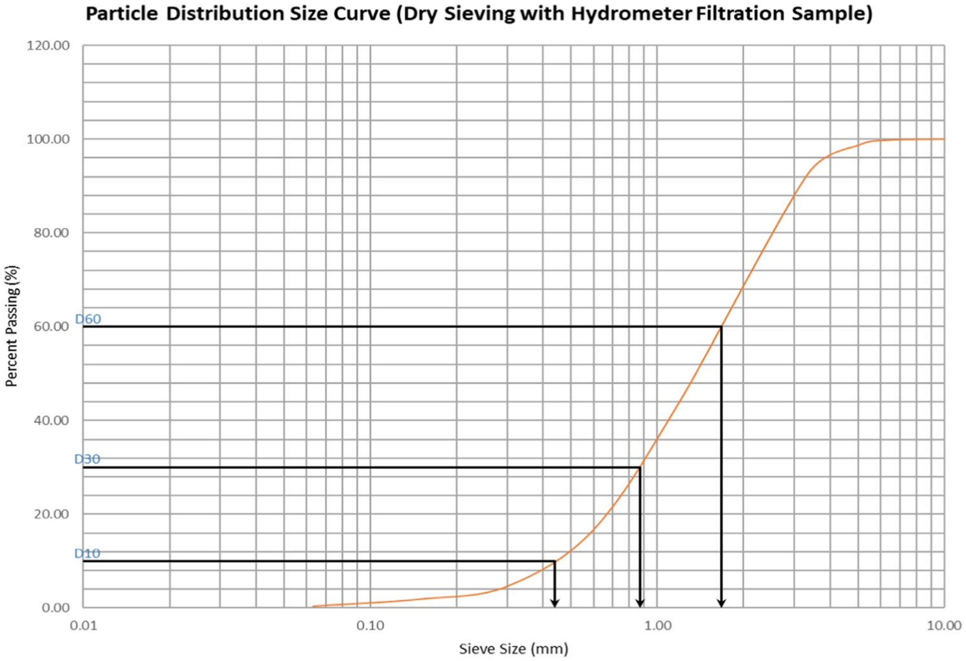
However, the resulting soil's physical properties, such as its distribution of particle sizes, which is important for peat classifications. The process of particle size distribution was carried out in compliance with BS EN ISO 17892. [25], and Fig. 1 shows the produced distribution curve of particle sizes.

The test yielded a uniformity coefficient (Cu) equals 3.82 and a coefficient of curvature (Cc) equals 1.02 for the particle size distribution curve. The Cc value indicates a well-graded classification for the soil, whereas the Cu value indicates a poorly graded classification. Overall, due to their disparity, the soil is generally classified as poorly graded. Referring to the Unified Soil Classification System (USCS) in Fig. 2, the soil falls into the highly organic category, specifically peat. This classification is based on the characteristics noted in the soil classification chart: primarily organic matter, dark colour, and organic odour, consistent with the visual analysis for the obtained samples. Therefore, this soil is categorised as peat with the group symbol PT.

Table 1 The untreated peat soil characteristics

Parameters	Values
Natural moisture content (%)	474.49
Organic content (%)	85.52
Liquid limit (%)	110.80
Plasticity index (%)	16.86
Specific gravity (Mg/m3)	1.59
Maximum dry density (g/cm3)	0.527
Optimum moisture content (%)	63
pH	3.86
Radforth system peat category	11
Von post humification scale	H3

Fig. 1 Particle size distribution graph of peat soil



On the other hand, the Atterberg limits—liquid, plastic, and shrinkage—define critical soil properties used in international soil classification and strength assessments and were conducted according to BS EN ISO 17892. [25],

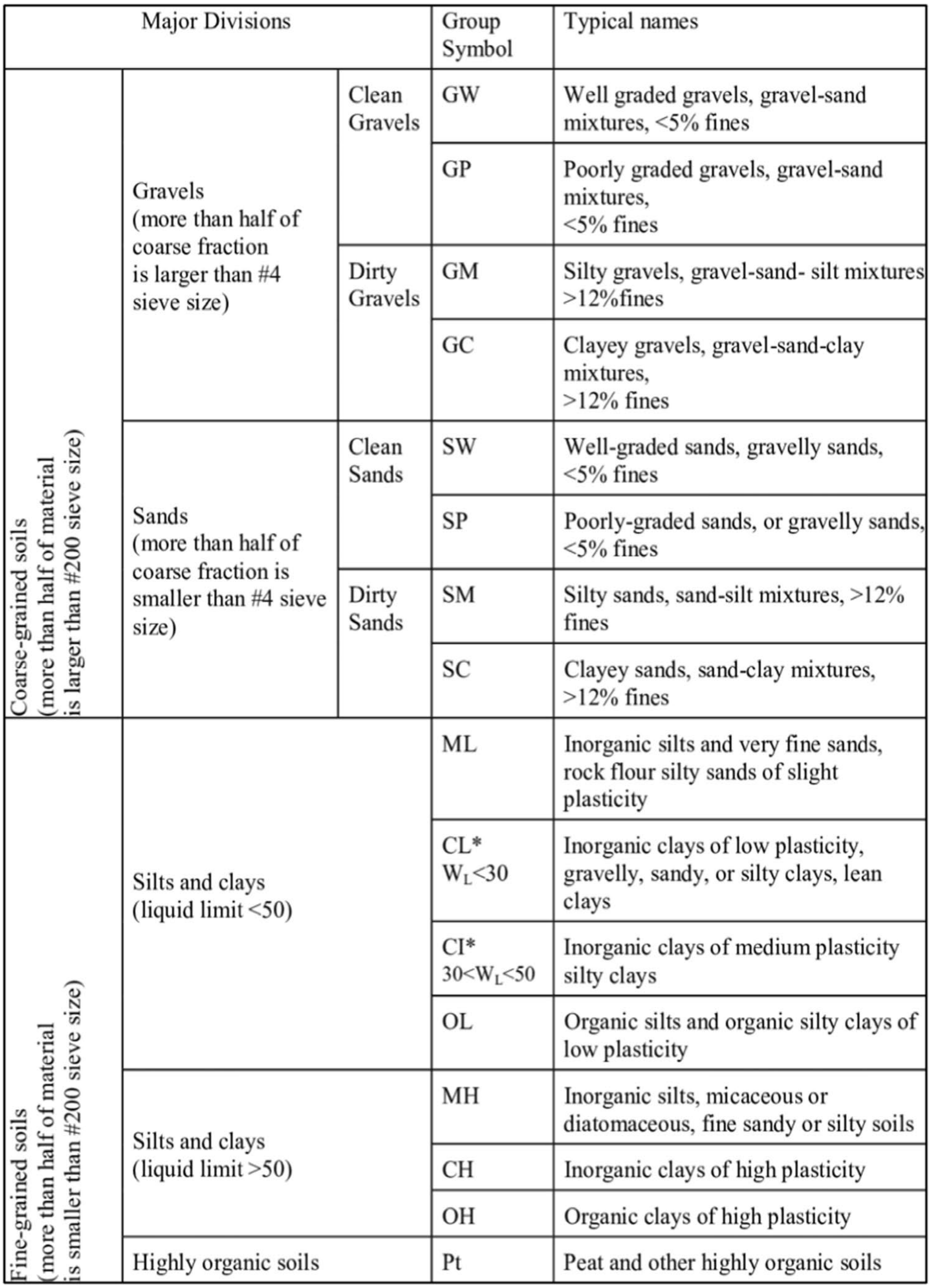
the liquid Limit and Plastic Limit of the peat soil were determined to be 110.80% and 93.94%, respectively, yielding a plasticity index of 16.86%. According to soil mechanics principles, a low plasticity index suggests the presence of silt or clay, while a high index indicates clay and a near-zero index implies little to no silt or clay. The peat soil in this study falls into the medium plastic category (7% to 17%), indicative of high organic content and significant decomposition. This classification and the high liquid limit and organic content (85.52%) were obtained from the loss of ignition test according to BS 1377-2. [27] confirms that the soil is peat. The classification of the soil as peat is confirmed with the amount of organic contents that should be greater than 75 % [30]. These properties lead to high compressibility, low shear Strength, and high sensitivity to moisture changes, typical characteristics of peat soil.

In addition, the optimum moisture content was obtained from the standard soil compaction test per BS 1377–2. [27], The Standard Proctor method determined the optimum moisture content and maximum dry density. In a typical Proctor mould, the peat soil was compacted into three layers with 25 blows in each layer. After testing various moisture contents, a compaction curve was created (as shown in Fig. 3) that revealed a maximum dry density of 0.527 g/cm^3 and an optimum moisture content of 63%. This test is essential for determining moisture content when designing structures like embankments and foundations. In this study, these values are crucial for calculating the gypsum and peat needed for backfill material in each layer.

On the other hand, regarding the mechanical characteristics of the studied peat soil, the UCS test, according to BS ISO 17892–7. [31], was used to assess the compressive Strength of the collected peat soil before stabilisation. Peat UCS was tested three times, yielding strengths for trials 1, 2, and 3 of 39.12 kPa, 28.68 kPa, and 87.82 kPa, respectively. Based on these tests, an average value of 51.87 kPa for compressive Strength was determined.

Additionally, regarding chemical characteristics, a pH test was conducted according to ISO 10523. [28] using the pH meter. Ethanol was used as the solvent for this analysis. When conducting pH tests on peat soil, it is important to use a less dense solvent than water, as peat particles tend to float in water. For this test, ethanol was determined to be the suitable solvent due to its density of 789 kg/m^3. The peat soil under investigation has an acidic pH of 3.86, according to the findings of the pH test.

Fig. 2 USCS chart for soil classification [29]



Major Divisions			Group Symbol	Typical names
Coarse-grained soils (more than half of material is larger than #200 sieve size)	Gravels (more than half of coarse fraction is larger than #4 sieve size)	Clean Gravels	GW	Well graded gravels, gravel-sand mixtures, <5% fines
			GP	Poorly graded gravels, gravel-sand mixtures, <5% fines
		Dirty Gravels	GM	Silty gravels, gravel-sand- silt mixtures >12%fines
			GC	Clayey gravels, gravel-sand-clay mixtures, >12% fines
	Sands (more than half of coarse fraction is smaller than #4 sieve size)	Clean Sands	SW	Well-graded sands, gravelly sands, <5% fines
			SP	Poorly-graded sands, or gravelly sands, <5% fines
		Dirty Sands	SM	Silty sands, sand-silt mixtures, >12% fines
			SC	Clayey sands, sand-clay mixtures, >12% fines
Fine-grained soils (more than half of material is smaller than #200 sieve size)	Silts and clays (liquid limit <50)		ML	Inorganic silts and very fine sands, rock flour silty sands of slight plasticity
			CL* W_L<30	Inorganic clays of low plasticity, gravelly, sandy, or silty clays, lean clays
			CI* 30<W_L<50	Inorganic clays of medium plasticity silty clays
			OL	Organic silts and organic silty clays of low plasticity
	Silts and clays (liquid limit >50)		MH	Inorganic silts, micaceous or diatomaceous, fine sandy or silty soils
			CH	Inorganic clays of high plasticity
			OH	Organic clays of high plasticity
	Highly organic soils		Pt	Peat and other highly organic soils

Fig. 3 The compaction test curve

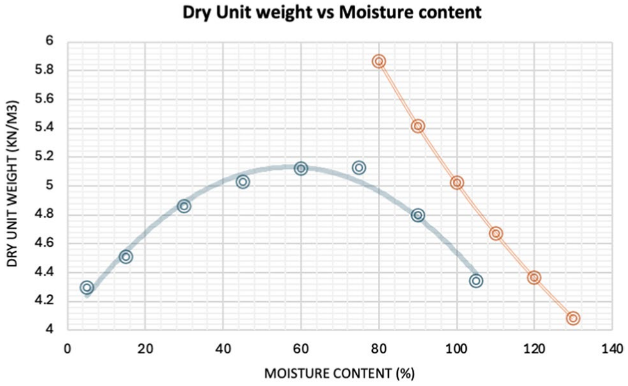


Table 2 A summary of the prepared samples system

Sample specimen	Number of peat layers	Number of gypsum layers	Total number of layers	Curing days
Sample 1	3	2	5	7, 28, 60
Sample 2	4	3	7	7, 28, 60
Sample 3	5	4	9	7, 28, 60

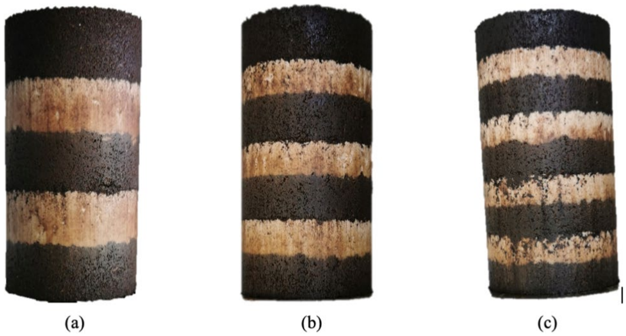


Fig. 4 Remoulded soil specimens prepared by: **a** 5 layers, **b** 7 layers and (**c**) 9 layers

2.2 Additive sample

Gypsum was collected as an additive material in the study from an industrial company that processed the rare earth mineral and produced the by-product waste Magnesium-rich synthetic gypsum (MRSG). The synthesised gypsum was collected and stored in a dry condition. According to ISO 10523. [28], the pH was tested and revealed that gypsum is a highly alkaline material, as its pH level is 9.47.

2.3 The research design

The methodology for this study on peat soil stabilisation using MRSG through a multi-layered backfill method follows a systematic approach. Initially, the study identifies challenges related to peat soil stabilisation and sets clear research objectives to enhance soil strength with MRSG. Soil samples and MRSG additives were collected and prepared. Then, layered sample specimens were meticulously prepared with varying configurations (5, 7, and 9 layers) and cured for 7, 28, and 60 days.

After the characterisation of untreated peat, the soil stabilisation using MRSG by the multi-layering backfill method was recreated on a small scale. The recreation was performed in the laboratory by developing layered sample specimens.

Laboratory testing includes the UCS test to assess bearing capacity and scanning electron microscopy (SEM), energy dispersive X-ray spectroscopy (EDX), and X-ray diffraction (XRD) analyses for microstructural and mineralogical characterisation. Results from these tests are analysed to evaluate the effectiveness of MRSG in enhancing peat soil strength under different curing durations. Conclusions drawn from the experimental findings guide recommendations for future research on optimising MRSG application in peat soil stabilisation for practical engineering applications.

3 Methodology

3.1 Sampling procedure

The sample specimens were backfilled with three different numbers of layers in order to know which numbered layer achieved the maximum strength. The first sample was prepared with three layers of peat and two layers of gypsum, which totalled up to 5 layers. The second layered specimen was prepared with four layers of peat and three layers of gypsum, totalling seven layered backfill specimens. As the final specimen, it was backfilled with five layers of peat and four layers of gypsum to a total of 9 layers. Table 2 summarises the prepared samples system for this study, while Fig. 4 shows the prepared sample specimens by backfilling method. All the sample specimens prepared are the same in size and diameter and cured for three different curing days, which are 7, 28 and 60 days. A peat controller was also prepared using the same method with the same size and diameter to compare the Strength of treated and untreated peat under an unconfined compression strength test.

The height of each layer in the sample specimens was determined based on the equivalent heights of each layer between the peat and the MRSG additive, where different configurations were systematically tested to assess their impact on soil strength. This method allowed for exploring various combinations of peat and gypsum layers (ranging from 5 to 9 layers) to identify which configuration maximally enhanced the mechanical properties of the peat soil.

After determining the optimal layering configurations, the samples underwent air curing, a method for stabilising peat soil by exposing it to air after combining it with gypsum. During air curing, gypsum interacts with organic components in the peat soil to form calcium sulfate, which binds soil particles together, reducing water content and compressibility. This process enhances the peat soil's Strength and resilience against erosive factors like weathering and erosion, which applies to both field and laboratory samples. Following air curing periods of 7, 28, and 60 days, the samples were evaluated to measure the increased Strength of gypsum-stabilised Peat. Over time, as the curing progressed, moisture content decreased, resulting in hardened and strengthened peat soil [32].

3.2 Experiment procedure

3.2.1 Mechanical properties analysis

The UCS test was conducted according to BS EN ISO 17892–7. [31] evaluates the strength and deformation properties of the studied peat. Remoulded cylindrical specimens for untreated Peat and MRSG-treated Peat with 5, 7, and 9 layers (length: 76 mm, diameter: 38 mm) were prepared based on Proctor data. These samples were cured for 7, 28, and 60 days. The test involves placing cured specimens between two plates and applying an axial load until failure, with load and axial deformation recorded using a semi-electronic controlled MTS UCS testing apparatus. Data collected electronically were analysed to calculate the unconfined compressive Strength. Each test was repeated three times for statistical significance. The results, including stress–strain curves, compressive Strength, and failure type, provide insights into the soil's compressive Strength and geotechnical properties.

3.2.2 Mineral & morphological analysis

Mineral analysis involves identifying and quantifying the minerals in peat soil, such as quartz, mica, plagioclase, and feldspar [33]. The description and measurement of the size, porosity, structure, color, texture, shape, and distribution of soil particles, aggregates, as well as horizons are the main objectives of morphological analysis [34]. The current study used SEM, energy-dispersive X-ray spectroscopy (EDX), and X-ray diffraction (XRD) methods to investigate the structure and composition of peat soil. These methods of analysis offer a thorough comprehension of the soil's morphological and mineralogical properties essential for determining if the soil is suitable for stabilization and other geotechnical uses.

1. SEM analysis: this analysis involves producing high-resolution images for the analyzed sample's morphology and topography [35]. In this study, SEM analysis was conducted to analyze the structure and content of peat soil before and after stabilization, which is conducted by using a concentrated electron beam to scan the soil samples surfaces. This analysis was carried out in accordance with the ASTM E1508 [36] standard, and offer comprehensive images providing details about the shape, texture, as well as arrangement of
2. EDX analysis: This type of analysis represents an analytical approach that is employed in order to discover the elements distribution and composition [37]. According to Brostrøm et al. [38], EDX system detects different X-rays generated by the analyzed sample when triggered by the electron beam in the SEM. The EDX employed in this study was performed in accordance with ASTM E1508 [36], and the results disclose the components contained in the stabilized peat soil.
3. XRD analysis: XRD is a test used to detect and quantify the materials' crystalline phases [39]. In this study, the XRD analysis was conducted according to the ASTM D8453 [40] standard, which was carried out by concentrating an X-ray beam on the peat sample and analyzing the diffraction pattern, hence, identifying the crystalline arrangement and chemical composition of the tested peat soil. The XRD was performed on the stabilized peat soil samples in order to detect the mineral composition changes and cementation material formation. Following a 28-day curing period,

several soil samples were examined using XRD with a phase size of 0.02°, a scan phase duration of 0.1 s, and a 2θ range from 5° to 80°. These analyses were performed using a D8 Advance Bruker instrument, specifically the LYNXEYE model, equipped with an X-ray tube that emits Cu K radiation.

Table 3 summarises the experimental tests conducted for mechanical, mineral, and morphological analysis.

The data analysis for this study will encompass several facets. Firstly, it will compare the UCS results from testing untreated peat soil against samples treated with varying configurations of gypsum layers (5, 7, and 9 layers). These comparisons will be conducted across different curing periods of 7, 28, and 60 days to evaluate the influence of gypsum addition and curing duration on soil strength. Additionally, mineral and morphological analyses will be performed on the peat samples to assess changes induced by gypsum layers and curing periods. This comprehensive analysis aims to elucidate the effects of layering and curing on peat soil's mechanical and structural properties, providing insights into its potential stabilisation mechanisms.

Ethical considerations centred on safeguarding the confidentiality and integrity of data collected from samples and participants. Measures were taken to ensure privacy and anonymity. As for limitations, challenges included sample variability, which may affect the general applicability of findings. Despite these constraints, rigorous experimental protocols were followed to minimise biases and provide robust results.

4 Results and discussion

4.1 Effect of MRSG on pH of peat soil

Peat is inherently very acidic, which can negatively impact soil strength. Therefore, adding MRSG for stabilisation purposes can effectively raise the pH of peat soil. Initial pH testing on untreated peat samples from the Gebeng site revealed a highly acidic pH of 3.86, influenced by microbial decomposition, cation exchange, and atmospheric acids. In contrast, MRSG used for stabilisation showed a pH of 9.47, demonstrating its alkaline nature. Subsequent pH testing on treated peat samples confirmed that mixing with MRSG neutralises the soil's acidity, thereby balancing its pH level. Table 4 presents the pH results for untreated peat treated with layered and raw gypsum.

The pH results indicate significant changes in the acidity levels of peat samples after treatment with layered gypsum over different durations. Following treatment, the pH of peat samples gradually shifted towards neutrality. After seven days of treatment, pH values ranged from 7.63 to 7.80 across different layers, indicating effective neutralisation. This trend continued at 28 and 60 days, stabilising pH values between 7.46 and 7.91, demonstrating sustained pH-balancing effects. These results underscore layered gypsum's efficacy in neutralising peat soil's acidity, making it more suitable for various construction applications where soil pH is critical for optimal performance.

4.2 Effect of MRSG on UCS of peat soil

The UCS test assesses the Strength of samples after 7, 28, and 60 days, measuring both force and deformation. Table 5 presents lab results, showing Strength for each layer number and curing days.

Table 3 Experimental summary

Test	Sample type	Layers	Curing periods	Number of samples
Unconfined compressive strength (UCS)	Untreated	–	–	3
	Treated	5, 7, 9	7, 28, 60 days	27
Mineral analysis (XRD)	Untreated	–	–	3
	Treated	5, 7, 9	7, 28, 60 days	27
Morphological analysis (SEM)	Untreated	–	–	3
	Treated	9	7, 28, 60 days	9
Energy dispersive X-ray (EDX)	Untreated	–	–	3
	Treated	9	7, 28, 60 days	9

Table 4 Results on pH values of untreated peat, raw gypsum, and treated peat with gypsum by layers and curing days

Types of samples	Layers	pH value	Condition
Untreated peat	–	3.86	Acidic
Raw gypsum	–	9.50	Alkaline
Treated peat (7 days)	5	7.70	Neutral
	7	7.63	Neutral
	9	7.80	Neutral
Treated peat (28 days)	5	7.84	Neutral
	7	7.80	Neutral
	9	7.91	Neutral
Treated peat (60 days)	5	7.87	Neutral
	7	7.46	Neutral
	9	7.81	Neutral

Table 5 Average Strength achieved by each type of soil specimen according to curing days

Soil sample	Average strength obtained (kPa)			
	No curing	Seven days curing	28 days curing	60 days curing
Peat controller	51.87	–	–	–
5 Layers	–	117.89	146.01	141.92
7 Layers	–	163.44	146.39	148.09
9 Layers	–	210.33	182.96	198.96

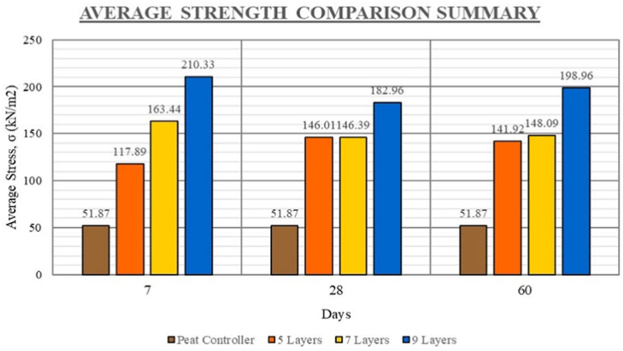


Fig. 5 Average strength summary and comparison of all treated and untreated peat specimens under different layers and curing days

The average UCS value of 51.87 kPa for the peat controller indicates that untreated peat has low shear Strength. In the context of UCS, this low value suggests that the soil has relatively weak resistance to axial compressive stresses when not laterally confined. A low UCS implies a weaker soil structure, making it prone to breaking or deforming under applied stresses. Such soil may lack the Strength needed to support foundations or buildings adequately.

Using multiple layering, treated Peat with MRSG backfill ranges from 141.92 to 210.33 kPa based on layer number and curing days. Figure 5 graphically displays the average compressive strengths for comparison between treated and untreated values.

The untreated peat soil demonstrated the lowest Strength at 51.87 kPa, highlighting its inherent weakness. Among the gypsum-treated samples, the 9-layer backfilled specimen exhibited the highest Strength at 210.33 kPa after seven days. This is significantly higher compared to the 5-layer and 7-layer specimens, which showed strengths of 117.89 kPa and 163.44 kPa, respectively. These results indicate that the Strength of peat soil increases with the number of layers of gypsum backfill, with the highest Strength achieved within the first seven days of treatment.

However, over time, the Strength of the treated specimens showed some variations. After 28 days, the Strength of the 7-layer and 9-layer specimens slightly decreased to 146.39 kPa and 182.96 kPa, respectively, while the 5-layer specimen's Strength increased to 146.01 kPa. This fluctuation suggests that while the initial stabilisation is highly effective, the strength gains can vary as the soil consolidates and interacts with the stabilising agent. The similar strength values of the 5-layer and 7-layer specimens at 28 days could be attributed to differences in consolidation and curing conditions, where the stabilisation effect may plateau or exhibit nonlinear behaviour.

After 60 days, the Strength of the 7-layer and 9-layer specimens increased again to 148.09 kPa and 198.96 kPa, respectively, whereas the Strength of the 5-layer specimen decreased slightly to 141.92 kPa. These observations suggest that a longer curing period allows for continued interaction between the peat and the gypsum, potentially leading to further stabilisation and strength gains in certain conditions.

Overall, the 9-layer backfilling with MRSG consistently achieved the highest Strength throughout the testing periods, making it the most suitable method for stabilising peat soil. This layered approach facilitates better distribution and interaction of the stabilising agent within the soil matrix, contributing to improved mechanical properties and increased soil strength. The observed fluctuations in Strength, including the initial drop after seven days for higher-layer specimens, may be due to the complex interactions between the gypsum and organic matter, moisture content variations, and consolidation dynamics over time.

Many recent studies employed the UCS test in order to measure the soil stabilization additives' efficiency, including [41–44]. UCS is notably important in road construction and foundation works, where it serves as a primary design standard [21, 42].

Recent studies such as Koaly & Pui [45] and Almsedeen et al. [46] have shown varying increases in UCS values with gypsum treatments. Koaly & Pui [45] reported an increase in peat UCS from 20 kPa to 44.94 kPa with 6% gypsum after 28 days, highlighting significant improvements. Similarly, Almsedeen et al. [46] observed an increase in UCS from 15.45 kPa at 0% MRSG to 59.15 kPa at 5% MRSG added into the soil after 28 curing days. In contrast, our study employed an MRSG layering approach, demonstrating even higher UCS values. The untreated peat exhibited a UCS of 51.87 kPa, which increased notably to 182.96 kPa for the 9-layer configuration after the same curing period (28 curing days). This significant enhancement suggests that the layering method may provide more effective soil stabilisation and stronger mechanical properties than traditional mixing methods with gypsum.

4.3 Effect of MRSG on microstructure analysis of peat soil

4.3.1 Scanning electron microscopy (SEM)

The microstructure analysis was conducted on the treated peat sample specimens to discover the bonding between peat and synthetic gypsum. Figures 6 and 7 show the image generated via SEM analysis. As depicted in Fig. 6, the untreated peat soil sample exhibits a rounded shape, high porosity, significant voids, loose organic fibres, and coarse organic particles. The morphology of untreated peat soil particles lacks an apparent microstructure orientation, appearing randomly arranged.

The SEM analysis was conducted on the samples with the highest UCS results, specifically the 9-layer backfilled treated sample, after seven days of curing and 90 days. The results are shown in Fig. 7.

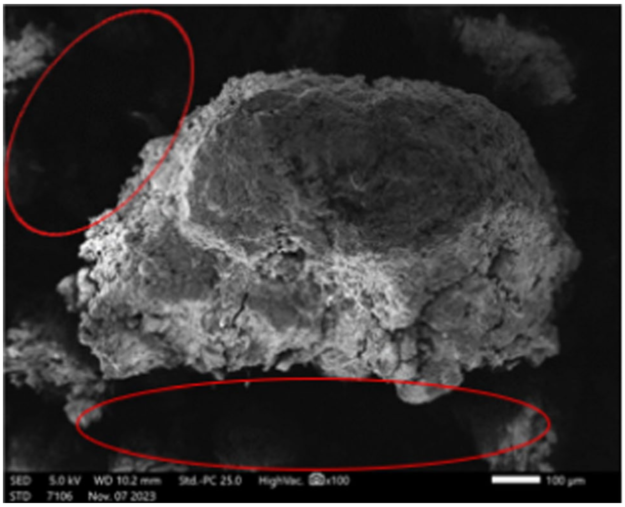


Fig. 6 Microscopic image from SEM analysis for peat sample before stabilisation

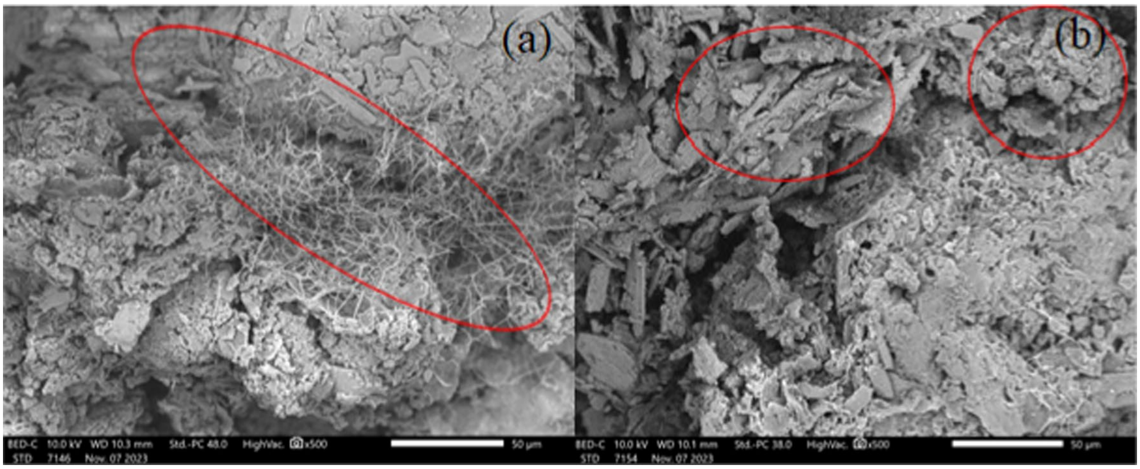


Fig. 7 Microscopic image from SEM analysis for nine layers of the backfilled treated sample (**a**) after seven days of curing and (**b**) after 60 days

As shown in Fig. 7 (a), the SEM analysis reveals significant changes in the sample structure after seven days of curing. The initially observed large lumps appear compressed, with a visible reduction in voids, indicating the beginning of coagulation and bonding formation when peat is treated with synthetic gypsum. According to Ebailila [47], this bonding process is facilitated by ettringite, which acts as a key mechanism in stiffening the peat-gypsum composite.

Upon reaching 60 days of curing, Fig. 7 (b) illustrates well-defined, robust structures with a rough, crystalline surface, illustrating a strong interlocking relationship between gypsum and peat. This crystalline structure highlights the robust bond formed between the two materials.

The SEM analysis of this study's stabilised peat soil samples revealed the formation of robust cementitious bonding structures, particularly at longer curing times. This is consistent with the findings of Mustapa et al. [48], who used SEM to observe the development of dense, interlocking crystalline structures when gypsum was added to organic soil. The SEM images in their study showed the gradual filling of pore spaces and the formation of a more compact soil matrix over time, which they attributed to the cementitious reactions between the gypsum and soil particles. Similarly, Ahmad et al. [9] employed SEM to analyse the microstructural changes in peat soil treated with cement kiln dust and rice husk ash, noting the presence of hydration products that contributed to the observed strength gains. The current study's SEM analysis and recent investigations highlight the importance of cementitious bonding in enhancing the engineering properties of peat soil when stabilised with gypsum and other cementitious additives.

4.3.2 The X-ray diffraction (XRD) analysis

The X-ray diffraction (XRD) was carried out to identify the minerals and reveal the pozzolanic activities in stabilised peat upon treatment with Mg-rich synthetic gypsum. The diffraction patterns of the studied treated peat showed that it was a heterogeneous material comprising a mixture of crystalline phases. Figure 8 illustrates the XRD results of untreated Peat, Peat treated with Mg-rich synthetic gypsum (MRSG).

The XRD analysis of the stabilised peat samples was conducted after 7 and 60 days of curing. Quartz (SiO2) was identified as the primary mineral with the highest peak in untreated peat. Conversely, in peat treated with MRSG using a 9-layer backfill method after 7 and 60 days, bassanite (2CaSO4·H2O) emerged as the predominant mineral, alongside gypsum (CaSO4·2H2O), which is related to bassanite. These minerals indicate a high pH environment due to the abundance of CaSO4·2H2O, suggesting effective neutralisation of acidity and enhancement of soil properties. Sharp peaks in the XRD patterns at both curing periods for the 9-layer configuration indicate increased crystallinity over time. This enhancement in crystalline structure supports the formation of cementitious products, notably observed in Fig. 8, such as ettringite, calcium silicate hydrate (C-S-H), and calcium aluminium silicate hydrate (C-A-S-H). These products contribute to a robust bonding network that enhances interparticle friction and soil stability. The higher peak intensities in treated peat than untreated peat indicate substantial mineral formation attributed to MRSG's pozzolanic reactions [9].

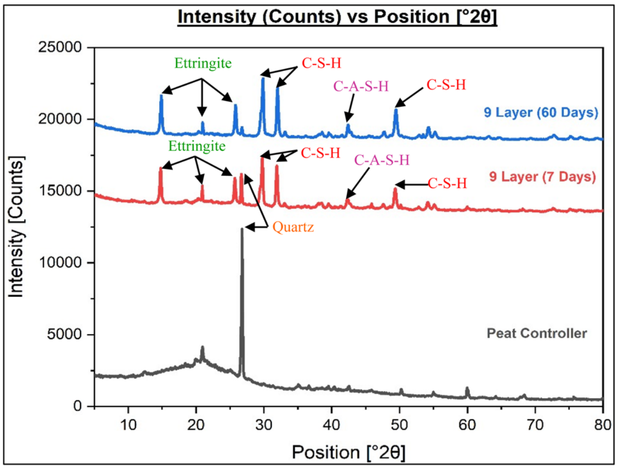


Fig. 8 XRD analysis of untreated and treated peat for seven and 60 days

4.3.3 Energy dispersive X-ray (EDX) analysis

EDX analysis was conducted on both treated (with nine MRSG layers) and untreated peat samples to compare the elemental composition after 7, 28, and 60 days. The results are summarised in Table 6.

EDX analysis was employed to analyse the elemental composition of untreated and treated peat samples with nine layers of MRSG backfill after curing periods of 7, 28, and 60 days, revealing significant insights into the chemical transformations occurring during stabilisation. Initially, untreated peat showed predominant levels of carbon (55.08%) and oxygen (39.66%), characteristic of high organic content. The addition of MRSG backfill caused significant alterations in elemental composition, notably in increased magnesium (Mg), silicon (Si), and aluminum (Al) content within seven days of curing and remained to climb for 60 days. This behavior can be related to hydration actions triggered by magnesium hydrate inside the MRSG, which result in the formation of cementitious compounds such as magnesium silicate hydrate (M-S–H) and magnesium aluminate hydrate (M-A-H). These chemicals function as binding agents, increasing the cohesiveness and durability of the peat soil matrix with time.

According to Zimar et al. [49], the increase in magnesium, silicon, and aluminium levels reflects the progressive incorporation of these elements into the stabilised peat structure, forming durable bonds that improve mechanical properties such as compressive Strength and shear resistance. The observed chemical transformations underscore MRSG backfill's effectiveness in altering peat's elemental composition and promoting long-term stability and resilience against environmental factors.

Table 6 Presence of chemical elements in both treated and untreated peat

Element	Mass (%)		
	Peat controller	9 Layers (7 Days)	9 Layers (60 Days)
Carbon, C	55.08	29.56	6.83
Oxygen, O	39.66	42.21	47.76
Silicon, Si	2.37	1.07	0.71
Aluminium, Al	2.55	1.81	0.04
Calcium, Ca	NA	4.96	23.61
Magnesium, Mg	NA	7.38	4.38
Sulphur, S	NA	4.09	16.17

5 Conclusion

This research has delineated the engineering attributes of peat soil in Gebeng, Pahang, an industrial locale. It delved into the Strength of stabilised peat soil analysis using MRSG through the multi-layering backfill approach, with curing at intervals of 7, 28, and 60 days. The experimental analysis led to the following conclusions.

1. pH Adjustment: MRSG effectively neutralised the highly acidic nature of peat soil, raising pH levels from 3.86 (untreated) to approximately 7.63–7.91 after 7, 28, and 60 days of curing. This pH adjustment enhances soil stability for construction applications.
2. UCS Improvement: Peat soil treated with MRSG, particularly with a 9-layer backfilling method, exhibited significant UCS improvements. The Strength increased from 51.87 kPa (untreated) to 210.33 kPa after seven days of curing, demonstrating enhanced mechanical properties essential for load-bearing applications.
3. Microstructural Changes: SEM analysis revealed the development of compact, bonded structures in MRSG-treated peat soil. These structures evolved into robust, interconnected networks over time, indicating effective cementitious bonding and reduced porosity.
4. Chemical Composition: EDX and XRD analyses showed increased magnesium, silicon, and aluminium content in treated peat soil, suggesting pozzolanic reactions and the formation of durable cementitious compounds like gypsum and bassanite. These compounds contribute to improved soil cohesion and stability.

In conclusion, the application of MRSG through layered backfilling demonstrates its efficacy in significantly improving the engineering properties of peat soil, thereby rendering it suitable for sustainable construction practices. However, this study's limitation lies in its focus on a specific type of peat soil from Gebeng, Pahang, which may limit direct applicability to peat soils with differing characteristics in other regions. Therefore, future research should further investigate this stabilisation method's effectiveness across various types of peat soils and explore optimal application conditions and long-term performance to refine its utilisation in diverse environmental settings.

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Author contributions J.S wrote the main manuscript and contributes in data analysis A.J. M contributes in revising the technical part of the manuscript and prepared the tables and figures in the manuscript. N.M review the main manuscript and contribute to the main idea of the research as well as data interpretation.

Data availability The authors declare that the data supporting the findings of this study are available within the paper. Should any raw data files be needed in another format they are available from the corresponding author upon reasonable request. Source data are provided with this paper.

Declarations

Competing interests The authors declare no competing interests.

References

1. Parish F, Lew SY, Mohd Hassan AH. National strategies on responsible management of tropical peatland in Malaysia. Tropical Peatland Eco-Manag. 2021. https://doi.org/10.1007/978-981-33-4654-3_26.
2. Khan F. Types Of Soil. Construction How. 2020. https://constructionhow.com/types-of-soil/. Accessed 21 Jun 2024.
3. Li W, O'Kelly BC, Yang M, Fang K, Li X, Li H. Briefing: The specific gravity of solids is related to ignition loss for peaty soils. Geotechn Res. 2020;7(3):134–45. https://doi.org/10.1680/jgere.20.00019.
4. Khanday SA, Hussain M, Das AK. A review on chemical stabilisation of peat. Geotech Geol Eng. 2021;39(8):5429–43.

5. Lihua P, Xingyu Y, Yue G, Zhaochang W, Yi Z. Influence of organic matter content and ingredient on the physical and mechanical properties of peat soils. Hydrogeol Eng Geol. 2022;49(2):77–85. https://doi.org/10.16030/j.cnki.issn.1000-3665.202106009.
6. Ritonga AS. Shear strength parameters of peat soil of district of Asahan by direct shear test. IOP Conf Series Materi Sci Eng. 2020;801(1):012013. https://doi.org/10.1088/1757-899X/801/1/012013.
7. Suhairiani S, Panjaitan NH, Sinaga E, Yuzni S. 2022 Analysis of the addition of 10% lime on unconfined compressive strength test of Humbang Hasundatan's soil peat. Proceedings of the 4th International Conference on Innovation in Education, Science and Culture, ICIESC 2022 11 October 2022 Medan, Indonesia.
8. Saida NA, George AD, Mohamad HM. A review on experimental investigations and geotechnical characteristic of peat soil stabilization. Int J Adv Res Eng Innov. 2023;5(1):1–19.
9. Ahmad A, Sutanto MH, Ahmad NR, Mohamad ME, Bujang M. Microstructural characterisation of fabric peat stabilised with Portland cement and silica fume. Materials. 2022. https://doi.org/10.3390/ma16010018.
10. Barman D, Dash SK. Stabilisation of expansive soils using chemical additives: a review. J Rock Mechan Geotechn Eng. 2022;14(4):1319–42. https://doi.org/10.1016/j.jrmge.2022.02.011.
11. Aishat Sani M, Umar Chinade A, Mamuda A, Batari A, Dalhatu AM. Effect of gypsum in proportion of other additives used in stabilization of deficient soils: a review. J Civil Constr Environ Eng. 2021;6(6):161. https://doi.org/10.11648/j.jccee.20210606.11.
12. Phanikumar BR, Raju ER. Compaction and strength characteristics of an expansive clay stabilised with lime sludge and cement. Soils Found. 2020;60(1):129–38. https://doi.org/10.1016/j.sandf.2020.01.007.
13. Verma H, Ray A, Rai R, Gupta T, Mehta N. Ground improvement using chemical methods: a review. Heliyon. 2021. https://doi.org/10.1016/j.heliyon.2021.e07678.
14. Paul SC, Kong SY, Ong CM, Jayaprakash J, Tao X. Properties of high-strength mortar incorporating recycled gypsum in concrete: a novel approach to improve environmental sustainability. Constr Build Mater. 2022;362: 129699. https://doi.org/10.1016/j.conbuildmat.2022.129699.
15. Wahab A, Embong Z, Hasan M, Musa H, Zaman QU, Ullah H. Peat soil engineering and mechanical properties improvement under the effect of EKS technique at Parit Kuari, Batu Pahat, Johor West Malaysia. 2020. Bull Geol Soc Malaysia. https://doi.org/10.7186/bgsm70202011.
16. Mekonnen E, Kebede A, Tafesse T, Tafesse M. Application of microbial enzymes in soil stabilisation. Inter J Microbiol. 2020;2020(1):1725482.
17. Mohamad ME, Ahmad A, Sadon HB, Sutanto MH, Bujang M, Kifli ABZ, Mohamad SNA. Peat stabilization using waste crumb rubber tire. Civil Eng Archit. 2022;10(7):3253–63. https://doi.org/10.13189/cea.2022.100735.
18. Fatima B, Alshameri B, Hassan W, Maqsood Z, Jamil SM, Madun A. Sustainable incorporation of Plaster of Paris kiln dust for stabilisation of dispersive soil: a potential solution for the construction industry. Constr Build Mater. 2023;397: 132459. https://doi.org/10.1016/j.conbuildmat.2023.132459.
19. Hassan W, Alshameri B, Maqsood Z, Haider A, Jamil SM, Mujtaba H. An innovative application of fine marble dust for the construction industry to mitigate sodium-rich clay's piping, internal erosion and dispersion problems. Constr Build Mater. 2023;408: 133834. https://doi.org/10.1016/j.conbuildmat.2023.133834.
20. Hassan W, Alshameri B, Haider A, Maqsood Z, Jamil SM, Shahzad A. A novel technique for the construction industry to mitigate sodium-rich clays' dispersibility and internal erosion problems by using Water-Soluble potassium-rich ions material. Constr Build Mater. 2023;400: 132780. https://doi.org/10.1016/j.conbuildmat.2023.132780.
21. Hassan W, Alshameri B, Jamil SM, Maqsood Z, Haider A, Shahzad A. Incorporating potassium-rich waste material sustainably stabilises dispersive clay: a novel practical approach for the construction industry. Constr Build Mater. 2023;400: 132717. https://doi.org/10.1016/j.conbuildmat.2023.132717.
22. Hassan W, Farooq K, Mujtaba H, Alshameri B, Shahzad A, Nawaz MN, Azab M. Experimental investigation of mechanical behaviour of geosynthetics in different soil plasticity indexes. Trans Geotechn. 2023;39: 100935. https://doi.org/10.1016/j.trgeo.2023.100935.
23. ASTM D4427 – 23. Standard Classification of Peat Samples by Laboratory Testing. United States of America: ASTM International. 2023.
24. BS EN ISO 17892–4. Geotechnical investigation and testing – Laboratory testing of soil – Part 4: Determination of particle size distribution. PKN. 2017.
25. BS EN ISO 17892–12. Geotechnical investigation and testing. Laboratory testing of soil. Part 12: Determination of liquid and plastic limits. 2018.
26. BS ISO 17892–3. Geotechnical investigation and testing — Laboratory testing of soil — Part 3: Determination of particle density. ISO/TC 182 Geotechnics. 2015.
27. BS 1377–2. Methods of testing for soils for civil engineering purposes. Classification tests and determination of geotechnical properties. 2022.
28. ISO 10523. Water quality — Determination of pH. 2008.
29. Smith SL, Burgess MM, Lawrence DE. Digital Borehole Geotechnical Database for the Mackenzie Valley-Delta Region. Her Majesty the Queen in Right of Canada; 2005.
30. Huat BBK. Organic and peat soils engineering. Serdang: Universiti Putra Malaysia Press; 2004. p. 146–50.
31. BS EN ISO 17892–7. (2018). Geotechnical Investigation and Testing. Laboratory Testing of Soil Part. 7: Unconfined Compression Test. Strength.
32. Kolay PK, Pui MP. Peat stabilisation using gypsum and fly ash. J Civil Eng Sci Technol. 2010;1(2):1–5. https://doi.org/10.33736/jcest.75.2010.
33. Amupitan AJ. Mineralogy, geochemistry and potential uses of clay in Pandogari area, north-central, Nigeria (Doctoral dissertation). 2021. http://repository.futminna.edu.ng:8080/jspui/handle/123456789/15018. Accessed 2 July 2024.
34. Owens PR, Libohova Z. Soil morphology. Ref Mod Earth Syst Environ Sci. 2022. https://doi.org/10.1016/B978-0-12-822974-3.00142-7.
35. Ali A, Zhang N, Santos RM. Mineral characterisation using scanning electron microscopy (SEM): a review of the fundamentals, advancements, and research directions. Appl Sci. 2023;13(23):12600. https://doi.org/10.3390/app132312600.
36. ASTM-E1508. (2012). Standard Guide for Quantitative Analysis by Energy-Dispersive Spectroscopy
37. Hodoroaba VD. Energy-dispersive X-ray spectroscopy (EDS) characterisation of nanoparticles. Amsterdam: Elsevier; 2020.

38. Brostrøm A, Kling KI, Hougaard KS, Mølhave K. Electron transparent beam-sensitive samples are analysed using scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy. Microsc Microanal. 2020;26(3):373–86. https://doi.org/10.1017/S1431927620001464.
39. Ali A, Chiang YW, Santos RM. X-ray diffraction techniques for mineral characterisation: a review of the fundamentals, applications, and research directions for engineers. Minerals. 2022;12(2):205. https://doi.org/10.3390/min12020205.
40. ASTM D8453–22. Standard test method for mineralogical analysis of soils and rocks by X-Ray diffraction (XRD). ASTM Inter West Conshohocken PA. 2022. https://doi.org/10.1520/D8453-22.
41. Naqeeb M, Muhammad N, Nawaz M, Hassan HW, Chong S, Strength UC. Sustainable incorporation of Plaster of Paris kiln dust for stabilization of dispersive soil: a potential solution for construction industry. World Congr Struct Congr. 2022;16–19:2–4. https://doi.org/10.1016/j.conbuildmat.2023.132459.
42. Hassan W, Alshameri B, Nawaz MN, Ijaz Z, Qasim M. Geospatial and statistical interpolation of geotechnical data for modelling zonation maps of Islamabad, Pakistan. Environ Earth Sci. 2022;81(24):547. https://doi.org/10.1007/s12665-022-10669-2.
43. Nawaz MN, Chong SH, Nawaz MM, Haider S, Hassan W, Kim JS. Estimating the unconfined compression strength of low plastic clayey soils using gene-expression programming. Geomechan Eng. 2023. https://doi.org/10.12989/gae.2023.33.1.001.
44. Attah IC, Etim RK, Ekpo DU, Onyelowe KC. Understanding the impacts of binary additives on the mechanical and morphological response of ameliorated soil for road infrastructures. J King Saud Univ Eng Sci. 2021. https://doi.org/10.1016/j.jksues.2021.12.001.
45. Kolay PK, Pui MP. Peat stabilization using gypsum and fly ash. J Civil Eng Sci Technol. 2010;1(2):1–5. https://doi.org/10.33736/jcest.75.2010.
46. Almsedeen A, Muhammad N, Ishak MF. Preliminary strength characterization of peat soil stabilized with Mg-rich gypsum waste. AIP Conf Proc. 2024. https://doi.org/10.1063/5.0196830.
47. Ebailila M. Sulfate soil stabilisation with silica fume-based binders. Pontypridd: University of South Wales (United Kingdom); 2022.
48. Mustapa NA, Rashid AS, Wan Ibrahim WZ, Ibrahim WN. Chemical stabilisation of peat soils using alkaline activated binder: a review. IOP Conf Series Earth Environ Sci. 2021;682(1): 012027. https://doi.org/10.1088/1755-1315/682/1/012027.
49. Zimar Z, Robert D, Zhou A, Giustozzi F, Setunge S, Kodikara J. Application of coal fly ash in pavement subgrade stabilisation: a review. J Environ Manage. 2022;312: 114926. https://doi.org/10.1016/j.jenvman.2022.114926.