Available online at www.CivileJournal.org

Civil Engineering Journal

(E-ISSN: 2476-3055; ISSN: 2676-6957)

Vol. 9, No. 01, January, 2023

Peat Soil Compaction Characteristic and Physicochemical Changes Treated with Eco-Processed Pozzolan (EPP)

Mohd Syeddre Sutarno [1], Habib Musa Mohamad [1*]

[1] *Faculty of Engineering, Universiti Malaysia Sabah, Jalan UMS, 88400 Kota Kinabalu, Sabah, Malaysia.*

Received 22 August 2022; Revised 24 November 2022; Accepted 11 December 2022; Published 01 January 2023

Abstract

Peat soil was defined as the highly organic surface layer derived primarily from plant remains. Peat, on the other hand, was the subsurface of wetland systems, consisting of unconsolidated superficial layers with a high non-crystalline colloid (humus) content. Peat soils have a low shear strength of 5 to 20 kPa, a high compressibility of 0.9 to 1.5, and a high moisture content of >100%. The purpose of the study was to prognosticate the potential of Eco-Processed Pozzolan (EPP) as peat soil stabilization material with improved technique and its consequence of the methods, which was the peat soils index properties and analyse the characteristics of the peat soil stabilization before and after treatment using Eco-Processed Pozzolan (EPP). The soil was mixed with 10, 20, and 30% Eco-Processed Pozzolan (EPP) and then compacted (compaction test) in a metal mould with an internal diameter of 105 mm using a 2.5 kg rammer of 50 mm diameter, freefalling from 300 mm above the top of the soil Three layers compaction of approximately equal depth and 27 blows spread evenly over the soil surface for each layer. The expected result to accomplish the main purpose was to prognosticate the potential Eco-Processed Pozzolan (EPP) as peat soil stabilization material with improved technique and its consequence of the methods. According to the findings, peat soil treated with EPP will transform its qualities from peat to usable soil. However, the presence of moisture will reduce the mixture's ability. According to the findings of this study, the optimum EPP for stabilizing peat soils was 30-40%. Correspondingly, the elemental composition of peat soil mixed with EPP improved regardless of Carbon, Ca composition. Comparatively, the amount of Silicon, Si increased from 6.5% (Peat + EPP 10%) to 12.9% (Peat + EPP 40%) due to the crystallization of EPP and peat.

Keywords: Peat; Stabilization; Eco-Processed Pozzolan; Crystallization; Soil Compaction.

1. Introduction

In the previous study, the term "peat soil" was defined as the highly organic surface layer that was derived primarily from plant remains. On other hands, peat was unconsolidated superficial deposits with high non-crystalline colloid (humus) content, constituting the subsurface of wetland systems. Generally, it has a dark brown to black colour, an organic odour, and a mostly spongy consistency. There was a time when plant fibers were visible, and they may not be in advanced stages due to peat soil decomposition, as claimed [1]. Botanical composition and degree of coalification were the main things that needed to be considered before categorizing the types of peat soils. The coalification process was only beginning, and lignin, cellulose, and even microorganism proteins can be seen in its structure. The pyrolysis of peat generates a compound typical for its component that allows identification of information on the peat component, classification of the peat by its origin, and the evaluation of the degree of coalification [2].

Peat soil can be found in the swamp area, which was the surface area was an organic layer of soil that consists partially of decomposed organic matter derived mostly from plant matter that has accumulated under conditions of

* Corresponding author: habibmusa@ums.edu.my

http://dx.doi.org/10.28991/CEJ-2023-09-01-07

waterlogging, high acidity, oxygen deficiency, and nutrient insufficiency. Based on the previous work of Razali et al. [3], peat soils have a low shear strength of around 5–20 kPa, high compressibility (0.9–1.5), and a high moisture content (>100%). Peat also has a large deformation, high magnitude, and rates of the screen, containing organic matter (>75%). Therefore, the peat soil was not suitable for the placement of any foundation or road and any construction in the peatland. Peat commonly occurs as extremely soft, wet, unconsolidated superficial deposits and is normally an integral part of wetland systems [4]. They may also occur as stratum underneath layers of superficial deposits. The term "peat" was described as a highly organic chemical formed mostly from plant components that occur naturally. It was formed when organic matter accumulates more quickly than it decays. This was usually occurring when organic matter was preserved below high-water tables like in swamps or wetlands. Peat soils need to be stabilized so that can be used for the construction area and any other uses in the future. Therefore, this research will focus on stabilizing the peat soils on the compaction characteristics by using the method of compaction testing of the peat soils at Klias Peat Swamp Forest, Sabah. The result of the test was taken before and after mixing the sample with Eco-Processed Pozzolan (EPP). Expecting result was the soil stabilized that will give a high shear strength, low compressibility, and normal moisture content.

In terms of chemical properties, peat soils contain a high-water content of around 88–92% and 50–60% carbon, typically consisting of hydrogen (5-7%), nitrogen (2-3%), phosphorus (<0.2%), and mineral nutritional elements and oxygen, which does not have more than 35% of the dry ingredient weight mass [5]. Peat soils were characterized by a high-water table, an absence of oxygen, a reducing condition, low bulk density and bearing capacity, a soft, spongy substratum, low fertility, and usually high acidity. Peatland vegetation includes Sphagnum mosses, rushes and sedges, bog cotton, ling heather, bog rosemary, bog asphodel, and sundew. There were also forested peatlands in Europe (Alder forests) and humid lowland tropical areas of Southeast Asia (freshwater swamp forests and mangroves). Peat soils were characterized by the high-water table, absence of oxygen, reducing condition, low bulk density and bearing capacity, soft spongy substratum, low fertility, and usually high acidity [6]. Peat soils occur in all regions, but they are more common in the Northern Hemisphere's temperate and frigid zones. North America has covered 117.8 *M ha* (million hectares) of peatlands, which are the largest among the other regions, followed by Europe at 75.0 M ha while 23.5 M ha in Asia and the Far East, 12.2 M ha in Africa, 7.4 M ha in Latin America, and 4.1 M ha in Australia. The latest research [7] found that 1,689,171 km^2 was in the tropical peatland zones. Miettinen et al. (2011) [7] discovered a 1.0 percent annual reduction in forest cover throughout insular Southeast Asia (including the Indonesian half of New Guinea); peat swamp forests experienced the highest deforestation rates of 2.2%, with main change trajectories to secondary vegetation and plantations. Total land in Malaysia was covered by peat soil about 2.5 million ha (7.74%).

Peat soil was regarded as one of the most problematic soils to work with. Peat has high compressibility, low shear strength, high moisture content, and low bearing capacity [8]. Peat was considered an undesirable soil for supporting foundations in its natural state due to its high compressibility (0.9–1.5), moisture content (>100%), and low shear strength (5–20 kPa) values [3]. Peat also contains high organic matter (>75%), large deformation, high compressibility, and high magnitude and rates of creep. These characteristics lead to problems and challenges in the construction process in various aspects, such as pre-construction difficulty, post-construction failures, cost of construction, maintenance issues, as well as short- and long-term impacts. Sustainable design, selecting suitable materials, reducing the cost of construction, prolonging the service duration, and minimizing the necessity of maintenance impacts were the challenges to be considered and adopted before constructing infrastructure on peatland [9]. There were several techniques and methods to overcome the problem of the compaction characteristic of peat soil; thus, this study employed the technique of Eco-Processed Pozzolan (EPP). Eco-processed pozzolan (EPP) is a sustainable product recycled from spent bleaching earth (SBE). It was recently used as a blended cement. The pre-treatment method of palm oil generates SBE as waste material in the refinery plant. Despite sending the SBE to the landfill, which can lead to environmental pollution, it was extracted to produce sustainable products. The physical, chemical, mineralogical, and microstructural characteristics of EPP were analyzed [10]. The physical properties of EPP. The particle size, d90 of EPP 94.36 μm. The mean particle size, d50, of EPP was 29.3 μm. Based on the results, the specific gravity of EPP is 1.93. The XRF result reveals that the EPP is composed of SiO_2 at 47.6% and the combined value of SiO_2, aluminum oxide (Al_2O_3), and iron oxide (Fe_2O_3) is 68.98%. The value was less than 70% according to the c However, it was more than 50%, which the EPP can be classified as a Class C pozzolan. The EPP contains a high percentage of SiO_2. The loss on ignition of EPP was 3.3%, which was less than 6% as specified in the ASTM C618 standard.

From the chemical compositions, according to the ASTM C168 standard, the EPP can be classified as a Class C pozzolan. In this research, the compaction test was used for determining maximum unit weight and optimum moisture content principal factors influencing maximum dry unit weight and optimum moisture content. Terzaghi's principle of experimental examination and its effective stress were discussed [11]. An amount of EPP was added to the peat to stabilize the soil, and the results were tested again. The result of this study to accomplish the main purpose was to prognosticate the potential Eco-Processed Pozzolan (EPP) as peat soil stabilization material with improvement technique and its consequence of the methods.

1.1. Eco Processed Pozzolan (EPP)

Pozzolanic materials have long been utilized as cement substitutes. The usage of pozzolans will reduce the amount of cement used [12, 13]. Carbon 23 dioxide emissions from the cement industry were one of the most significant sources of CO_2. Cement manufacturing accounts for 5-7 percent of worldwide carbon dioxide emissions [13]. Pozzolanic materials can be used as cement substitutes, however, cement was still required to initiate the pozzolanic process, resulting in CO_2 emissions [14]. The major component of EPP's chemical composition was SiO_2, and the overall quantity of SiO_2, Al_2O_3, and Fe_2O_3 was 68.98 percent, which was more than half of what ASTM C618 requires. EPP's SEM micrograph picture revealed some irregularly shaped particles, some reasonably spherical particles, and aggregation of its particles. At 7 and 28 days, the compressive strength of mortar containing 20% EPP as a cement substitute was greater than the control specimen. At 7 and 28 days, EPP's strength activity indices were 114.4 percent and 104.2 percent, respectively. Blended cement was now made with eco-processed pozzolan (EPP) material [10, 15]. It's made from the waste products of refinery facilities' crude palm oil degumming and bleaching processes. Spent bleaching earth (SBE) was the name for this waste product. SBE from refinery plants was often disposed of at landfills in Malaysia. SBE disposal in landfills has the potential to pollute the environment [16].

X-ray fluorescence was used to study the chemical makeup of the materials (XRF). The mortar was tested for compressive strength according to ASTM C109. The strength activity index (SAI) test was used to measure EPP's pozzolanic reactivity by ASTM C311. A scanning electron microscope was used to examine the morphology of EPP (SEM). SiO_2 was the primary component of EPP, accounting for 47.6%, while the total combined quantity of SiO_2, Al_2O_3, and Fe_2O_3 was 68.98%, above the 50% threshold set by ASTM C618. EPP has a loss on ignition of 3.3 percent, which is less than the ASTM C618 limit of 6%. According to ASTM C618, EPP can be categorized as a Class C pozzolan based on chemical composition. The physical characteristics of EPP and OPC have mean particle sizes of 29.3 m and 27.4 m, respectively. EPP and OPC have particle sizes d90 (90 percent of particles are under this size) of 80.42 m and 94.36 m, respectively. EPP has a specific gravity of 1.93, while OPC has a specific gravity of 3.27. EPP has a lower specific gravity than OPC due to its greater mean particle size. Figure 13 shows the micrograph pictures of EPP and OPC. OPC was irregular in form, whereas EPP was made up of irregularly shaped, some relatively spherical, and agglomerated particles, as shown in the SEM picture. EPP's particles have a porous texture, as can be observed in the photograph. Particles having a porous structure have lower specific gravity than those without [17]. EDX has been conducted to study the chemical composition of peat soil [13]. It has been discovered that peat is composed partially of calcium (Ca), Magnesium (Mg), Aluminum (Al) and Silicon (Si). While Azmi et al. (2017) study on FESEM-EDX showed that, the largest element in peat is Carbon (C) at 69.87% and Silicon, Si at 1.27% [18].

1.2. Mechanical Compaction Test

Soil compaction is a process in which soil is subjected to mechanical stress and densification. Soil comprises solid particles and spaces filled with water or/and air. Soil as a three-phase system provides a more extensive explanation of soil's three-phase nature. Soil particles were redistributed within the soil mass when stressed, and the void volume decreased, resulting in densification. Kneading, as well as dynamic and static approaches, can be used to apply mechanical stress. The change in the dry unit weight of the soil, d, was used to determine the degree of compaction. Soil compaction is the process of forcing soil particles to pack closer together by minimizing air gaps, usually using mechanical means with water as the lubricating medium [19]. The air spaces decreased throughout this procedure, but the water content did not. Compaction was used to decrease unwanted settlement, permeability, and swelling, as well as to improve slope stability and soil shear strength, which improves the soil's bearing capacity. In a 1000 cm^3 cylindrical mould, it has been proposed laboratory methods for compaction in which soil particles were compressed at the required compaction effort to imitate the energy that a soil compaction machine delivers to the soil in the field. In most cases, regular Proctor compaction was used for routine traffic loading scenarios, whereas a modified Proctor compaction test was used for situations involving significant unit weights, such as airport pavements [20]. The results of the test, which was conducted in the laboratory using either standard Proctor compaction [21] or modified Proctor compaction (ASTM D-698:2012), were graphically represented as an inverted "V" curve, with the peak referred to as the maximum dry density (MDD) and the corresponding moisture content referred to as the optimum moisture content (OMC) of the soil.

2. Testing and Method

This research aims to investigate the compaction characteristics of peat soil stabilized with Eco-Processed Pozzolan (EPP). The flow planning technique used in this research was discussed in more detail in this chapter. The relevant laboratory work and tests were applied in this chapter in accordance with BS1377-1:1990 [22], British Standard Research Methods for Soil Civil Engineering Purposes, and all required components of this analysis were briefly described in depth to establish the results of the study. This section presents an experimental evaluation recommended in this research of peat soil compressibility action and discusses the methodologies utilized in the consolidation analysis. This research was carried out to investigate the mending and hardening effects of Eco-Processed Pozzolan (EPP) on peat soil. The relevance of compaction in the process of soil stabilization was defined using the descriptive research approach. The tests were separated into three stages and done in accordance with BS1377-1:1990 [22]. Tests for index characteristics and settlement behaviour were included in the studies. It was possible to do so by referring to the "British Standard" clause for every test. The descriptions of the test procedures are presented on the following pages. A few investigations were conducted to determine index qualities, including natural moisture content and a pH test. These tests were explained in BS1377-1:1990 [22]. The soil hemic deposit was carried out at Klias Peat Swamp Field Center (KPSFC), Beaufort. The purpose of the laboratory test on a peat soil sample was to explore the sample's soil properties and features, differentiate the soil sample, and analyze the site-specific fundamental index properties. Figure 1 depicts the research approach.

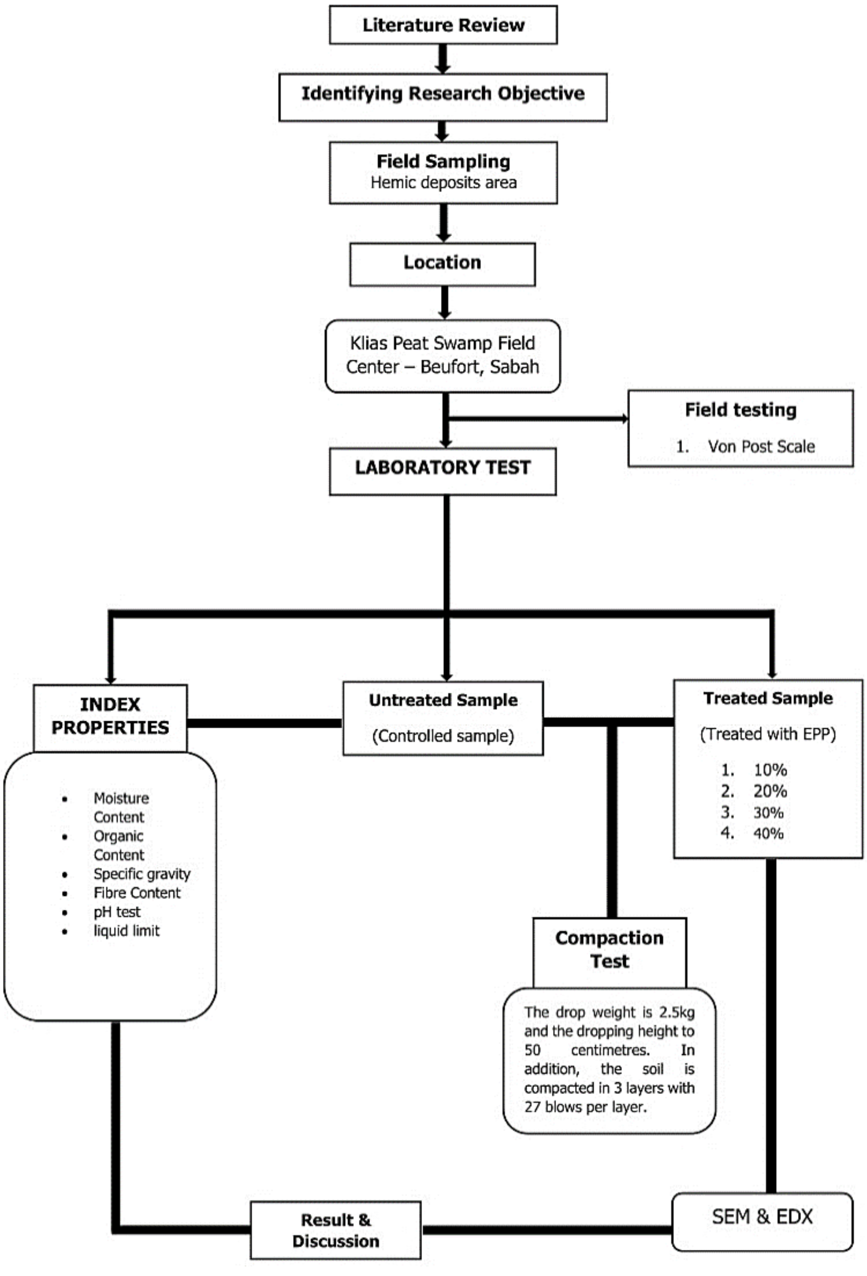


Figure 1. Research flowchart

Data at Klias Peat Swamp Field Center (KPSFC), Beaufort Sabah, locations have been recorded. The indicated place was confirmed when there was an adequate peat soil deposit. The samples were transported from the field to Malaysia University's Sabah Geotechnical Laboratory. The procedure for storing samples was explained and addressed. A Von Post scale was taken during the sampling of peat soil from the site. The research will include three types of tests: index properties and treated and untreated soil. Standard tests were done, and the soil was taken to assess the degree of humification, moisture content, and other index qualities. Compaction tests were performed on the settling behaviour using a 2.5 kg drop weight and a 50 cm drop height. The earth was also compacted into five levels, each with 27 blows. Beaufort, Sabah, who stresses the significance of peat deposit peat at Klias, recently conducted an engineering study on peat soil in Sabah.

This research was carried out in the Beaufort region of Sabah, Malaysia's southern state (Figure 2), which has a large wetland area. This swampy lowland plain was known as the Klias Peninsula. Beaufort has a total area of 466,804 hectares. This area gets between 2,500 and 3,000 mm of yearly precipitation. The rest of the Klias Peninsula was covered in wetlands. It serves as a "buffer zone" to the 'core.' Between Kimanis Bay to the north and Brunei Bay to the south, it faces the South China Sea. It was encompassed by the administrative boundaries of both the Beaufort and Kuala Penyu districts. The region was often referred to as a forest reserve (red boundaries are indicated as forest reserves in Figure 3). Some consider the area between 115.45' and 115.72'N and 5.42' and 5.15'E to be a completely covered peat swamp forest (Class 1). Soil samples were investigated in Klias, Beaufort, for this study. This place was well established as a peat deposit area based on some of Sabah's difficult zones dealing with peat soil, and Figure 3 shows the side view of KPSFC. In Figure 2, the peat specimen symbol was labeled by location. A sample of peaty soil was gathered and desired. The purpose of the undisturbed sample taken for this sample was to determine the proper test findings. Because all research and conclusions were based on a soil sample, the sampling procedure utilized must be appropriate for the intended soil type and soil ability.

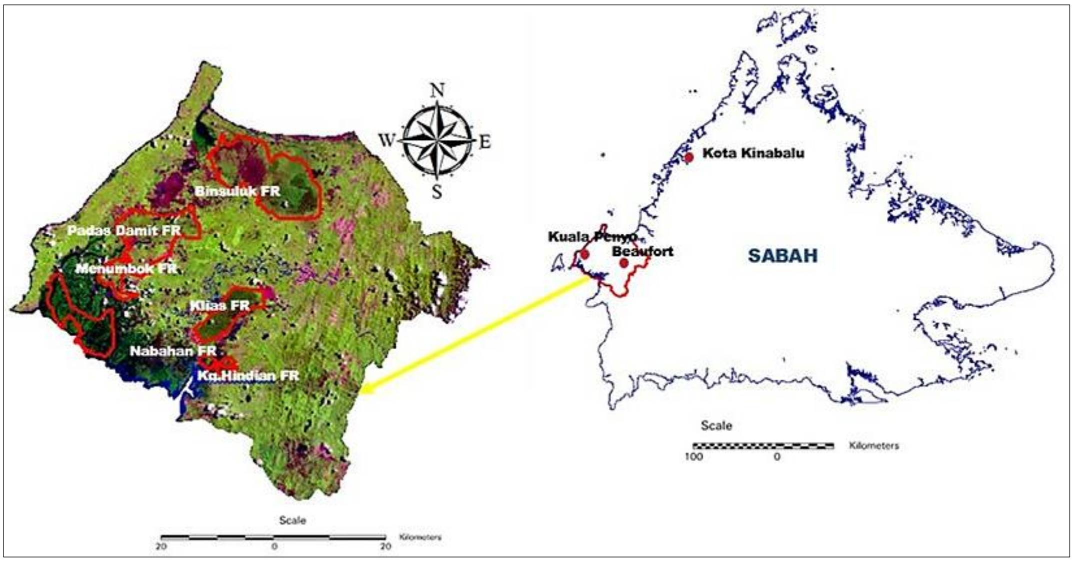


Figure 2. Location of Klias Peninsula, Sabah, Malaysia

Figure 3. Klias site location for peat soils

Correct soil sampling procedures were essential for obtaining samples from the area and extrapolating laboratory results to the field. A thin wall sampler, also known as a Shelby, was a soil sampling method used to gather relatively undisturbed peat soil samples for strength and consolidation tests. The field of soil samples was dug to a depth of 0.5 m. The soil was penetrated by the tube sampler, which has a diameter of 105 mm. A very stringent care procedure was adopted to prevent exposing samples to air conditions to ensure the completeness of soil samples polluted by any contaminants. Appropriate soil preservation and transfer were determined for preventive and monitoring purposes, and samples were properly packed and bundled as samples. Manpower was utilized to assist with field testing and sample activity in soil sampling.

Disturbed soil samples do not retain the in-situ features of the soil throughout the collecting procedure. Testing for disturbed soil samples was often used to analyze soil type and texture, moisture content, and nutrient and contaminant analyses, among other things. Clearing and grubbing were done at the same time to prepare the site for the sample. After clearing and grubbing, excavation operations began immediately to collect topsoil from where the groundwater table was less than 2 meters below ground level and up to a depth of 0.5 m below ground level. Disturbed soil samples were collected using a tiny shovel. Large samples of excavated peat soil were stored in heavy-duty plastic bags as a backup storage medium. The disrupted sample was placed in a plastic bag in a heavy-duty container (64), and it was transported to the laboratory, where it was stored at room temperature to retain moisture. A visual examination of the peat soil was carried out after the collection of disturbed samples as indicated in the Von Post categorization system. The sample consists of this kind of undisturbed sample that would be at most unaltered under BS 5930:1999, the code of practice for site investigations.

Peat soil and EPP sample preparation were carried out accordingly. The technique and procedure for obtaining soil samples vary depending on the objective of sampling. Soil samples may need to be analyzed to discover the qualities and features of the soil. This study defines soil sampling for research purposes, which was used to enhance peat soil utilizing compaction stabilized by EPP. Five samples will be used for this research: peat soils, peat soils + 10% EPP, peat soils + 20% EPP, peat soils + 30% EPP, and peat soils + 40% EPP. The chosen amount of EPP used is based on the previous research and fills the gap because, in the previous research, no researcher used the same amount of EPP and only used EPP as a stabilizer.

Organic content, pH, moisture content, fibre content, and other index properties of peat soil were identified. The compaction characteristic was investigated by adding Eco-Processed Pozzolan (EPP) to the peat soils. A sample of peat soil was obtained from Klias, Beaufort. The sample was undergoing compaction test at Geotechnical Laboratory Faculty of Engineering, University Malaysia Sabah. The undistributed soil sample was taken 0.5 m underground from the surface in a cylindrical shape, 150 mm high and 90 mm inner diameter. The soil was mixed with 10, 20, 30, and 40% Eco-Processed Pozzolan (EPP) and then compacted in a metal mould with an internal diameter of 105 mm using a 2.5 kg rammer, of 50 mm diameter, free falling from 300 mm above the top of the soil. Three layers of soil were compacted to equal depths using 27 blows spread evenly across the surface of the soil for each layer.

The BS 1377-1:1990 [22] specifies three alternative soil compaction test procedures. Compaction of the soil was a critical phase for any building because if it was not done correctly, the structure would fail. After the compaction was finished, a sample was obtained to ensure that the overall material amount needed by the testing agency was met. Soil compaction is the process of raising the density of soil through mechanical means. This was an important aspect of the construction process. If done incorrectly, soil settling might occur, resulting in needless maintenance expenses or structural collapse. Mechanical compaction methods were used on almost all construction sites and projects. If the sample was moist, dry it with a trowel until friable. Drying may be done in the open air or using a drying device set at a temperature of no more than 60°C (140°F). Break apart aggregations thoroughly while preserving the natural size of individual particles. The dirt was then properly blended with enough water to give it a low water content value. For sands and gravelly soils, the starting value of w should be about 5%, while for cohesive soils, it should be around 8% to 10% less than the soil's plastic limit. The rammer technique, which uses a 2.5 kg rammer.

The dirt was then compacted in three layers of about equal depth in a metal mould with an internal diameter of 105 mm and a 2.5 kg rammer with a 50 mm diameter, free-falling from 300 mm above the top of the soil. Each layer receives 27 blows uniformly distributed throughout the soil's surface. The mould and quantity of dry soil used in this compaction test where the 2.5 kg rammer technique is used, but the test sample was compacted with a greater force than the 2.5kg rammer used to make sure the peat soils tested followed the natural soil, which followed BS 1377-11990 [22]. The sample was then analyzed using SEM. The SEM characteristic was conducted at 28kv, x700 enlargement with 20 μm. The scanning electron microscope (SEM) produces images by scanning the peat soil sample to study the characteristic X-rays. Energy Dispersive X-Ray Analysis (EDX) carried out to identify the elemental composition of materials with 10 μm.

3. Results and Discussion

Natural moisture content was determined using the oven dry method, which involves heating the item in the oven for 24 hours at a temperature of 105 ℃. 4 plates of samples were prepared for testing and the average moisture was obtained. Data were collected before and after the samples have dried, subtracting the weight of the plates. The natural moisture content of peat soils that were obtained from this investigation was 587.57% on average. Peat moisture content can range from 200 to 2000 percent [23], which was significantly higher than clay and silt deposits, which seldom surpass 200 percent. According to the previous finding, the moisture content of KBpt was recognized to be between the ranges. Different numbers of moisture content have been observed in earlier research on moisture content, including 546.43 percent [24], 678 percent according to Hauashdh et al. [25], and 491.16 to 985.3 percent according to Zainorabidin & Mohamad [26]. The differences in results, according to Zainorabidin & Mohamad [27], were due to climate change because of changes in temperature, precipitation, and rainfall influencing soil saturation intensity, in which the water table forms in a relatively horizontal plane and may emerge to a level greater or less than the actual water table. According to Andriesse [28], there was a variation in moisture content, which was impacted by a variety of elements such as the degree of decomposition and botanical origin. According to Sina et al. [29], the moisture content of the soil and its shear strength was inversely related.

The average loss of ignition from laboratory testing of organic content was 96%. The weight of the sample before heating minus the weight after heating was the "initial" loss on ignition. The percentage of loss on ignition was then calculated by dividing "initial loss" by the original weight of the sample and multiplying by 100. Peat was defined by soil scientists as organic soil with an organic content of more than 35%. A geotechnical engineer, on the other hand, considers all soils with an organic content of more than 20% to be organic soil, however, "peat" was an organic soil with an organic content of more than 75% to be organic soil [29]. According to Zainorabidin & Mohamad [26], the organic content for peat soil was between 53.97% - 95.51% and findings were in the range 96.22% - 96.35% for peat soils located at Tun Zaidi Stadium Sibu, Sarawak [9, 30]. According to the results of the test, the average value of KBpt was 2.34, indicating that it was acidic. This would have influenced the acidic component of peat soil due to its location and decomposition processes. The properties of peat soil profiles may indicate whether the soil was acidic or alkaline. Peat acidity varies from 4.0 to 4.9 on the acidic scale, according to [26], and peat pH ranges from 3.16 to 3.71 on the acidic scale, according to Sutejo et al. [31] and according to bin Zainorabidin et al. [24]. Fibrous peat was defined by Von Post scale and ASTM D-2607 (1990) classifications based on fibre content, with groups H1 through H3 comprising more than 67% Fibric. Hemic peat was composed of 33 to 66% fibres and belongs to the classes H4 to H7. Sapric peat was the final three groups, H8 to H10, with fewer than 33% fibres. Fibre content was one of the index properties that was essential for this research. Before and after the test, the weight of fibre contained in peat soils was referred to. It was commonly expressed as a weighted percentage. 50– 55g of peat soil was used for the test by adding the soil sample with 400ml water,5ml Hydrochloric acid (HCL), and 5g of Sodium hexametaphosphate $(NaPO_3)_4$ in the beaker. Then, for about 15 minutes, place the beaker on the hot plate magnetic stirrer, before rinsing it with water, and filter with a filter cloth until the water was completely released. Based on the results in Table 1, the peat soils were classified as fibrous peat within the Von Post scale in range H1-H3 within the fibre content was 69.36% and was greater than 67%. Fibrous peat has a high organic and fibre content and a low humification level. It was formed of undigested fibrous organic debris, was easily identified, and was exceedingly acidic. Sapric peat includes a lot of degraded stuff.

Table 1. Index properties of Klias peat soil

Properties	Value
Natural Moisture Content, w (%)	587.57
Specific Gravity (Gs)	1.47
Acidity (pH)	2.34
Organic Content (%)	96
Fiber Content (%)	69

The original plant fibres were essentially gone, and the water-holding capacity was often lower than that of fibrous or hemic peat. It was often very dark grey to black and has very stable physical qualities. Sapric peat deposits have lower vacancy ratios, lower permeability, lower compressibility, a smaller friction angle, and a larger coefficient of earth pressure at rest than fibrous peat deposits. Hemic peat has qualities that fall between fibrous and Sapric peat [32]. According to Zainorabidin & Mohamad [26] the fibre content of peat ranges from 61.61 to 79.40 percent. According to other researchers, the fibre content of peat soil ranges between 70.45 and 76.659 percent [29]. According to Table 1, the moisture content of peat soil, which represents the liquid limit of peat, was between 133% - 180%. Previous researcher has observed that the range of the liquid limit of peat was 211 - 299.5% [26], whereas Huat [8] discovered that the range of liquid limit was 190 - 360 percent. The results of the specific gravity test for peat soil were shown in Table 1. The average specific gravity of peat soil was 1.47, according to the test findings. Peat has a specific gravity of 1.4 and a unit weight of 1.04 g/cm^3. Peat was an extremely soft soil with a water-dominated structure, as shown by its physical property. Peat with a 67% or higher organic content has a specific gravity ranging from 1.3 to 1.8, with an average of 1.5. The Von Post scale served as the breakdown indicator. Based on the "type of liquid expressed on squeezing", "proportion of peat extruded between fingers," and "nature of plant remnants," the Von Post scale is a ten-class categorization system created for characterising peat soils in the field. Squeezing the peat and the material that is extruded between the fingers, analysing the substance, and categorising the soil as belonging to one of ten (H1-H10) humification or decomposition groups are all part of the Von Post humification. Based on the Von Post scale during the site visit, the peat soil in KPSFC can be categorized as H6-H7, which shows muddy to strongly muddy for the peat as shown in Figure 4.

Figure 4. Von Post scale at Klias, Beufort

The untreated peat soils were employed for the compaction test. As a consequence, the Figure 5 graph was in a downward trend, with two identical data points of 0.58 Mg/m^3 dry density in tests 3 and 4, while the greatest dry density was 0.59 Mg/m^3. R^2 for the test was 0.0347, and the highest moisture content was 55%. The R^2 is low, the error may cause it during the test because the test is not finished in a day. A few days are taken to get all the data. Figure 6 shows the dry density of peat mixed with 10% of EPP. The peat soils were added to a mixture of 10% of EPP for the compaction test. Therefore, Figure 6 shows the graph was in an upward trend, with the highest dry density being 0.63 Mg/m^3 which was in test no 4 meanwhile the lowest dry density was in test no 1 0.57 Mg/m^3. R^2 for the test was 0.9047, and the highest moisture content was 69%.

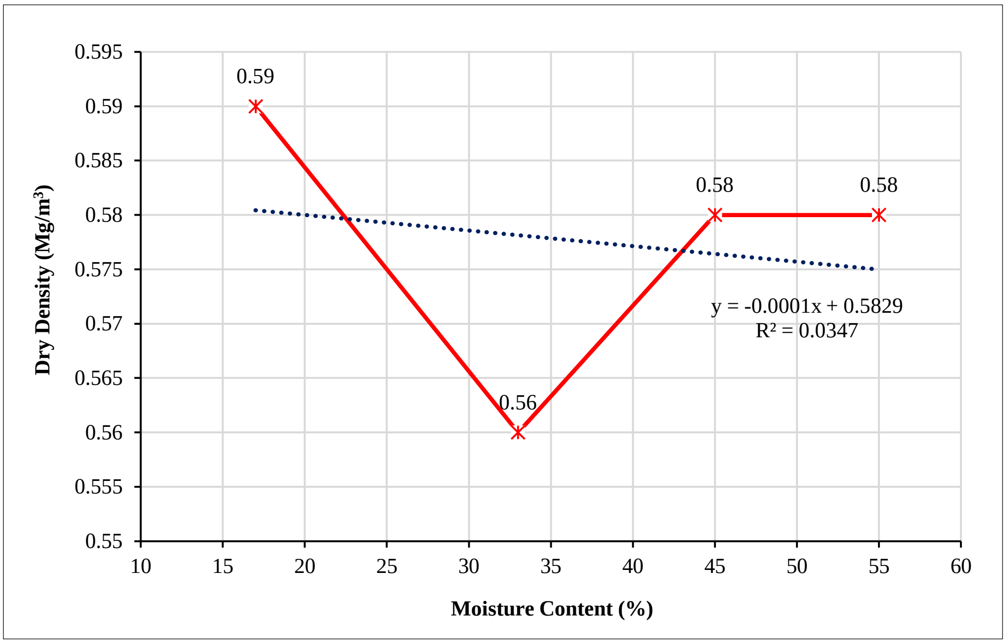


Figure 5. Dry density vs. Moisture content (untreated)

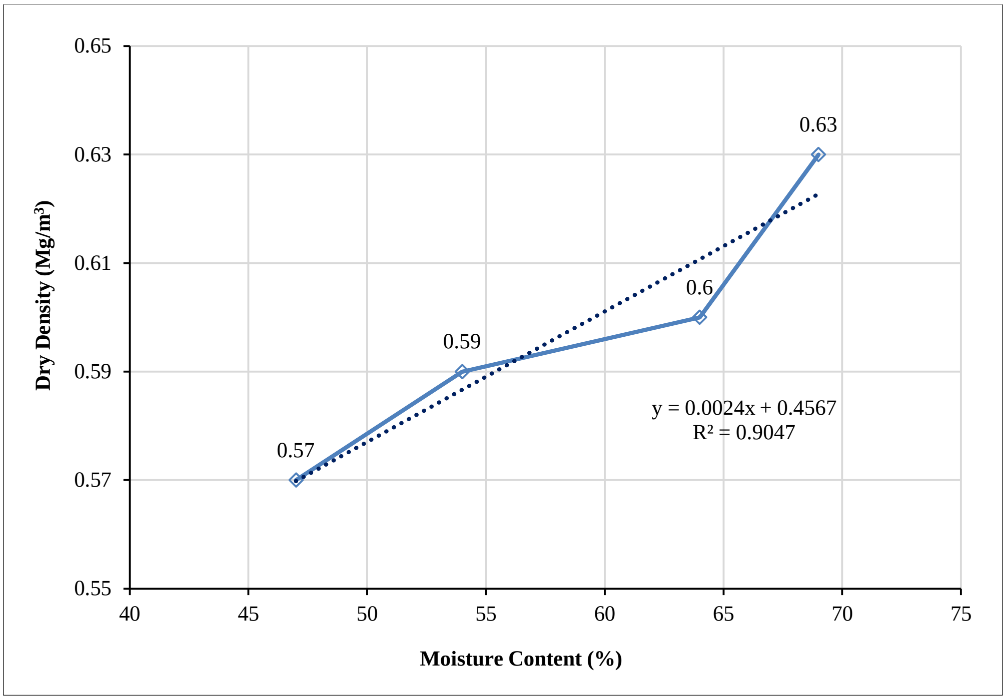


Figure 6. Dry density vs. Moisture content (peat + 10% EPP)

The peat soils have been mixed with 20% EPP for the compaction test. Therefore, Figure 7 shows the graph was in an upward trend, with the highest dry density being 0.65 Mg/m^3, which was in test no. 4, while there was an identical dry density in tests 1 and 2, 0.62 Mg/m^3. $R2$ for the test was 0.9245, and the highest moisture content was 61% while the lowest was 36% as shown in Figure 7. Moreover, the peat soils added a mixture of 30% EPP for the compaction test. Therefore, Figure 8 shows the graph was in an upward trend, with the highest dry density being 0.7 Mg/m^3, which was in test no. 4, while the lowest dry density was in test 10.67 Mg/m^3. R^2 for the test was 0.999, and the highest moisture content was 55% while the lowest was 32%. In the same manner, as shown in Figure 8, the peat soils have added a mixture of 40% EPP for the compaction test. Therefore, Figure 9 shows the graph was in an upward trend, with the highest dry density being 0.7 Mg/m^3, which was in test no. 4, while the lowest dry density was in test no. 1, 0.66 Mg/m^3. R^2 for the test was 0.8239, and the highest moisture content was 51% while the lowest was 31%.

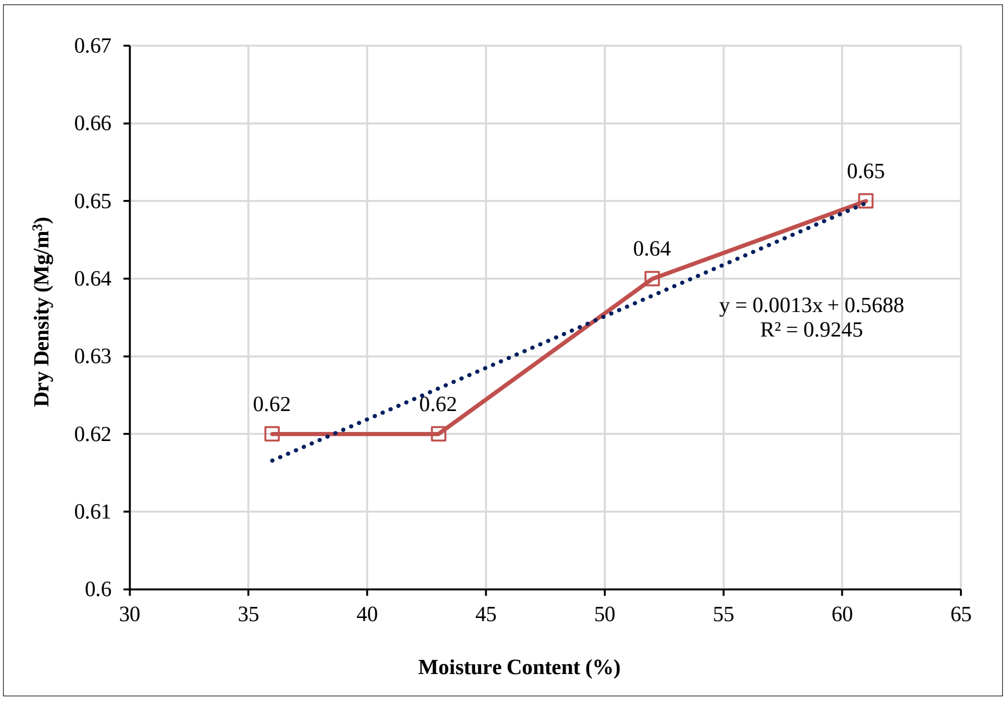


Figure 7. Dry Density vs Moisture Content (peat + 20% EPP)

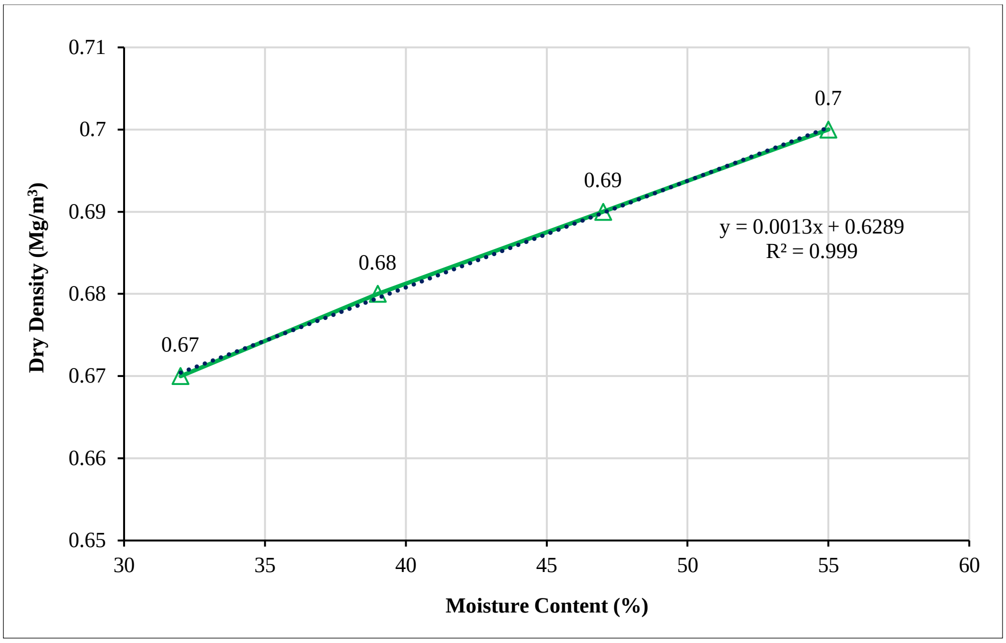


Figure 8. Dry density vs. Moisture content (peat + 30% EPP)

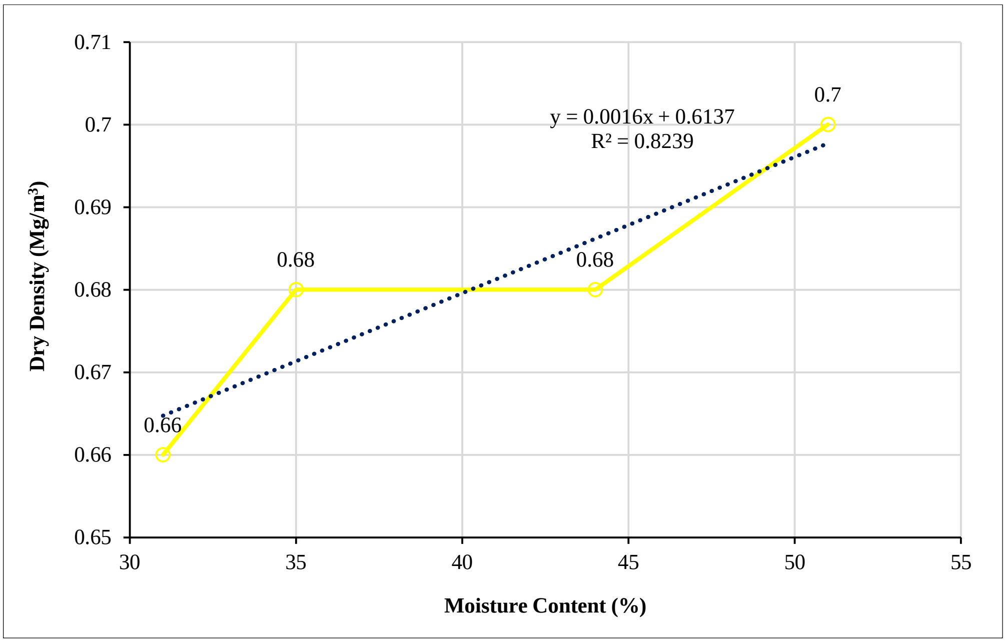


Figure 9. Dry density vs. Moisture content (peat + 40% EPP)

Peat soil was regarded as one of the most problematic soils to work with. Peat has high compressibility, low shear strength, high moisture content, and low bearing capacity [8]. Data such as the weight of the moulded, the weight of the moulded + sample, the moisture content of the sample utilized, and dry density data were collected as discovering parameters during the experiment. Each of the five samples being investigated has a total weight of 2000 g and underwent a compaction test for four tests, with 200 ml of water added to each sample for each test. Every test will collect a portion of the sample that was utilized to determine the moisture content of the sample. As previously stated, the four samples evaluated may be classified as Sample 1, Sample 2, Sample 3, Sample 4, and Sample 5. Sample 1 was the control sample, peat soil without any stabilizer and with EPP as a binder. Sample 2 was peat soil with a 10% EPP added, followed by sample 3 with a 20% EPP added to peat soils. Samples 4 and 5 were peat soils that had been treated with 30% and 40% EPP, respectively. Sample 1 was a peat soil without any stabilizer added 2000 g of peat soil was tested. Sample 2 was weighed of 1800 g of peat soils added with 200 g of EPP powder and added 200 ml for each set, afterwards will undergo compaction test. 1600 g of peat soils were weighed, plus 400 g of EPP powder for sample 3. Sample 4 represented 1400 g of peat soils with the addition of 600 g of EPP powder, and sample 5 was the weight of 1200 g of peat soils with the addition of 800 g of EPP powder. Every sample will undergo the same test as sample 1. Table 2 shows the mix that was formulated during the compaction test in this research.

Table 2. Mixed design for compaction test

Description	Untreated Sample	Peat soils + 10% EPP powder	Peat soils + 20% EPP powder	Peat soils + 30% EPP powder	Peat soils + 40% EPP powder
Mixture	Peat soils 2000g + 200 ml water was added for each set	Peat soils 1800g + EPP powder 200g + 200 ml water was added for each set	Peat soils 1600g + EPP powder 400g + 200 ml water was added for each set	Peat soil 1400g + EPP powder 600g + 200 ml water was added for each set	Peat soils 1200g + EPP powder 800g + 200 ml water was added for each set
Compaction	2.5 kg Rammer Method with free falling height 300 mm was used. Compacted in 3 layers with each layer applied 27 blows				

Figure 10 shows the behaviour of untreated peat soil treated with EPP. Fortunately, for the untreated peat soil, the behaviour was seen to be almost constant in dry density, which was 0.59, 0.56, 0.57, and 0.58 (Mg/m^3). The untreated sample shows a slight percentage increase in moisture content, which was 55%, the highest rate in 4 sets. Unfortunately, a treated sample containing 10% EPP (Sample 2) showed a slight uptrend in movement, followed by the dry density and moisture content. The dry density trend shows the uptrend results, starting from 0.57, 0.58, 0.6, and 0.62 (Mg/m^3), and Sample 2 also has the highest moisture content among the samples, which was 69%, as can be seen in Figure 10. Drastic changes in the behaviour of peat soils can be seen after EPP treatment is added to the soils. Consequently, in sample 2, the behaviour significantly showed improvement. The behaviour of peat soils improved with EPP treatment for the following treatment. Sample 3 shows the change in dry density result, which was higher than samples 1 and 2. The dry density range in sample 3 was 0.62-0.65 (Mg/m^3), followed by the percentage of moisture content between sample 1 and sample 2 in the field of 36–61%.

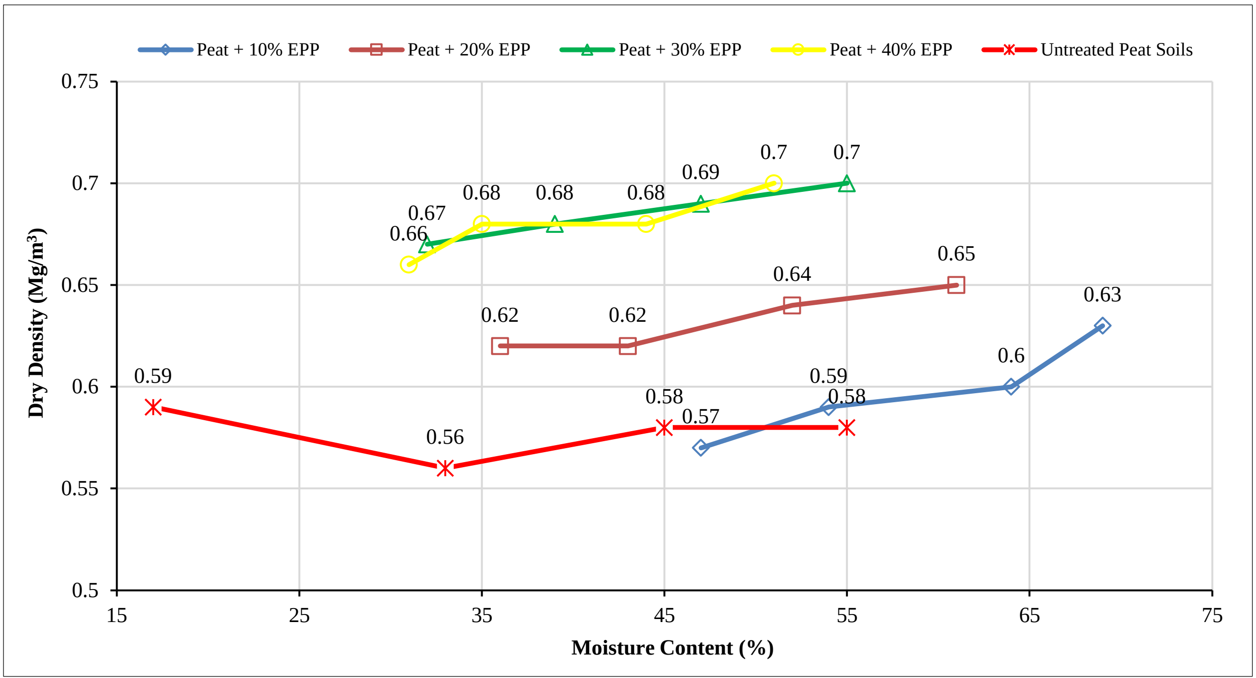


Figure 10. Behaviour of peat soils, dry density and moisture content

In addition, for samples 4 and 5, it has been observed that the dry density was highest in Sample 1, Sample 2, and Sample 3, which both samples hit up to 0.7 (Mg/m^3), even though the lowest dry density was 0.67 for sample 4 and 0.66 for sample 5, but still the highest between the three samples. Moisture content for sample 4 was in the range of 32%-55%, and for sample 5 in the range between 31%-51%. Both samples show the uptrend movement and were almost identical in data. Based on the data, the use of EPP as a stabilizing material for peat soil perceptivity was high. The result from this study shows that samples 4 and 5 contained the optimum amount of EPP that can be used to improve peat soils mixed with 30–40% of EPP. Consequently, using EPP as a peat soil stabilizer has a high potential for generating stable soil that may alleviate soil problems [33].

When the percentage of additives used increases, the maximum dry density of the soil increases while the optimal moisture content drops [33]. Stabilization of peat by mixing soil with binding material will improved the strength characteristics of soil [34]. Based on the previous study, treated peat soils with SF and OPC as soil stabilizers were tested using standard compaction. Figure 11 shows the results of the compaction test. All the lines have their peak point for dry density, and the highest peak was peat soil + SF (15%) + OPC (15%) in the range (1400–1600) kg/m^3 [35]. The moisture content of peat soil + SF and OPC was 5–50%, which was a percentage near the same as the results of this study using Eco-Processed Pozzolan (EPP) as a stabilizer. In terms of the graph, as shown in Figure 11, it started to uptrend, hit the peak point, then changed to a downtrend differ with this study which was the sample with EPP, will show the uptrend movement with dry density and moisture content. In prior research, treating peat soils with cement as a soil stabilizer was examined using conventional compaction. The moisture content of peat soils + cement ranges from 10% to 35%, similar to the percentages found in this research employing Eco-Processed Pozzolan (EPP) as a stabilizer. In terms of the graph, as shown in Figure 9, it began to rise and then fell. However, in this research, the sample with EPP will exhibit an upward trend with dry density and moisture content.

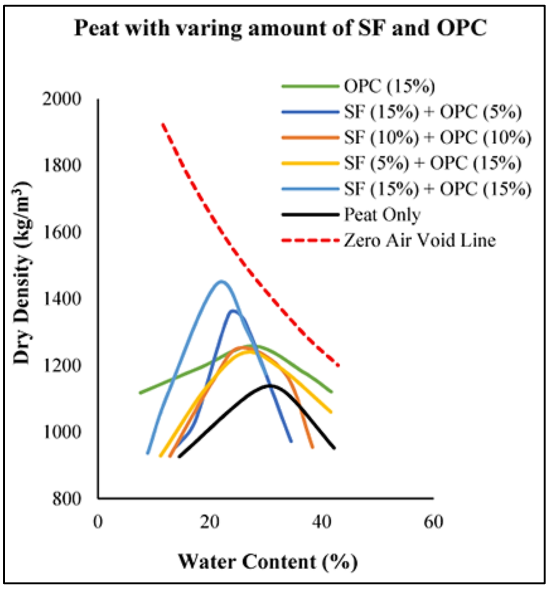


Figure 11. Treated peat soil

In this research, each sample was subjected to four rounds of testing, as illustrated in Figure 12. A small amount from each sample was taken and used to determine the moisture content. According to the graph, the red line represents untreated peat soils, the blue line represents peat soils + 10% EPP, the orange line represents peat soil + 20% EPP, the green line represents peat soils + 30% EPP, and the yellow line represents peat soils + 40% EPP. The graph demonstrates that all four samples treated with EPP were trending upward, in contrast to untreated peat soil, which was trending downward. The initial and final readings of the dry density values were utilized to create this graph. The yellow and green lines exhibit data like the blue and orange lines but differ somewhat. The lowest dry density was 0.57 Mg/m^3 in the blue line, while the greatest dry density was 0.7 Mg/m^3 in the red line. The scanning electron microscope (SEM) results were studied from the images produced with a high-energy beam of electrons, as shown in Figure 13, which shows 5 microstructures for peat soil mixes.

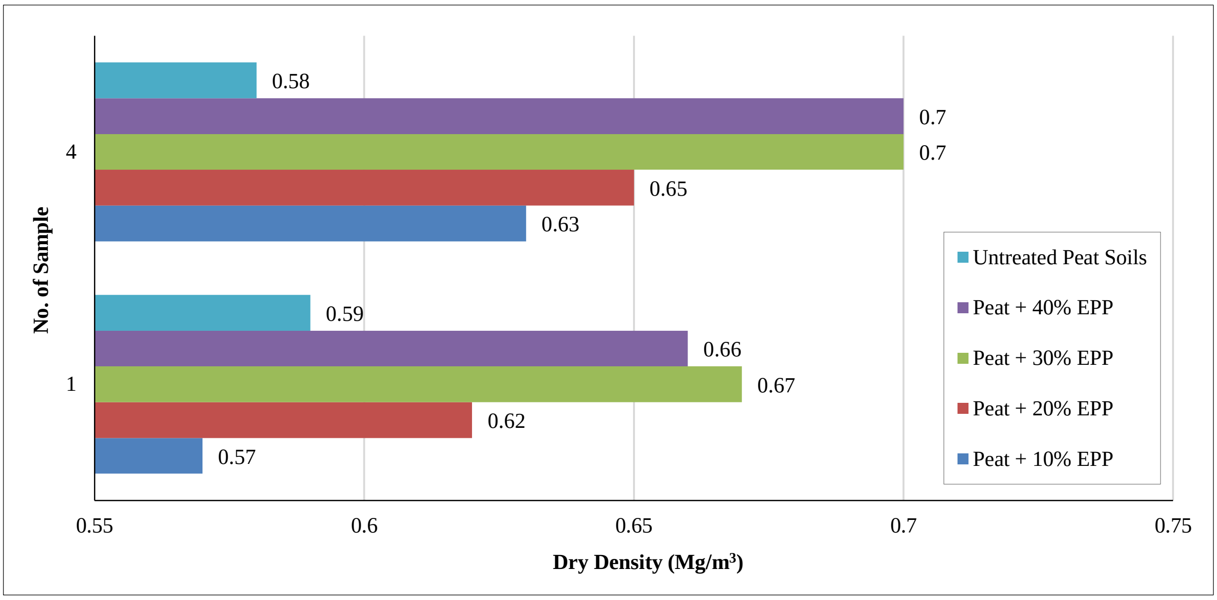
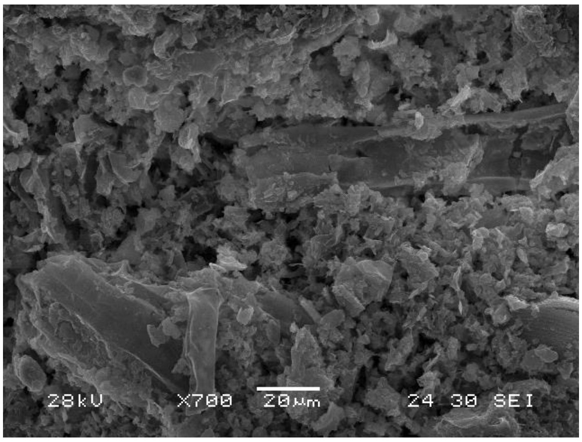
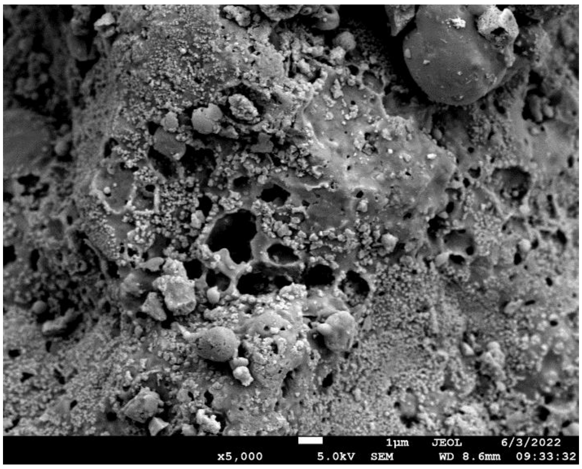


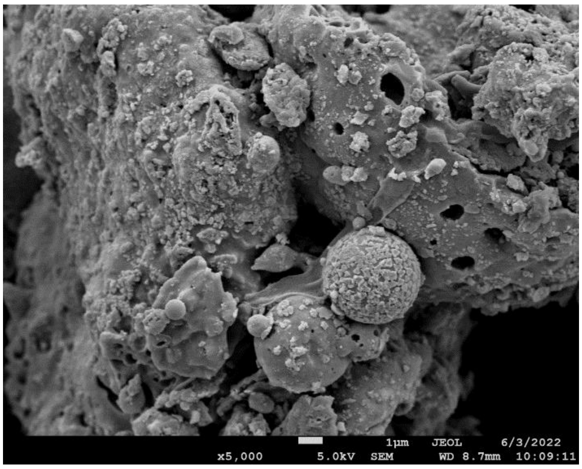
Figure 12. Dry density vs. No. of Sample



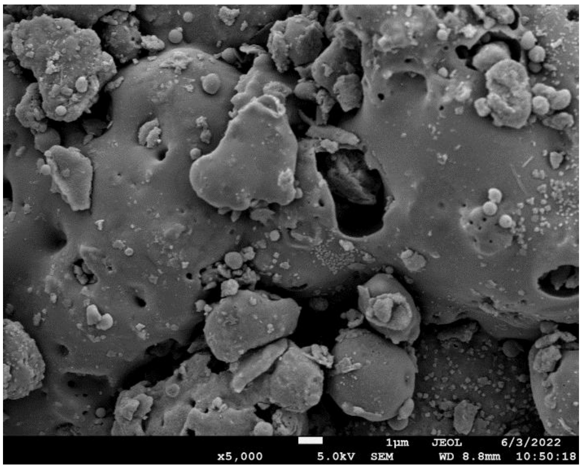
(a) Peat Soil



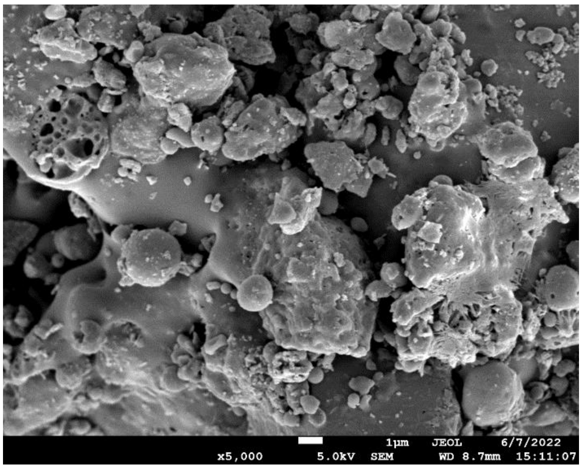
(b) peat mixed with 10% EPP



(c) peat mixed with 20% EPP



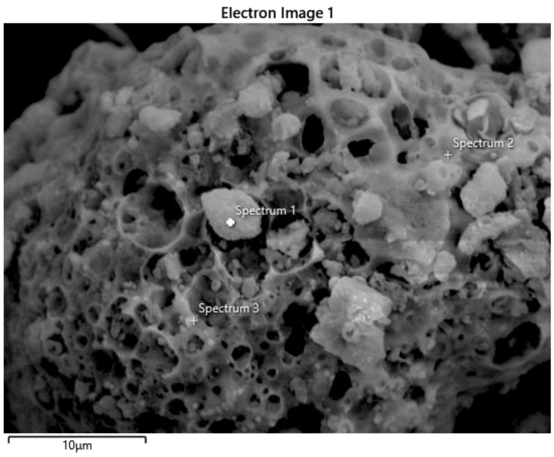
(d) peat mixed with 30% EPP



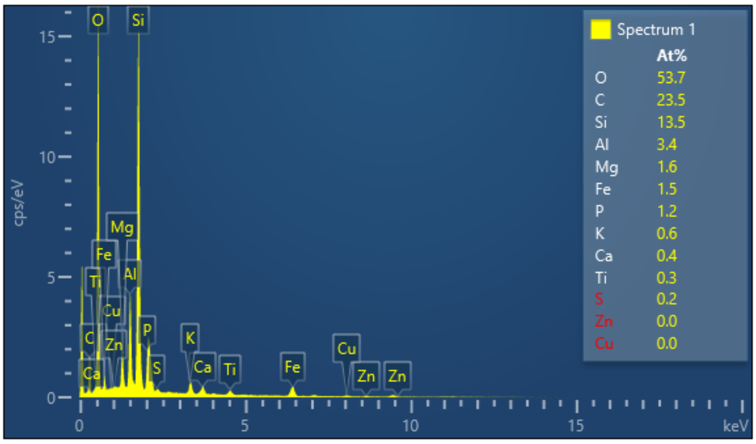
(e) peat mixed with 40% EPP

Figure 13. Scanning Electron Microscope (SEM) of 5 microstructures for peat soil mixes

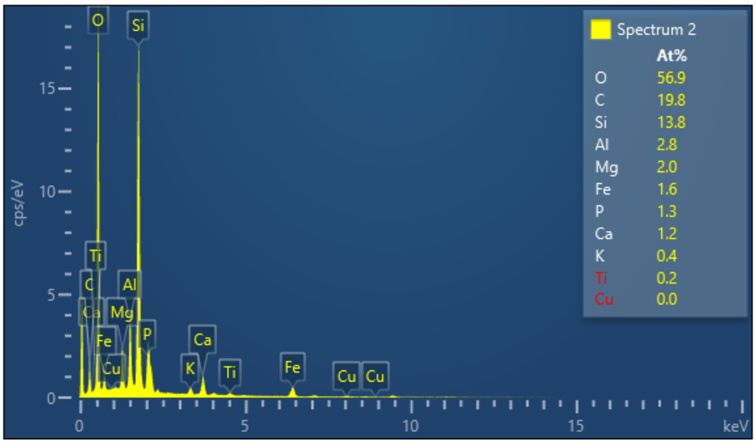
Figure 13-a shows that the peat structure developed with highly confined spaces and voids generated from unknown particles in various elements. Identically, it has been discovered where the EPP was blended equally with the pores in peat and filled the gaps between the spaces in peat, as shown in Figures 13-b, 13-c, 13-d, and 13-e. This is due to the micro sizes of EPP material being smaller than those of peat components. The combination of EPP and peat was more pronounced with a higher composition of EPP at 40% compared to the specimen mixed with 10% of EPP. The more EPP content, the more void and spaces filled and combined with peat structure. The peat microstructure is scattered, and a void is likely in honeycomb form. The particle structure is in line with Jerzy & Emilia (2019) explanation of the elements of soil. As discovered in Figures 13-b and 13-e, the more EPP content, the more voids and spaces filled, and combined with peat structure, the energy dispersive X-ray analysis (EDX) test was carried out for 10% and 40% of the EPP amounts blended with peat soil specimens. Figures 14 and 15 show the energy dispersive X-ray analysis (EDX) spectra of peat and EPP at 10% and 40% residue adsorbent, respectively. Table 3 shows the results of elemental composition for peat soil and mixes of EPP 10% to 40%.



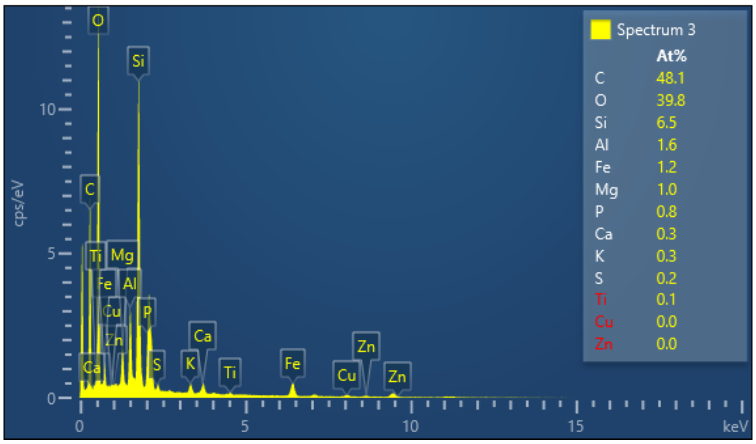
(a) Electron image



(b) Spectrum 1

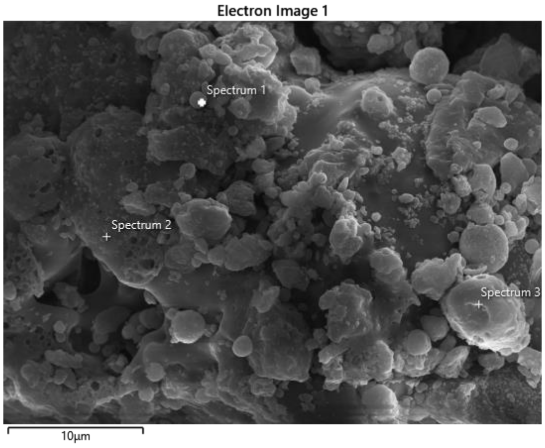


(c) Spectrum 2

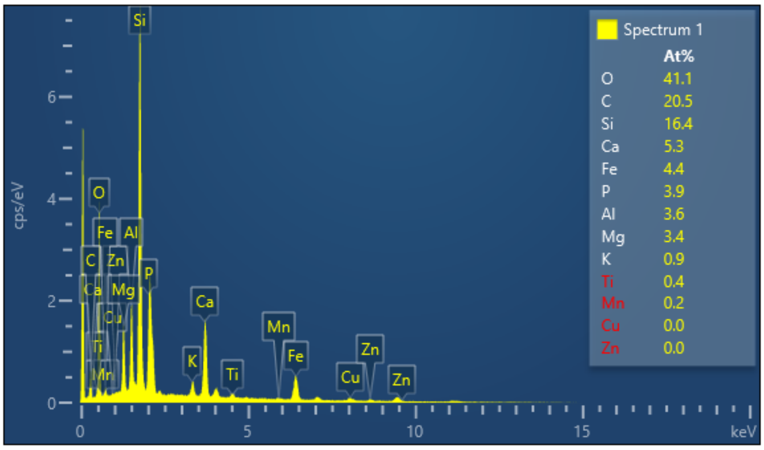


(d) Spectrum 3

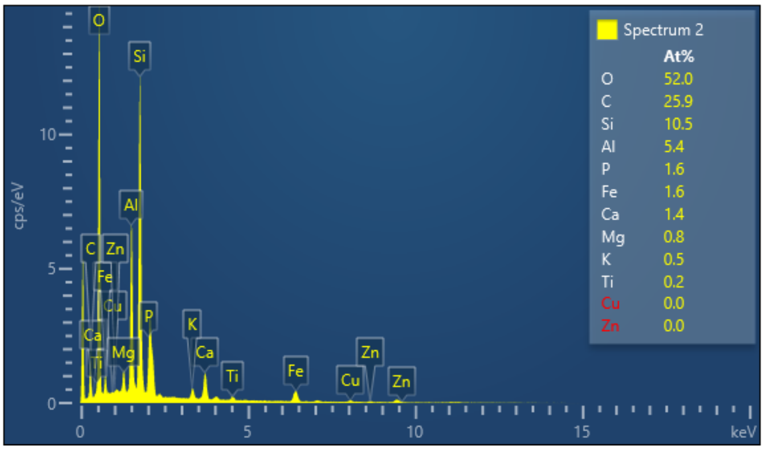
Figure 14. Energy dispersive X-ray analysis (EDX) spectrum of peat and EPP (10%) residue adsorbent



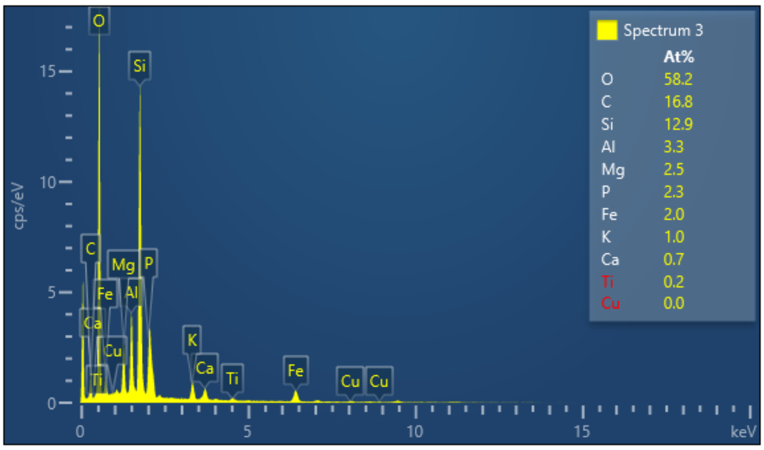
(a) Electron image



(b) Spectrum 1



(c) Spectrum 2



(d) Spectrum 3

Figure 15. Energy dispersive X-ray analysis (EDX) spectrum of peat and EPP (40%) residue adsorbent

Table 3. Elemental composition of peat soil mixed with EPP

Elements	Peat + EPP 10% (%)	Peat + EPP 40% (%)
Oxygen, O	48.1	58.2
Silicon, Si	6.5	12.9
Magnesium, Mg	1.0	2.5
Iron, Fe	1.2	2.0
Carbon, C	48.1	16.8
Aluminum, Al	1.6	3.3
Calcium, Ca	0.3	0.7
Phosphorus, p	0.8	2.3

Correspondingly, the elemental composition of peat soil mixed with EPP improved regardless of Carbon, Ca composition. Comparatively, the amount of Silicon, Si increased from 6.5% (Peat + EPP 10%) to 12.9% (Peat + EPP 40%). Compared to the Kassim & Yaacob [36] study, the amount of Silicon, Si is about 1.27%. This is due to the aerobic condition of origin peat while, in this study, peat improved with additive material known as EPP. Thus, EPP was seen as a potential material for improving peat properties and characteristics. The magnesium element developed from 1.0% to 2.5%, as seen in Table 3, compared to Kalantari & Huat [37], and was found Mg in 0.95%.

This development amounts of Magnesium, Mg identically contributes by EPP material. The increments in elemental composition values from Peat + EPP 10% (%) to > Peat + EPP 40% (%) show the potential of EPP research as a stabilizer material. This finding is in line with the statement of the previous study, which is that EPP can potentially help reduce the shrinkage by almost 66.66% [38]. These improvements were identified as the phase of a crystalline material between peat and EPP relationships as discovered by Suhaimi & Mohamad [39], who observed crystalline structure in the presence of EPP and cement in peat soil. The set of reflections proves unambiguously that Eco Processed Pozzolan (EPP) contributed to peat soil stabilization. Uniquely, the crystallization of EPP and peat seen occurred in this study while recorded improvement in EPP and peat mix from 10% to 40%.

4. Conclusion

The behaviour of peat soil following stabilization with EPP was investigated. The behaviour of peat soil before and after stabilization may also be monitored. Four compaction tests were available, each with a different admixture value of 10, 20, 30, and 40% of EPP. Determination of the Index Properties of a Peat sample collected in Klias, Beaufort. The index properties assessed include moisture content, pH, specific gravity, liquid limit, organic content, and fibre content. The sample's moisture content was 587.57%, according to the findings of this study. The resulting number was then compared to earlier research to confirm that it was within the allowed range (to ensure there was no error during the testing). After that, three samples of peat soil were tested for pH to estimate the average pH of the peat. Due to the high acidity content of peat, the average pH of peat was 2.34. The cone penetration technique was used to conduct a liquid limit test for this investigation. A graph depicts the link between average penetration and moisture content. The moisture content of the liquid limit was 133.91–180.3%, which was still within range, according to prior tests. In addition, the percentage of fibre in the fibre content test was determined using a simple computation. The fibre percent may be used to define the kind of peat, and the peat soil in this study was fibrous because the value was the same at 67% and the fibre content value in this study was 67%. This study's specific gravity was 1.47, which was still within the range of prior research. Loss of Ignition (LOI) testing of organic content found a value of 96 percent, which was within the range of prior tests. Based on the outcomes of this investigation, peat soil may be verified as problematic when compared to conventional soil. Because the numbers were substantially equal to the previous findings, all testing results were judged acceptable. Some variables, such as the site's location and agricultural activities, influence the little difference in value achieved.

Peat behaviour after stabilization with Eco Processed Pozzolan (EPP) has been categorized as soil that has high settlement upon being subjected to loading for a period of time because of the properties of the soil. This research revealed that there is just a little variation when the peat soil has been stabilized. When EPP was added to peat, the qualities of the peat soil changed. The results reveal that the peat's behaviour has improved following treatment. Despite the benefits, peat adds moisture to the mix, increasing the water content. According to the findings, peat soil treated with EPP will transform from peat to usable soil. However, the presence of moisture will reduce the mixture's ability. According to the findings of this study, the best EPP for stabilizing peat soils was 30–40%. The key conclusion was that the combination of the proper quantity of moisture, EPP, and cured peat soil helped stabilize the soil. As a result, this research backs up the hypothesis of treating peat with EPP to improve the qualities of peat soil and maintain settlement over time. The crystallization process occurred in peat soil mixed with 10, 20, 30 to 40% EPP. The crystallization process contributes to the improvement of mineral stabilization in peat.

5. Declarations

5.1. Author Contributions

Conceptualization, H.M.M. and M.S.S.; methodology, H.M.M.; investigation, M.S.S.; data curation, H.M.M. and M.S.S.; writing—original draft preparation, H.M.M. and M.S.S.; writing—review and editing, H.M.M. and M.S.S. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

Data sharing is not applicable to this article.

5.3. Funding

Authorship, and/or publication of this article supported by Universiti Malaysia Sabah (UMS).

5.4. Acknowledgements

This research was supported by Universiti Malaysia Sabah (UMS). We thank our colleagues from UMS who provided insight and expertise that greatly assisted the research, although they may not agree with all of the interpretations/conclusions of this paper.

5.5. Conflicts of Interest

The authors declare no conflict of interest.

6. References

[1] Huat, B. B. K., Prasad, A., Asadi, A., & Kazemian, S. (2014). Engineering properties of peat and organic soils. CRC Press, Boca Raton, United States. doi:10.1201/b15627.

[2] Moldoveanu, S. C. (1998). Analytical pyrolysis of natural organic polymers. Elsevier, Amsterdam, Netherlands.

[3] Razali, S. N. M., Bakar, I., & Zainorabidin, A. (2013). Behaviour of peat soil in instrumented physical model studies. Procedia Engineering, 53, 145–155. doi:10.1016/j.proeng.2013.02.020.

[4] Mostafa, H. H. (2022). Lateral response evaluation of single piles based on pressuremeter test results (using Foxta) versus standard penetration test results (using Lpile). Innovative Infrastructure Solutions, 7(4), 1-10. doi:10.1007/s41062-022-00870-4.

[5] Jones, D., & Brischke, C. (2017). Nonwood bio-based materials. Performance of Bio-Based Building Materials, 97–186, Woodhead Publishing, Sawston, United Kingdom. doi:10.1016/b978-0-08-100982-6.00003-3.

[6] Osman, K. T. (2018). Peat Soils. Management of Soil Problems, 145–183, Springer, Cham, Switzerland. doi:10.1007/978-3-319-75527-4_7.

[7] Miettinen, J., Shi, C., & Liew, S. C. (2011). Deforestation rates in insular Southeast Asia between 2000 and 2010. Global Change Biology, 17(7), 2261-2270. doi:10.1111/j.1365-2486.2011.02398.x.

[8] Huat, B. K. (2004). Organic and peat soils engineering. Penerbit Universiti Putra Malaysia, Seri Kembangan, Malaysia.

[9] Mahmod, A. A. W., Mohd, S., Mohd Masirin, M. I., Tajudin, S. A. A., Bakar, I., Zainorabidin, A., Kifli, A. Z., & Hua, L. J. (2016). Construction of buildings on peat: Case studies and lessons learned. MATEC Web of Conferences, 47, 3014. doi:10.1051/matecconf/20164703013.

[10] Rahman, R. F. A., Asrah, H., Rizalman, A. N., Mirasa, A. K., & Rajak, M. A. A. (2020). Study of eco-processed pozzolan characterization as partial replacement of cement. Journal of Environmental Treatment Techniques, 8(3), 967–970.

[11] Johnson, A. W., & Sallberg, J. R. (1962). Factors influencing compaction test results. Highway Research Board Bulletin, 319, Highway Research Board, Washington, United States.

[12] Chindaprasirt, P., Kanchanda, P., Sathonsaowaphak, A., & Cao, H. T. (2007). Sulfate resistance of blended cements containing fly ash and rice husk ash. Construction and Building Materials, 21(6), 1356–1361. doi:10.1016/j.conbuildmat.2005.10.005.

[13] Benhelal, E., Zahedi, G., Shamsaei, E., & Bahadori, A. (2013). Global strategies and potentials to curb CO2 emissions in cement industry. Journal of Cleaner Production, 51, 142–161. doi:10.1016/j.jclepro.2012.10.049.

[14] Gartner, E. (2004). Industrially interesting approaches to “low-CO_2” cements. Cement and Concrete Research, 34(9), 1489–1498. doi:10.1016/j.cemconres.2004.01.021.

[15] Ahmed, T. I., & Tobbala, D. E. (2022). The role of granite dust in engineered cement composites as a partial replacement of fine aggregate. Innovative Infrastructure Solutions, 7(1), 1-11. doi:10.1007/s41062-021-00699-3.

[16] Loh, S. K., James, S., Ngatiman, M., Cheong, K. Y., Choo, Y. M., & Lim, W. S. (2013). Enhancement of palm oil refinery waste - Spent bleaching earth (SBE) into bio organic fertilizer and their effects on crop biomass growth. Industrial Crops and Products, 49, 775–781. doi:10.1016/j.indcrop.2013.06.016.

[17] Tangchirapat, W., Saeting, T., Jaturapitakkul, C., Kiattikomol, K., & Siripanichgorn, A. (2007). Use of waste ash from palm oil industry in concrete. Waste Management, 27(1), 81–88. doi:10.1016/j.wasman.2005.12.014.

[18] Azmi, W. H., Usri, N. A., Mamat, R., Sharma, K. V., & Noor, M. M. (2017). Force convection heat transfer of Al2O3 nanofluids for different based ratio of water: ethylene glycol mixture. Applied Thermal Engineering, 112, 707-719. doi:10.1016/j.applthermaleng.2016.10.135.

[19] Sridharan, A., & Nagaraj, H. B. (2005). Plastic limit and compaction characteristics of finegrained soils. Proceedings of the Institution of Civil Engineers - Ground Improvement, 9(1), 17–22. doi:10.1680/grim.2005.9.1.17.

[20] Viji, V. K., Lissy, K. F., Sobha, C., & Benny, M. A. (2013). Predictions on compaction characteristics of fly ashes using regression analysis and artificial neural network analysis. International Journal of Geotechnical Engineering, 7(3), 282–291. doi:10.1179/1938636213Z.00000000036.

[21] ASTM D 698-12. (2014). Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12400ft-lbf/ft^3 (600kN-m/m^3)). ASTM International, Pennsylvania, United States. doi:10.1520/D0698-12.

[22] BS 1377-1:1990. (1990). Methods of test for soils for civil engineering purposes- Part1: General requirements and sample preparation. British Standard, London, United Kingdom.

[23] Mesri, G., & Ajlouni, M. (2007). Engineering Properties of Fibrous Peats. Journal of Geotechnical and Geoenvironmental Engineering, 133(7), 850–866. doi:10.1061/(asce)1090-0241(2007)133:7(850).

[24] Bin Zainorabidin, A., binti Saedon, N., Bin Bakar, I., & bt Mohd Seth, N. F. (2015). An investigation of soil volume changes at four dimensional points of peat soil sample in Parit Nipah and Pontian. Applied Mechanics and Materials, 773–774, 1491–1496. doi:10.4028/www.scientific.net/amm.773-774.1491.

[25] Hauashdh, A., Radin Mohamed, R. M. S., Abd Rahman, J., & Jailani, J. (2018). Analysis of leachate from solidified peat soil. MATEC Web of Conferences, 250, 06015. doi:10.1051/matecconf/201825006015.

[26] Zainorabidin, A., & Mohamad, H. M. (2016). A geotechnical exploration of Sabah peat soil: Engineering classifications and field surveys. Electronic Journal of Geotechnical Engineering, 21(20), 6671–6687.

[27] Zainorabidin, A., & Mohamad, H. M. (2016). Preliminary peat surveys in ecoregion delineation of North Borneo: Engineering perspective. Electronic Journal of Geotechnical Engineering, 21(12), 4485–4493.

[28] Andriesse, J. P. (1988). Nature and management of tropical peat soils (No. 59). Food and Agriculture Organization of the United Nations, Rome, Italy.

[29] Sina, K., Bujang, B. H., Arun, P., & Maassoumeh, B. (2011). Effect of peat media on stabilization of peat by traditional binders. International Journal of Physical Sciences, 6(3), 476-481.

[30] van Asselen, S., Erkens, G., Stouthamer, E., Woolderink, H. A., Geeraert, R. E., & Hefting, M. M. (2018). The relative contribution of peat compaction and oxidation to subsidence in built-up areas in the Rhine-Meuse delta, The Netherlands. Science of the Total Environment, 636, 177-191. doi:10.1016/j.scitotenv.2018.04.141.

[31] Huat, B. B. (2006). Deformation and shear strength characteristics of some tropical peat and organic soils. Pertanika Journal of Science & Technology, 14(1-2), 61-74.

[32] Sutejo, Y., Saggaff, A., Rahayu, W., & Hanafiah. (2019). Effect of temperature and heating time variation on characteristics of fibrous peat soils. IOP Conference Series: Materials Science and Engineering, 620, 012038. doi:10.1088/1757-899x/620/1/012038.

[33] Mohd Zambri, N., & Md Ghazaly, Z. (2018). Peat Soil Stabilization using Lime and Cement. E3S Web of Conferences, 34, 1034. doi:10.1051/e3sconf/20183401034.

[34] Boobathiraja, S., Balamurugan, P., Dhansheer, M., & Adhikari, A. (2014). Study on strength of peat soil stabilized with cement and other pozzolanic materials. International Journal of Civil Engineering Research, 5(4), 431-438.

[35] Ahmad, A., Sutanto, M. H., Ahmad, N. R. B., Bujang, M., & Mohamad, M. E. (2021). The implementation of industrial byproduct in Malaysian peat improvement: A sustainable soil stabilization approach. Materials, 14(23). doi:10.3390/ma14237315.

[36] Kassim, N. Q. B., & Yaacob, A. (2017). Microscopic Study of Peat Profiles Using FESEM Coupled with EDX Technique. International Journal of Chemical Engineering and Applications, 8(1), 33–36. doi:10.18178/ijcea.2017.8.1.627.

[37] Kalantari, B., & Huat, B. B. (2009). Effect of fly ash on the strength values of air cured stabilized tropical peat with cement. Electronic Journal of Geotechnical Engineering, 14, 1-14.

[38] Sulaiman, M. S., Mohamad, H. M., & Suhaimi, A. A. (2022). A Study on Linear Shrinkage Behavior of Peat Soil Stabilized with Eco-Processed Pozzolan (EPP). Civil Engineering Journal (Iran), 8(6), 1157–1166. doi:10.28991/CEJ-2022-08-06-05.

[39] Suhaimi, A. A., & Mohamad, H. M. (2021). Settlement behaviour of stabilized peat: an assessment with Eco-Processed Pozzolan (EPP) in modified electro-osmotic triaxial cell. International Journal of GEOMATE, 21(88), 86–96. doi:10.21660/2021.88.j2296.