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STABILIZING REINFORCED PEAT USING CALCIUM-BASED ADDITIVE (SH85)

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Abstract

Due to its low shear strength, high compressibility, and bearing capacity, peat is classified as problematic soil and has become a major issue in construction development. This peaty soil presented geotechnical challenges due to its instability and rapid rate of settlement. In this study, shredded rubber crumb (RC) was added to peat (Pt) extract from Kota Samarahan, Sarawak, Malaysia, at regulated percentages of 5%, 10%, and 15%. Cement (C) that act as a binder added at a constant percentage of 5% with 3% to 6% powdered calcium-based resin (SH-85) that serve as an additive. The reinforced peat was prepared at the optimum moisture content for all design mix and cured for 7, 28, and 56 days at room temperature before tested for unconfined compressive strength (UCS) test. California bearing ratio (CBR) test specimens were cured for 7 and 28 days before the test was conducted. The findings indicate that UCS of 398.9 kPa was reached with the design mix of Pt+5%C+10%RC+3%SH-85 over a 7-days curing period. This was approximately 35 times higher than the strength of untreated soil. Whereas the maximum strength was 513.3 kPa for soil mixed with 5%C+15%RC+6%SH-85 after 56 days of curing. Results of the CBR test shows that the design mix of Pt+5%C+5%RC+3%SH-85, exhibit the highest strength of the reinforced peat which is 28.3% at 28-days curing period. It exceeds the minimum CBR value requirement between 5% and 12% stated by Public Works Department (PWD), Malaysia. This study also analysed the microstructure of the treated peat soil. Images taken by scanning electron microscopy (SEM) shows that the voids in treated peat have been significantly reduced and occupied by the new component formed by the interaction of peat with SH-85 and cement. This resulted in a continuous soil fabric, which produced denser and stronger soil. The results of the laboratory tests showed that the treated peat soil increases soil shear strength and load-bearing capacity. Therefore, it is recommended that the stabilized peat can be used as a subgrade layers, as the addition of SH-85 and shredded rubber crumb improve peat engineering properties.

Keywords: Peat stabilization, Powdered resin, Rubber crumb, Scrap tire, Strength enhancement

1. Introduction

Peat is categorized as one of the soft soils and its high-water content, high compressibility, and low shear strength are recognized by various researchers [1-3]. Research conducted by Khing [4] and Rahgozar and Saberian [5] also stated its high compressibility characteristic. Owing to these poor physical characteristics, various researchers agreed that peat soils are not suitable for the foundation of any engineering structure [6-9]. This is due to the soil’s behaviour that also leads to significant failures, such as foundation instability and excessive settlement. As a result of the aforementioned issues, it was evident that peat soil requires significant improvement prior to construction.

In Malaysia, peat covers an important region, especially in the land of Sarawak. Peat soil covered about 8% of the organic soil which is about 3 million hectares in Malaysia making it one of the major soil groups in the country [10, 11]. Sarawak has the largest peat area in the country, constituting 13% of the state and covering approximately 16,500 km^2 of the total land area [12, 13]. A study conducted by M. Sa’don et al. [14] has reported that 90% of peat in Sarawak is categorized as deep peat that is more than 1.5 meters and can be found mostly in low-lying areas. The depth of peat is surprisingly exceeding 10 meters and the peat layer depth was found increases from the coast towards the inland. It is therefore a very challenging task for Geotechnical engineers when dealing with the existence of the deep peat in Sarawak.

Peat or highly organic soil is one of the biggest challenges in the infrastructure construction in Sarawak. With increased growth in population as well as industrialization, roads and other infrastructure on peat land have become vital. Previous case study by Khing [4] indicate that land sinking is a major issue in Sarawak. The problem requires a regular refilling and repairing to restore any platforms, infrastructure, and structures that infected.

Thus, alternative construction approaches can be used to improve the physical and mechanical geotechnical properties of the original soil through soil stabilization. The process of soil stabilization is to treat the soil in order to maintain construction materials and when the quality soil is unavailable from the project area. Soil stabilization is the process of enhancing a soil's physical and engineering properties such as increase bearing capacity, decrease settlement, and minimize lateral deformation in order to meet predetermined objectives and fulfil the design criteria. Therefore, soil stabilization may be a viable acceptable alternative for enhancing the geotechnical properties in such conditions [15]. In addition, the method is intended to be accessible and environmentally friendly, as it makes use of waste materials such as, fly ash, quarry dust, saw dust, rice husk ash and scrap tyres [16].

The use of a stabilizing agent on a subgrade with weak soil improves strength parameters such as cohesiveness, which results in the embankment being strengthened [17]. This statement was agreed by Khanday et al. [18] as he stated that stabilization of soil improves properties such as strength, permeability, and stiffness. As a result, it is capable of achieving predetermined performance and satisfactory results, particularly in terms of construction for a variety of civil engineering projects on peatland [5, 7]. Therefore, researchers have developed a series of peat stabilization techniques. Sapar et al. [19] reported that many researchers used numerous underlaying mechanisms of soil stability such as mechanical, chemical, biological, and electrical to improve the physical and engineering properties of soil. These methods are basically used to improve a soil's engineering properties. Researchers have used various methods to improve the engineering properties of the organic soil, such as soil removal, piles, stone columns, preloading with stage building, and chemical treatment [20, 21]. However, compared to the other soil improvement methods, the stabilization method for peat soil is more advantageous.

The materials used as soil improvement additives are numerous, with an extensive variety of types, and characteristics. In general, it involves anything from natural soils to chemical additives and even recycled waste products. Shredded tire chips are one of the waste materials that were chosen to stabilize peat soil. The application of waste tires in geotechnical engineering has been widely studied in recent years, especially that relates to soil reinforcement technology.

An experiment conducted by Al-Neami [22] on a specimen of sand mixed with 8% tire chips showed that the load-bearing for the soaked CBR increased up to 1.6 times compared to unstabilised sand. The increase in physical interactions between sand particles and tire chips improves the load-bearing capacity of treated sand. Whereas, Sa'don et al. [16] in their studies finds that the shear strength of the reinforced peat with scrap tires increases to 6.6 times with the addition of 5% scrap tires at 28 days curing period. However, the UCS value obtained is less than the targeted threshold of 345 kPa recommended by ASTM D4609. Therefore, they suggested further investigation in determining the optimized percentage of fibres or other material needed to be added to enhance the strength in order to achieve the targeted UCS threshold as recommended by ASTM D4609.

Furthermore, a study by Chan [23] reveals that a mixture of cement and recycled rubber shreds effectively enhanced the mechanical properties of the clayey sand. The cement dosage was kept at a minimum of 4% to bind the soil and rubber shreds for long term durability, while the rubber shreds served as a flexible filler material, without compromising the targeted strength and compressibility. Results from her study shows that when 2% rubber shreds were added to the mixture of 4% cement, a slight drop in the strength can be observed.

Mokhtar and Chan [24] studied about inorganic silt and organic clays stabilized with 5% mixture of cement and various quantities of rubber chips. Results from direct shear tests shows that cement mixed with rubber chips could clearly improve the undrained shear strength of the soft soil and addition of 15% rubber chips also enhance the cohesion value of the soft soil from 0.06 to 0.70 kN/m^2.

The researchers paid serious attention to the use of a number of chemical additives to optimize geotechnical characteristics in order to solve soil problems. Chemical stabilization entails mixing pulverized peat with cementitious materials and additives, which results in a compact structure with increased load-bearing capacity and reduced settlement after the reaction [16]. Chemical stabilization by use of chemical stabilizers can be classified into two types: traditional and non-traditional stabilizers [7]. Chemical stabilizing additives include traditional stabilizers such as cement and lime and non- traditional stabilizers such as enzymes, resins, sulphates, liquid polymers, acids, silicates, lignin derivative, calcium chloride, sodium chloride and various combinations [25]. Traditional stabilizers such as cement, lime, fly ash, and bituminous materials have been extensively explored, and their fundamental methods of stabilization have been recognized in the literatures.

However, the use of traditional stabilizer has some limitations as production of Portland cement and lime consumes a large amount of energy, resulting in releases of substantial amounts of carbon dioxide (CO_2). Therefore, other alternatives for soil stabilization have been used by using non-traditional stabilizers to determine whether the soil that rich in organic matter is suitable for the stabilization process.

Non-traditional additives have received increasing attention in recent years for soil stabilization due to their low cost, simplicity of application, short curing period, and lesser carbon dioxide emissions [26]. Previous research has shown that non-traditional additives can improve soil strength over time [11, 25, 27]. These stabilizers are frequently applied in a variety of fields, mainly in construction field. The stabilizers are categorized based on their primary chemical component [7, 28]. It is possible to define a non-traditional stabilizer as a chemically formulated stabilizer or a modification of a traditional stabilizer. A variety of companies are selling various kinds of chemical additives either in liquid or powder forms. Furthermore, the impacts of these products are not well known, and their patented chemical composition makes it very difficult to determine and predict the stabilizing mechanisms.

For treating weak materials, non-traditional soil stabilizers are commonly used. Such additives are the alternatives to a cost and time effective than the traditional additives such as lime and cement. It has been well documented that the size, shape, and arrangement of soil particles would progressively be influenced by the treatment of natural soil with chemical additives [29]. According to Md Zahri and Zainorabidin [7] the use of non-traditional stabilizers in terms of engineering properties as well as chemical composition seems to have more advantages than traditional stabilizers. The advantages are that it develops a ductile rather than brittle nature, enabling the treated soil to become more ductile and stronger. Furthermore, it has the potential to shorten the curing period, which will have a direct impact on construction costs. Non-traditional stabilizers are also less harmful to the natural eco-system, which can help to reduce carbon dioxide emissions. A recent literature by Sa'don et al. [16] stated that chemical stabilization is a frequently used, low-cost, and successful technique for improving a soil's physical and mechanical properties.

The strength and microstructural characteristics of organic soil stabilized with magnesium chloride ($MgCl^2$) were examined in a study by Wan Hassan et al. [30]. According to the findings, $MgCl^2$ improves the compressive strength of organic soil. During the first 7 days of curing, the strength of $MgCl^2$ stabilized organic soil is approximately 3 to 5 times higher than that of untreated soil.

Moayedi and Mosallanezhad [31] investigated the physicochemical properties and shrinkage rate of highly organic soil using sodium-based stabilizers. The results suggest that the more sodium-based stabilizers being used, the greater the shrinkage rate. The amount of non-traditional materials used affects UCS outcomes. According to the results of the tests, calcium oxide additions highly improve the unconfined compressive strength values, increasing the value by up to 500% when compared to untreated samples.

Previously, Latifi et al. [32] conducted a study to investigate the time-dependent responses between laterite soil and two types of nontraditional additives, TX-85 and SH-85. Based on the results, it was discovered that both additives can increase the laterite soil strength. The soil strength increased around 4 and 5 times, gained in the first 7 days of curing period. Furthermore, SEM data showed that the new component filled the pore spaces of the untreated soil, implying that the treatment with SH-85 and TX-85 resulted in denser soil fabric.

Another study was conducted by Kasim et al. [33] on clay soil stabilized with nontraditional additive in the form of powdered SH-85. Thirty clay soil samples were prepared with different curing times which is 0, 7, 14, and 28 days. The clay samples then mixed with different amounts of SH-85 (5%, 7%, and 9%). The findings of the tests indicate that the strength of the clay soil increases about 6 times more with 9% SH-85 treated sample compared with untreated soil after a 7-day curing period. At 28 days of curing, the highest strength for soil mixed with 9% SH-85 was 1216 kPa. The SEM images illustrate an unbreakable soil fabric, as the voids in the clay were filled by the new component formed by the reaction of the SH-85 stabilizer with the natural clay samples, which resulted in more dense and strong soil.

Latifi et al. [34] in their study also claimed that the use of a low carbon, non-traditional soil stabilizer at a reasonable cost as an alternative to cement and lime is also a sustainable solution. Results in their study indicated that the addition of SH-85 powder had a significant stabilizing effect on the laterite soil, with the UCS values increasing 5 times after a 7-days curing period. Instead of mechanism identification, most laboratory and field studies with non-traditional additives have concentrated on performance evaluation. However, there are very little literature available concerning non-traditional additive stabilization mechanisms for peat soil.

As a result of the presented published studies, the authors are inspired to examine the strength of the fibre reinforced technique on Sarawak peat by utilizing scrap tyre. The objective of this study is to give a comparative investigation of the unconfined compressive strength (UCS) and California bearing ratio (CBR) values of fibre reinforced peat mix with shredded rubber-crumb and SH-85 with a minimum cement content of 5% that act as a bonding agent. The study aims for a UCS value of at least 345 kPa, as defined by ASTM D4609 and with a minimum threshold of 5% to 12% CBR value, respectively. Attempts were also made to determine the effects of rubber crumb and chemical additions on stabilized reinforced peat from a microstructural perspective by using Scanning Electron Microscopy (SEM).

In this study, the geotechnical properties and strength improvements of the design mixture containing shredded rubber-crumb, cement, and SH-85 resin for reinforced peat are reported. A number of physical and mechanical experimental tests were carried out at the Geotechnical Laboratory, Faculty of Engineering, UNIMAS, Sarawak. Unless otherwise specified, all testing, including Proctor compaction tests, unconfined compressive strength (UCS) tests, and California bearing ratio (CBR) tests, were conducted according to BS1377: Part 2:1990.

2. Materials

This study used Sarawak peat, OPC as a binder, shredded rubber crumb as reinforcement, and SH-85 resin as an additive.

2.1. Peat

The peat samples for this study were collected from Kampung Endap, Kota Samarahan. The majority of the surrounding location is mostly dominated with pineapple plantation. This location can be found in Fig. 1 and is categorized under moderately to severely degraded of peat. The classification of peat soil by Von Post classification system are shown in Table 1. Preliminary, top vegetation was cleared to remove unwanted grass and roots from the upper soil layer. To obtain the samples for this study, a disturbed soil samples was collected by excavation of trial pits and taken from a depth of 0.3 to 1 m below the ground surface. To avoid further possible oxidation, all samples were immediately placed and sealed in a black plastic storage.

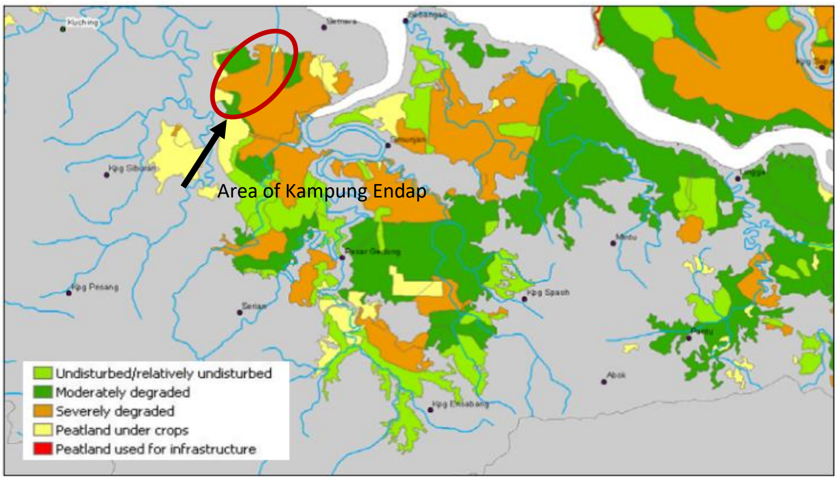

Fig. 1. Peat swamp forest distribution in Kota Samarahan Division.

Table 1. Von post classification system
(after Karlsson and Hansbo 1981) Adapted from [18].

Designation	Group	Description
Fibric (Fibrous peat)	H1 - H4	Low degree of decomposition. Fibrous structure. Easily recognizable plant structure, primarily of white masses
Hemic (Semi-fibrous)	H5 - H7	Intermediate degree of decomposition. Recognizable plant structure
Sapric (Amorphous)	H8 - H10	High degree of decomposition. No visible plant structures. Mushy consistency

The Von Post classification system was carried out to investigate the degree of decomposition of the studied soil during the peat sampling, and about two-thirds of the peat was escapes between the fingers and released a very small quantity of pasty water when squeezed. The overall texture of the peat also can be seen in a relatively homogenous paste. The visual classification of the test conducted is shown in Fig. 2. Thus, the peat is classified as sapric or amorphous peat which is categorized as H8; strongly smell peat with very indistinct plant residue and very dark brown in colour. The peat samples were dried directly under sunlight, grinded and sieved with a desired size before being used for the basic properties and mechanical testing. The organic content (OC) of peat is determined through the loss of ignition test and the value obtained is 86.83 %. Moisture content test also conducted and according to the result, the moisture content of the peat is exceptionally high at 580.20 %, which related to the high percentage of organic matter. The summary of the geotechnical properties of the studied Kota Samarahan peat is presented in Table 2.

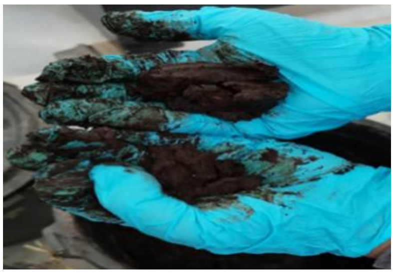

Fig. 2. Von post scale classification (Sapric peat, H8).

Table 2. Geotechnical properties of Kota Samarahan Peat.

Basic properties	Result
Degree of decomposition	H8 (Sapric)
Natural Moisture Content, w_N (%)	580.20
Undrained Shear Strength, c_u (kPa)	9 to 19
Organic Content, OC (%)	86.83
Specific gravity, G_s	1.67
Liquid limit, LL (%) - Natural	434.00
Liquid limit, LL (%) - Dry	114.40

2.2. Ordinary Portland cement (OPC)

In this study, Ordinary Portland Cement (OPC) was added as a binder to stabilize the peat soil at a controlled amount of 5% of the peat's dry weight. Due to the presence of organic matter and the low pH of peat, which tend to inhibit the hydration process, the use of OPC will accelerate the hydration process in the soil composition. In addition, the acidic character of peat soil will react with the calcium produced during cement hydrolysis to form an insoluble calcium humic acid due to its low pH value. This decreases calcium crystallization, resulting in an increase in the strength of the peat-cement mixture. Cahaya Mata Sarawak Cement Sdn Bhd (CMS) manufactures the OPC used in this study. The physical and chemical characteristics of the OPC substance can be referred in Balang et al. [35].

2.3. Processed scrap tire: shredded rubber crumb (RC)

Figure 3 depicts the processed scrap tyre used as a fibre reinforcing material in this study. This material was supplied by ZHA Environmental Sdn Bhd, a Sarawak-based company. A mechanical grinding machine is used to process scrap tyres that have been categorized by size. The reinforcing wire was removed from the waste tyre prior to its conversion into rubber crumbs, rubber powder, and fibre polyester. The rubber shreds used in this study range in size from 1 to 5 mm. The percentage of the reinforcing materials to the dry weight of the peat was controlled at 5%, 10%, and 15%.

Rahgozar and Saberian [5] studied the effects of adding sand to stabilized peat soils at a constant dosage of 400 kg m^{-3} and different doses of tyre chips (5% - 20% by weight). According to the findings of the study, a 10% shredded tyre chip mixture had the highest unconfined compressive strength of 405.4 kPa, that was approximately 64 times that of untreated peat. The sample with 10% tyre chips had the maximum stiffness and significantly improved ductility. Furthermore, Saberian and Rahgozar [36] investigated the efficacy of waste tyre chips (10% by weight) and sand (400 kg m^{-3}) reinforced with a pozzolanic binder (gypsum, lime, or cement) at 5%, 10%, and 15%

by weight as a peat stabilizing agent. All samples with additives showed increased unconfined compressive strength value. Based on the findings of previous studies, the authors decided to control the value of shredded rubber crumb at 5%, 10% and 15%.

Fig. 3. Shredded rubber crumb.

Fig. 4. SH-85 powder resin.

2.4. Calcium-based stabilizer (SH-85) resin

In order to enhance the engineering properties of the peat soil in the study area, a non-traditional calcium-based stabilizer (SH-85) in powder form is used as an additive. SH-85 is a bio-technological waste and is supplied by Probase Manufacturing Sdn Bhd, a local company based in Johor Bahru, Johor, Malaysia.

Table 3. Chemical composition of SH-85 powdered resin (Adapted from Latifi et al. [34]).

Properties	Percentage (%)
CaO	68.21
Al_2O_3	12.30
CO_2	10.24
SiO_2	9.25
Fe_2O_3	0

The product is a biotechnological innovation made from biomass silica waste to creates 'artificial laterite' in the soil mixture in order to meet the standards and requirements of the engineering design. The percentage of SH-85 to be mixed with peat samples in this study is varies at 3% and 6%, respectively with the total weight of dry peat. The SH-85 used for this study is in the form of a powder as shown in Fig. 4. The details and specification of SH-85 are listed in following Table 3.

3. Sample Preparations and Methods

A range of laboratory tests were performed on the collected peat that was reinforced with various percentages of shredded rubber crumb (RC), SH-85, and 5% cement (C). The cement acted as a binding agent, while the shredded rubber crumb serves as reinforced agents. The tests included Proctor compaction test, unconfined compressive strength (UCS) test, and the California bearing ratio (CBR) test. The design mix of the reinforced peat samples were prepared by varying the percentage of shredded rubber crumb and SH-85. RC was used as a filler in the mix design as a non-active additive material and were mixed in percentages of 5%, 10%, and 15%, while the SH-85 used were 3% and 6% from the total mass of dry weight of the mixture with and without 5% cement content. Prior to UCS and CBR testing, 74 and 23 specimens were prepared, respectively comprising unreinforced and reinforced peat with varying mix designs.

Several control samples are prepared for comparison with the reinforced peat samples. The measured parameters of the stabilized reinforced soil is to be compared to those control samples of (a) Untreated peat, (b) Pt + C, and (c) Pt + SH-85 to determine the degree of improvement in the mechanical properties of the test specimens and to attribute it to the various additives as suggested by Rahgozar and Saberian [5].

In this study, samples were prepared based on BS1377: Part 2:1990. The obtained peat soil samples are first sun-dried for roughly a week before being crushed by a grinder. The material is then sieved to a size finer than 2 mm. Using the results from Standard Proctor tests, water was added to the peat to achieve the optimum moisture content and maximum dry density. After adding the water, the mixture of Pt, C, and RC at various percentage of SH-85 is thoroughly stirred in a mixer for at least three to five minutes to ensure that all of the materials are evenly distributed before it was placed in moulds. For UCS specimens, the mixed materials were compacted into a 38 mm internal diameter and 76 mm height cylinder by three equivalent layers. The specimens were cautiously removed out of the moulds, wrapped in plastic film and left to cure at room temperature for 7, 28, and 56 days, including control samples.

CBR test is used to evaluate the effects of adding the reinforced materials on the strength of reinforced peat for sub-grade. The CBR tests are conducted for both unreinforced and reinforced peat at the same MDD and OMC for maintaining uniformity of the design mix. The mould was a rigid metal cylinder with an inside diameter of 152 mm and a height of 178 mm. The procedure of performing the CBR test in this study is following the standard procedure in BS 1377: Part 4: 1990. A metal rammer with 50 mm diameter and weighing 2.5 kg was used as the compacting tool for this test while 300 mm was maintained as the dropping height to ensure that standard forces were applied throughout the compacting process. After that, the prepared soil mixture was compacted in five layers with each layer receiving 62 uniformly distributed blows over the soil surface. After compaction, the moulding collar was removed, and the excess soil on top of the mould was trimmed using a steel straightedge to create a flat surface. Following that, the mould was weighted, and the design mixes were kept in their moulds for 7 and 28 days to cure.

In order to determine microscopic structure of the designated mixture, a high-resolution images of soil fabric before and after treatments were captured using a scanning electron microscope (SEM). The microscopic analysis was carried out using a Hitachi TM4000Plus under high vacuum. Specimens are attached to the specimen tub with conductive tape, and several procedures must be meticulously followed using the equipment specifications in order to obtain the specimen analysis. The observation was carried out utilizing a computer connected to the SEM equipment.

Various researchers [14, 16] studied the stability of peat using cement, and their findings guided the amount of cement used in this study. This selection is strengthened by a recommendation from Paul and Hussain [37], which indicates that 5% cement is sufficient to achieve the minimum strength criteria after 28 days of curing, regardless of the organic composition of the soil. In addition, the reasoning for the percentages of rubber content is based on the recommendations of previous published work by [5, 38]. The air-curing approach is used in this study to improve sample stability by gradually decreasing moisture content as indicated in a study conducted by Kalantari et al. [39]. By allowing peat to gradually lose moisture content and become drier and harder over time, no additional water is required throughout the curing process, as samples are not submerged in water.

4. Results and Discussion

The results of the proctor compaction test, unconfined compression strength tests, and California bearing ratio tests on the performance of reinforced peat with shredded rubber crumb (RC) combined with SH-85 are shown in this section.

4.1. Proctor compaction test - Effect of maximum dry density (MDD) with the optimum moisture content (OMC) on untreated and treated reinforced peat

The results of maximum dry density (MDD) of design mixtures for unreinforced peat and cemented reinforced peat are illustrated in Fig. 5. One can be seen that, with an increasing percentage of shredded rubber-crumb for cemented reinforced peat, the maximum dry density increased by significantly decreasing the optimum moisture content. This behaviour may be due to the higher water absorption of the resin used. The addition of cement into the peat also can be attributed to absorption of water development of hydration and bring changes in base exchange, aggregation and flocculation, resulting to an increase in the density of the mix.

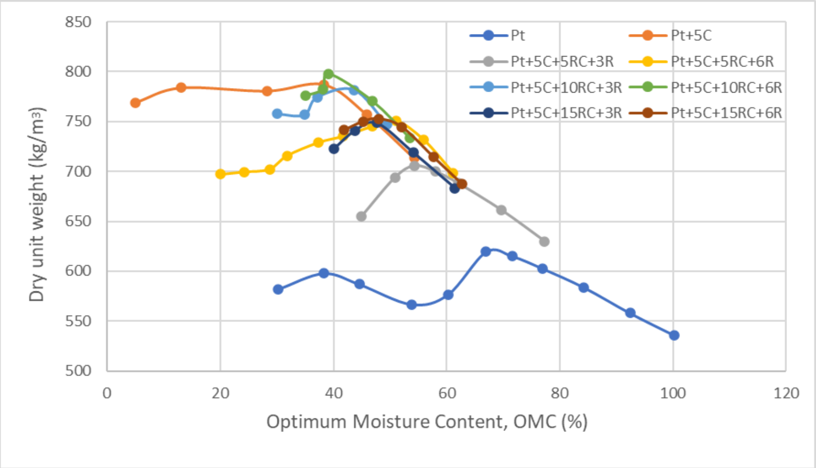

Fig. 5. MDD-OMC of untreated & treated reinforced peat.

4.2. Unconfined compressive strength (UCS) test - Effect of untreated and treated peat

A miniature compacter, which has a diameter of 38 mm and a height of 76 mm, was used to compact all of the reinforced peat samples, which were prepared at the optimum moisture content. A thin layer of grease was added to the inside of the cylindrical tube to reduce friction during sample extraction. The specimens were subsequently extruded using a jack, wrapped in plastic wrap, and cured for 7, 28, and 56 days before testing. The unconfined compressive strength test was carried out in accordance with BS 1377: Part 7 (1990) by applying axial compression load per unit area to the soil specimens until they failed.

Table 4 summarises the unconfined compression test results, and Figs. 6 to Fig. 8 presented the strength performance of the cemented reinforced peat for 7, 28 and 56 days.

As shown in Fig. 6 to Fig. 8, adding RC to the cemented reinforced peat increased the UCS value for curing periods of 7, 28, and 56 days, respectively. The design mix of cemented peat with 10% RC and 3% SH-85 has the highest unconfined compressive strength (UCS) for a 7-day curing period, which is 398.9 kPa (Fig. 5). The strength increase was significant when compared to the natural peat strength value of 11.2 kPa. However, the strength of the same design mixture decreased by 17.1% after 28 days of curing time but increased by 5.2% after 56 days of curing time. The improvement can also be seen in the other design mixture of RC with SH-85, which shows a continuous increase in strength over the curing period.

Table 4. Summary of UCS results.

Sample	**Design Mix**	**Unconfined Compressive strength, qu (kPa)**			
	Curing period (days)	**0**	**7**	**28**	**56**
Control sample	Pt only	11.2	-	-	
	Pt + 5% C	-	40.2	67.4	205.4
	Pt + 3% SH-85	-	72.8	84.5	466.4
	Pt + 6% SH-85	-	56.0	60.4	134.0
Reinforced samples	Pt + 5%C + 5%RC	-	193.1	334.9	433.0
	Pt + 5%C + 10%RC	-	209.3	376.1	400.7
	Pt + 5%C + 15%RC	-	173.7	187.2	217.5
	Pt + 5%C + 5% RC + 3% SH-85	-	156.5	196.7	324.1
	Pt + 5%C + 5% RC + 6% SH-85	-	129.2	135.5	203.9
	Pt + 5%C + 10% RC + 3% SH-85	-	398.9	330.6	347.8
	Pt + 5%C + 10% RC + 6% SH-85	-	117.4	218.1	264.4
	Pt + 5%C + 15% RC + 3% SH-85	-	252.3	283.4	417.5
	Pt + 5%C + 15% RC + 6% SH-85	-	293.0	342.4	513.3

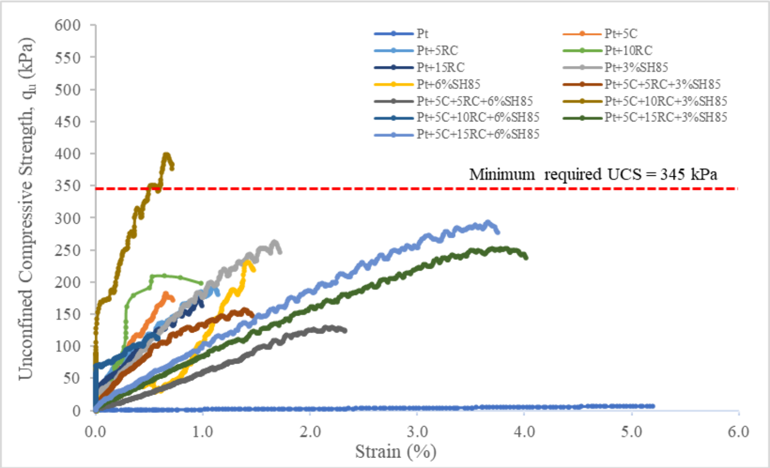

Fig. 6. Results of unconfined compression test at 7 days of curing period.

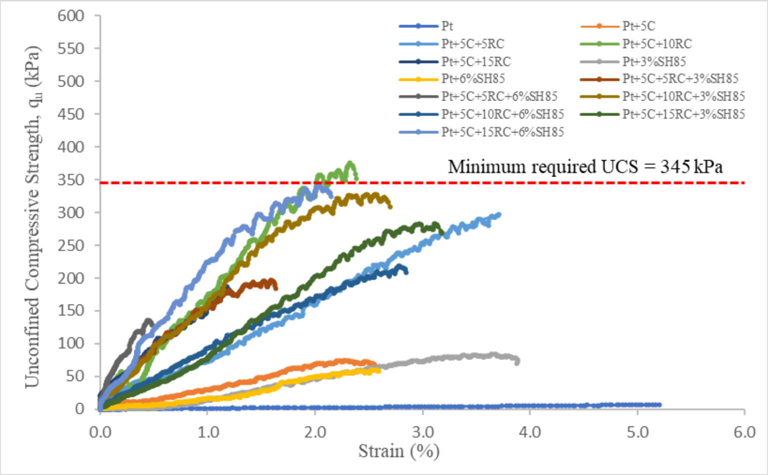

Fig. 7. Results of unconfined compression test at 28 days of curing period.

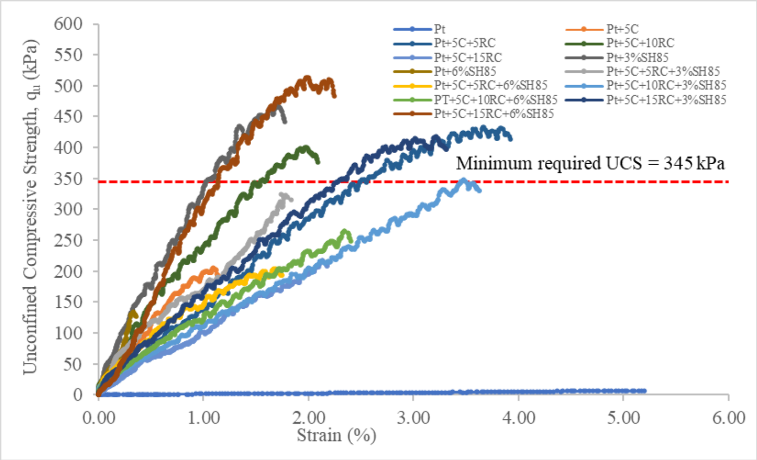

Fig. 8. Results of unconfined compression test at 56 days of curing period.

The design mix of cemented reinforced peat with the addition of 15% RC and 6% SH-85 shows a positive sign of incremental by curing period in reinforced peat with RC. The value increased slightly by 16.7% from 7 to 28 days of curing and continuously increased by 49.9% at 56 days of curing, achieving the highest strength increment of 513.3 kPa. When compared to other mix designs, the cemented peat mixture with 15% RC and 6% SH-85 had the highest value in the 28-day curing period.

In the control samples group, the peat mixture with 3% SH-85 shows a 72.8 kPa strength increment after 7 days of curing and continues to increase when 28 and 56 days are reached. The mixture of peat with 3% SH-85 has the highest increment in these control samples, at 466.4 kPa. As a result, it can be concluded that the use of SH-85 was able to improve peat strength with or without the addition of cement and RC, as evidenced by the strength of the reinforced peat samples.

The results show that the strength achieved by peat with 5% cement and various percentages of RC at 28 and 56 days is greater than the 7-day curing time. This demonstrates that the strength of the design mix of cemented peat with RC is improving and increasing over time. However, the compressive strength of this design mixture decreased as the crumb content increased. The compressive strengths at 7, 28, and 56-day curing periods show a decreasing trend when the crumb content increases to 15%, according to the results of the compressive strength tests for cement contents of 5%, 10%, and 15%. When compared to the addition of 5% RC, using 15% crumb rubber content can result in compressive strength reductions of up to 44% and 49% at curing ages of 28 days and 56 days, respectively. This decreasing trend could be attributed to changes in soil fabric caused by the presence of flexible fibres. However, the addition of 6% SH-85 to the cemented peat with 15% RC shows a surprisingly results in 56 days of curing time where the strength is increased by 136%.

According to the results of the UCS test, as depicted in Figs. 6 to 8, the strength increases with increasing percentages of RC for varying percentages of SH-85. In summary, it can be determined that the reinforced peat sample mix design containing 10% RC and 3% SH-85 works better at 7 days, whereas the reinforced peat containing 15% RC and 6% SH-85 produces positive outcomes at 28 and 56 days. The reason for this behaviour is the reaction of the SH-85 in combination with peat and RC. The addition of SH-85 binds the soil particles together, thus hardening the sample. The sample grows harder and stronger as the number of curing days increases. This explains why the mix's strength increases over time. The addition of rubber shreds increases the contact area and adhesion between the fibre-reinforced materials and soil particles, hence greatly enhancing the compressive strength of the mix. Additionally, the attraction induced by hygroscopic water on soil particles will result in the proper engagement of RC fibres, soil grains, and SH-85. Therefore, the soil's strength parameters are improved. From the observation of the mix design specimens, a higher percentage of processed scrap tire inclusion appears to be associated with a shorter fracture length. This behaviour is caused by an increase in the reinforced material content, which strengthens the bond between the reinforced materials and soil particles. As a result, increasing the friction makes it more difficult for the soil particles that surround the reinforced materials to move from one location to another, hence increasing the cohesion of the treated reinforced samples. The results are also consistent with Kumar and Gupta [40], which state that when local cracks appear in the soil, the applied reinforced materials will span the cracks and absorb the tension in the treated samples. Thus, it inhibits the establishment of additional cracks and increases the soil's resistance to the applied load. In addition, the curing duration effect for all the studied design mix using UCS testing indicates that the strength improved as the curing period extended from 7, 28 and 56 days. The increase in strength found after 56 days of curing is a result of the addition of 5% cement to peat containing recycled tires and SH-85. This shows that the complete contact area between the reinforced peat and the cement matrix has perfectly adhered as illustrated in SEM images (Fig. 8). Consequently, the friction and resistance between them increased.

Though most of the results show an increment in the strength, however it can be seen from Fig. 6 the reduction of strength at 28 days for reinforced peat with 10% RC and 3% SH-85, but it was subsequently increasing at 56 days of curing (Fig. 7). According to Dunky and Pizzi [41]; a bond line might deteriorate due to resin failure, leading to a reduction in hydrolysis resistance and a loss of bonding strength as a result of resin degradation. Failure of the contact between resin and the soil surface can also come from the displacement of secondary forces between resin and reactive soil surface areas by water or other non-resin substances. In addition, the breakage of bonds generated by mechanical forces and stresses leads to swelling and, consequently, movement of water-affected structural components in the sample. In addition, resin hardens substantially faster than cement, with resin achieving its maximum strength in hours (depending on the type and dosage), while cement hardening could take months and even years due to pozzolanic reaction [42].

Thus, at an early age of 7 days, rapid hardening of resin enhances the efficiency of soil strength development; however, as curing time increases, cement stiffness increases due to the stability of resin stiffness, resulting in an evident drop in liquid polymer efficacy [1]. Regardless of the possibility of resin polymerization and cement pozzolanic reactions that occur during the 28-day period, the strength of samples reinforced with resin reduced with time. Consequently, it is likely that the pozzolanic reaction of cement was prevented by the soil and cement hardening due to the polymerization reactions of the resin. Considering the increase in strength of stabilized samples after 56 days of curing, it is possible that polymerization activities impede the completion of the pozzolanic reaction in its early phases [43].

In accordance with ASTM D4609-Standard Guide for Evaluating Effectiveness of Admixtures for Soil Stabilization, an effective soil stabilization treatment must result in an unconfined compressive strength of 345 kPa or above. As depicted in Fig. 6, the observed UCS value for 7-days was higher than 345 kPa for the admixture of 10% RC with 3% SH-85, which is 398.9 kPa, while the maximum ductility was obtained from cemented peat with 15% RC and 3% SH-85 during 7-days of curing. In spite of the fact that the peat with 5% C, 10% RC, and 3% SH-85 mix design had the highest strength after 7 days of curing, it is important to note that the treated peat exhibits ductile behaviour alongside the specimens of 15% RC and 6% SH-85. This enhanced strength and ductility may aid in preventing the soil from cracking and/or failing under load [5]. It is undeniable, based on the results, that adding shredded rubber crumb and SH-85 to peat improves its strength in comparison to natural peat at the early age.

As illustrated in Fig. 7, after 28 days of curing, the admixture comprising 5% C and 10% RC had a higher UCS value of 376.1 kPa at a vertical strain of 2.3%. This is the greatest achievable UCS and stiffness value, exceeding the minimum requirement of 345 kPa. However, the behaviour of the peat-cement mixture was rather brittle, with maximum strength achieved at relatively small elastic strains. Brittle behaviour develops by a change and reduction in bonding between tire chips and soil that results from a reduction in both the homogeneity and consistency of the stabilized peat. In addition, the UCS values for 28 days curing period of the remaining admixtures were lower than the minimum strength requirement outlined by ASTM D4609. The effectiveness of adding SH-85 and rubber crumb to peat stabilization results in an increase in the peat's strength and stiffness compared to the untreated peat, according to the findings of this study.

Nevertheless, as shown in Fig. 8, after 56 days of curing, 6 out of 12 design mixes met the minimum strength requirement of 345 kPa, comprising Pt + 3% SH-85 (466.4%), Pt + 5% C + 5% RC (433.3%), Pt + 5% C + 10% RC (400.7%), Pt + 5% C + 10% RC + 3% SH-85 (347.8%), and Pt + 5% C + 15% RC. According to Rahzogar and Saberian [5], the purpose of tire waste in stabilized soil admixtures is equivalent to that of fibres in reinforced concrete as it prevents the formation of cracks and limits its enlargement. Due to the reduction in peat homogeneity and consistency, the addition of tyre crumbs reduces the bonding between soil and crumbs, resulting in a decrease in strength and stiffness. This behaviour is the result of an increase in the proportion of reinforced materials, such as RC, in the mixture, which strengthens the bond between the reinforced materials and the soil particles. As a result, friction is increased, making it harder for the soil particles around reinforced materials to change position, hence improving the cohesion of the treated reinforced samples [16]. The results also corroborate [40], who stated that when soil presents local fractures, the reinforced materials utilized will span the cracks and absorbs the tension in the treated samples. Therefore, it effectively limits future fracture growth and enhances the soil's frictional resistance to the applied load.

4.3. California bearing ratio (CBR) test - Effect of treated and untreated peat

For subgrade embankment applications, a California Bearing Ratio (CBR) test was done to study the strength effect and quantify the improvement of cemented reinforced peat. To ensure test consistency, the reinforced peat is formed in a cylindrical metal mould with an internal diameter of 152 mm and a height of 178 mm. The specimens were prepared at the same MDD and OMC as the UCS test, with a 7- and 28-day dry curing period. Figure 9 shows the outcomes of employing RC and SH-85 to reinforce the Sarawak peat. Based on the figure, the addition of reinforcing agents greatly increased the CBR value in comparison to the untreated sample. According to the Public Works Department (PWD) Malaysia Design Manuals (ATJ 5/85, JKR Malaysia, (1985)), the subgrade embankment for T1-T5 types of roadways must have a minimum CBR value between 5% and 12%. From Fig. 9, it can be shown that all of the design mixes using SH-85 have exceeded the minimum CBR requirement of 5%. The inclusion of 5% RC and 3% SH-85 results in a CBR value of 26.2% after 7 days of curing. Additionally, the inclusion of the resin at 6% and 12% SH-85 results in a 24.7% and 16.7% increase in CBR value, respectively. For 28 days of curing, the mixture of cemented peat with 5% RC and 3% SH-85 with a CBR of 28.3% attained the maximum CBR.

Rubber crumbs are small-particle, non-striped rubber materials that can be used to decrease the impact of soil after mixing. In addition, it can diminish the load on the foundation to improve the shear strength and other mechanical properties of the soil [44]. Increased in cohesion is mostly attributable to the increased strength of rubber-reinforced soil. It is shown in Fig. 9 that the tensile strength of the mixture is enhanced when RC is added, as the reinforcement increases the overall strength of the mixture. The rubber crumb mixture’s resistance is increased by the reinforcing characteristic. Granular rubber in the shape of longitudinal components leads to more effective reinforcement, improving strength and volumetric strain [45]. The reinforcing is more effective with larger RC particles, enhancing the strength and volumetric strain of the RC soil mixture. The RC particles are generally fragmented and can better occluded, thus allowing for an improved shear effect. Granular rubber strengthens soil by encouraging strong adhesion between rubber and soil particles. Since coarse rubber particles have a bigger surface area of soil mixture, it provides additional reinforcement, enhancing the strength of the mixture.

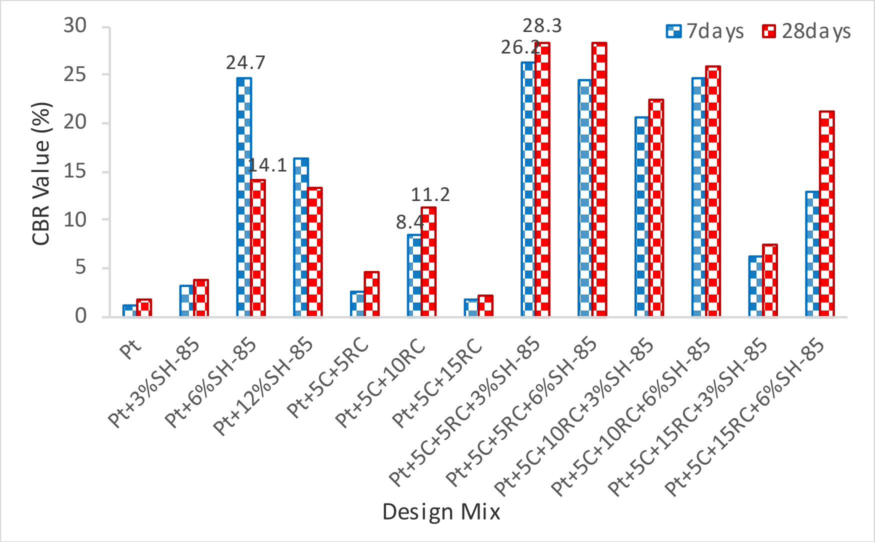

Fig. 9. Performance of CBR on rubber crumb and SH-85 addition.

As a result of this study, peat reinforced with RC and SH-85 showed a significant increase in strength by exceeding the minimum specified CBR value of 5%. This shows that the higher bearing capacity of stabilized soil is not just attributable to the cement hydration process, but also to the rubber and resin contents of the soil mixture. By increasing the CBR value, the total thickness of the pavement can be reduced significantly.

4.4. Scanning electron microscopy - Microstructure of treated and untreated peat

The results of the Scanning Electron Microscopy (SEM) analysis on air-dried samples of untreated and treated Sarawak peat are shown in Fig. 8. Soil samples were analysed using SEM to determine their microscopic structure. Figs. 10(a) - (d) depict the microstructure difference between untreated and treated peat. After conducting the UCS tests at 56 days, samples were collected for SEM analysis. On the basis of the microscopic image of the structure of the peat soil, it is apparent that the grain size ranged from small to large, and the grain shape was not consistent, that is, round and pointed. The rounded shape represents ground grain, whereas the pointy shape represents peat soil fibres. The majority of the peat structure, as represented in Fig. 10(a), contains wide pores that can store a substantial amount of moisture and produce a large initial void ratio. Comparing treated peat to untreated peat, it is noticeable that the amount of pore spaces in treated peat is significantly reduced. The reduction in pore space is primarily the outcome of the hydration process-induced crystallization. In addition, it has been discovered that the addition of cement to the mixture promotes the formation of crystallization.

From the electron micrographs shown in Figures 8(b), 8(c), and 8(d), it can be determined that the stabilized peat soil has a well-structured soil matrix with small pores, because of the crystalline development caused by the hydration process. As a result of the additives' pozzolanic activity, a significant portion of the voids are filled during the process. This decreased the soil's ability to retain pore water and improved its compressive bearing strength.

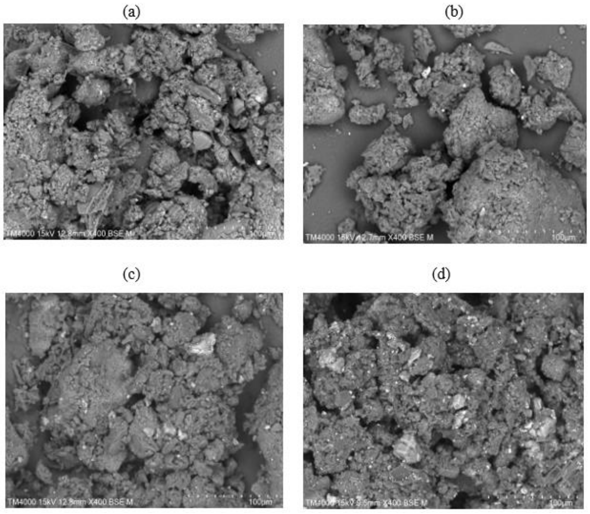

Fig. 10. SEM image of: (a) Untreated peat; (b) Peat stabilized with 3% SH-85; (c) Peat stabilized with 5% C + 5% RC; (d) Peat stabilized with 5% C + 15% RC+ 6% SH-85.

In addition, the cementation chemicals contributed to the formation of strong inter-particle bonds, which can provide excellent resistance to soil swelling and shrinking [46]. Related cementation crystals functioning as the binding agents of stabilized soils can be observed in SEM’s from other studies, of peat soil stabilized with shredded waste tyre chips in combination with gypsum and lime [36] and of peat soil stabilized with fibre-polyester and shredded rubber crumb [14]. Hence, images of SH-85 treated samples after 56 days of curing showed the formation of new compounds in the form of white lumps. Additionally, some interparticle holes were filled with gel in the treated samples. Therefore, the addition of SH-85 contributed to a denser soil structure.

5. Conclusions

The study was conducted on reinforced peat samples utilizing cement (C), shredded rubber crumb (RC) and SH-85. To investigate the strength enhancement for both cemented and uncemented reinforced peat, a series of unconfined compression (UCS) tests and California bearing ratio (CBR) tests was performed. The UCS test indicate the highest increase in strength, at 513.3 kPa with the addition of 5% C, 15% RC and 6% SH-85. In comparison to untreated peat, the CBR value of peat that has been reinforced was improved for all the studied design mixes. The design mixture of cemented peat reinforced with 5% RC and 3% SH-85 had the highest CBR value of 28.3%. The result surpassed the minimum requirement of 5% for subgrade from the Public Works Department (PWD), Malaysia. Images from SEM analysis indicate that the stabilized peat soil has a well-structured soil matrix as a result of the crystalline formation generated by the hydration process. Images of the treated samples after 56 days of curing revealed the formation of new compounds in the form of white lumps, and certain interparticle voids in the treated samples were filled with gel. Based on the findings of this study, it can be stated that using RC with SH-85 as an additive can enhance the engineering properties of Kota Samarahan peat and can be used to determine the optimal percentage of design mix for soil stabilization in the construction industry. Furthermore, reinforced peat with RC and SH-85 as additives has shown enormous progress in treating Kota Samarahan peat and hence have a lot of potential for peat stabilization in the future.

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