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California Bearing Ratio Properties of Peat Soil Stabilized with Crustacean Shell Waste (Chitosan) and Expanded Perlite (EP) Blends

Zeety Md Yusof[1,2], Nurul Aida Asri[1]*, Mohamad Afiq Let[1], Leow Chee Sin[3], Paulus Pramono Rahardjo[4]

[1] *Faculty of Civil Engineering and Built Environment, Universiti Tun Hussein Onn Malaysia, Parit Raja, Batu Pahat, 86400, MALAYSIA*
[2] *Research Centre for Soft Soil (RECESS), Institute for Integrated Engineering (IIE), Universiti Tun Hussein Onn Malaysia, Parit Raja, Batu Pahat, 86400, MALAYSIA*
[3] *Foundation and Geotechnical Specialist, Design Department, Geohan Sdn. Bhd.., 60000, Kuala Lumpur, MALAYSIA*
[4] *PT. Geotechnical Engineering Consultant (GEC), No. 11, Cipedes, Sukajadi, Kota Bandung, Jawa Barat, 40162, INDONESIA*

*Corresponding Author: nurulayedhaaida@gmail.com
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Peat soil, chitosan, expanded perlite, California Bearing Ratio

Abstract

Peat classified as soft soil, which leads to excessive settlement. This research is to characterize the physical properties of peat and to evaluate the enhancement in California Bearing Ratio (CBR) performance of peat stabilized using different proportions of chitosan-expanded perlite blends, with quantitative relationships between stabilizer concentration and CBR values under unsoaked conditions at 0-, 7-, 14-, and 28-day curing periods. Peat from Parit Nipah, Johor, were stabilized using chitosan percentages of 0.5%, 1.0%, 1.5%, and 2.0% in combination with a constant 10% expanded perlite. Both untreated and treated specimens were subsequently subjected to comprehensive physical and mechanical laboratory testing at the RECESS, UTHM. The results show peat highly organic (MC = 501%, G_s = 1.11, OC = 98.64%, FC = 21.07%, DOH = H7) with low compaction characteristics (MDD = 160 kg/m^3, OMC = 142%) and very weak untreated CBR performance (16.10 lbf), while chitosan–expanded perlite significantly increased CBR loads (up to 56.89 lbf at 0 days and 46.75 lbf at 7 days in bottom layers), achieved optimum improvement at 14 days, but exhibited a strength reduction at 28 days, indicating a time-dependent stabilization. CBR values show that 1.5% chitosan (higher content mixture) increases unsoaked CBR values of peat within the range 2.9 - 3.5%, identified as providing an optimal dosage for enhancing, which found to be 0.5% by weight. Chitosan-expanded perlite treatment in ground improvement applications significantly enhances bearing capacity compared to untreated peat, thereby demonstrating a practical and sustainable construction solution for improving weak foundation soils.

1. Introduction

Peat soil is indeed a highly organic material formed by the accumulation of partially decayed biomass, such as mosses, sedges, and shrubs, in waterlogged, anaerobic conditions [1]. Its makeup, which can include more than 90% water and under 10% solids in its natural form, results in extremely low shear strength and significant compressibility [2]. Peat soils contain fibrous organic matter with low mineral content, making their structural bonds weak between particles, and peat soils contain high compressibility, resulting in low shear strength and low bearing capacity [3]. The presence of humic acid in the peat soil results in a high acidic value. Acidification of the soil has a cementing effect on the structure and reduces soil stresses. As a result, the promotion of a load-bearing exceptional quality above ground, beneath its depth, does not become possible because the soil has an extremely high sedimentation tendency and low drainage properties under heavy loads (roads, buildings). This needs effective soil conditioning and stabilization strategies. From a technical perspective, it is very hard to provide appropriate base material for commonly used structures today [4].

Natural moisture levels in peat soils that contain more than 75% to 90% organic matter range from 200% to above 600%. A factor of low shear strength, less than 10 kPa, is an obstacle for road construction and leads to poor pavement serviceability. High traffic densities in areas including the Klang Valley and Teluk Intan make the local soils susceptible to major settlement issues, lateral displacement, and deterioration of structural stability. The effects can be seen through changes in the grooves and cracks in the pavement [5]. There is a need for an important and economical method in chemical stabilization, particularly to alter the soil structure. It functions to increase soil strength, minimizing compressibility and accelerating construction time [6]. The use of chemical stabilization is very widespread, especially in peat soils, because it can change their physicochemical properties, but it depends on the suitability of the chemicals and their percentage of use in the peat soil mixture. Chemical reaction factors change the physicochemical properties of peat soils by promoting bonding between soil particles, reducing compressibility, and reducing soil moisture susceptibility [7].

The chemicals in the soil undergo a pozzolanic reaction process. It also changes the cation exchange and agglomeration of the soil, together improving the soil characteristics to suit the current land use [8]. The development of sustainable materials is skyrocketing, especially by 2025-2026. The use of sustainable and waste-derived materials is highly encouraged in the industry. The construction industry is driven to use sustainable materials as a replacement for soil stabilizers. The increasing use of sustainable materials will not reduce the use of resources, as a major contributor to construction needs. This can also reduce construction costs and carbon emissions [9]. Wastes from the agricultural and marine industries have the potential to contribute to improving soil resilience based on the industry's research into reducing environmental impact. The effect can catalyze sustainable stabilization in advancing the economy, especially in the construction industry, which is always looking for solutions in improving the capabilities of challenging peat soils in geotechnical engineering applications [10], [11]. This investigation uses chitosan (obtained from crustacean shell waste) combined with expanded perlite (EP) to measure peat soil performance through California Bearing Ratio (CBR) assessment. Chitosan is low-cost and can decompose naturally [12], while expanded perlite is light and stable in terms of chemicals [13]. The mixture of these materials aims to reduce compressibility, increase stiffness, and increase resistance to penetration under load [14] using the CBR performance method of treated peat soils. In addition, it can have an impact on the effectiveness of chitosan-perlite composites as a sustainable option in soft soil areas like peat soils [15].

Geotechnical materials such as peat soil have challenges in controlling their water content because it may exceed 100%, high compressibility, low shear strength between 5 and 20 kPa, and high organic matter, making it inadequate for direct loading [16]. The instability of peat and structural deformation in construction projects are the primary factors that cause long-lasting and time-dependent settlement performance [17]. Weak soils, especially those with loose and fibrous soil composition, are often caused by high organic matter content that has not fully decomposed. It makes the particle connections weak and void. This allows for the fact that when there is a load on top, it will also produce another load, namely, an external load. In other conditions, soft soils such as peat easily settle due to such mechanical compression and particle damage caused by such loads, resulting in instability and reduced bearing capacity [18]. Soils with poor load transfer, such as peat soils, will damage the structure and have a high risk of soil compaction, making them unsuitable for supporting infrastructure such as roads and buildings without appropriate ground improvement or stabilization measures [19]. Peatlands in Johor are used to meet the current needs of the construction industry. The high capacity of peatlands in Johor presents a major challenge for infrastructure development, due to the risk of sedimentation in the short term [20], [21]. According to previous studies in Md Yusof *et al.* [22], O'Kelly & Pichan [23] and Foda & Ibrahin [24], moisture levels between 200% and 700%, organic matter percentages as high as 99%, and shear strength measurements typically below 25 kPa are reported, indicating that the engineering performance of peatlands is very poor. As a result, structures on untreated peatlands are unstable over time. This encourages consistent soil improvement or stabilization for user safety in areas dominated by peat [25]. Cement and other chemical additives have their own strengths to achieve high performance; however, they still have their own weakness in terms of limitations due to high material needs, reduced efficacy in acidic peat, and environmental concerns [26] – [28]. The high acid and alkali content of peat soils requires a material that can assist the hydration and pozzolanic processes. This is because peat soils with organic matter inhibit their strength development. The use of ineffective materials in untreated peat soils makes them brittle, prone to cracking, and reduces performance under cyclic or dynamic loading [29]. In addition, such high-strength and expensive binders may cause unhealthiness in cost matters, and given the support of carbon emissions and long-term impacts from an environmental standpoint. This makes peatland ecosystems vulnerable to pollution, and promoting the use of more sustainable and compatible stabilization is more necessary [30]. The desired additive should be a proper additive with respect to soil strength. Chitosan biopolymer is used as it has the ability to increase the strength of soil (shown by the CBR test). But its efficiency is based on the ratio and curing time [31], [32].

The second advantage is to form a strong soil bond that fills the pores while forming soil, which can decrease deformation and improve high load-bearing capacity [33]. The degree of curing and the amount of material used may also alter the stabilization efficiency since over-curing would also prohibit bond alterations. An overdose of the material can limit the efficiency of cementation and hamper workability [34]. In fact, materials such as perlite (a lightweight volcanic material) can help decrease density, improve drainage, and enhance durability. Other than showing pozzolanic properties when mixed with binders, it is also an excellent building material due to its loose, lightweight structure and irregular silicate arrangement [35], [36]. The characteristics of perlite allow it to be a useful additive in geotechnical engineering to improve the dynamic properties and usability of stabilized peat soils [37].

The mixing of chitosan with perlite used depends on the percentage composition of the material used, providing a sustainable, environmentally friendly, and efficient method to improve the engineering properties of weak and organic-rich soils such as peat [38], [39]. In selecting soil stabilization materials for construction, it is essential to understand the specific benefits they provide, which allow weak or in-situ soils to meet engineering requirements. Some benefits including increase soil strength, reduced volume changes, enhanced durability, and improved workability. Therefore, the benefits for engineering applications of chitosan and perlite are developed, such as reducing the need to excavate and dispose of infertile soil and avoiding the expense of importing high-quality aggregates, increasing subgrade strength, allowing for thinner pavement, sub-base, or base layers, and preventing differential settlement, erosion, and structural failure, thus increasing the lifespan of roads and foundations. There is a lack of chitosan – expanded perlite in peat soil. However, the composite, due to the combination of its components, is likely to offer superior removal rates for contaminants such as color and heavy metals, due to the combination of chemical binding and high, stable surface area.

2. Materials and Methodologies

Fig. 1 illustrates the location of sample peat soils at Parit Nipah, Johor, Malaysia. The location of sampling is at coordinates 1º 55'11" N, 103º 10'36" E, which is the area of very extensive and continuous peatland deposits.

Fig. 1 *Peat soil structure location in Parit Nipah*

Peatlands are classified as waterlogged, acidic, and highly organic soils. They are formed from the accumulation of vegetation, the majority of which has decomposed under anaerobic conditions over thousands of years [40]. A study by Nor *et al.* [41] showed that the peat at Parit Nipah presents the engineering issues common to peatlands, making it an exemplary location to study stabilization methods. Areas such as housing and agricultural land, including oil palm plantations, pineapple plantations, and cash crops, were used as sampling sites for additional research and possible future development initiatives. In a British Standard [42], the method can be implemented based on the properties of the soil. In fact, the application soil stabilization in ASTM standard at site can be carried out in existing settlement and agricultural areas [43]. It is essential to see the effectiveness of sustainable soil stabilization methods, as the treated peat needs to be maintained so that it can assist in the construction of roads, foundation supports, or improved drainage systems without negatively impacting adjacent land uses. Incorporating soil improvements is an initiative in the research to see to what extent the results can be used indirectly to improve the resilience of local infrastructure. Additives such as Chitosan and Perlite, derived from treated crustacean shell waste, offer sustainable and biodegradable biopolymers suitable for environmentally friendly soil remediation. Perlite is a lightweight volcanic material, in granular form, making it easy to handle, and it shows practical applicability for future use in the construction industry as well as in soft soil construction and improvement efforts.

The collected peat soil samples were dried to remove excess moisture. Using a 0.5 mm mesh, the physical properties of the soil were extensively evaluated, including moisture content, specific gravity, degree of decomposition, presence of fibers, and organic matter, to establish a detailed understanding of its natural characteristics and underlying conditions. Standard Proctor compaction tests were conducted to find the maximum dry density and optimum moisture content. The California Bearing Ratio (CBR) test assessed the load-bearing capacity and suitability of the soil for subgrade use. Additives such as chitosan in different amounts of 0.5%, 1.0%, 1.5%, and 2.0% were used, and expanded perlite at a stable level of 10%. Table 1 shows the details of the percentage composition of the additives used in this study.

Table 1 *Composition design of untreated soil and treated soil*

Label	Chitosan (%)	Expanded Perlite (%)	Curing days			
			0	7	14	28
Peat-only	-	-	1	-	-	-
S1	0.5	10	1	1	1	1
S2	1.0	10	1	1	1	1
S3	1.5	10	1	1	1	1
S4	2.0	10	1	1	1	1

The selection of the chitosan percentages typically in the range 1 – 3% (w/v) [12] and 10% expanded perlite is according to the optimization of mechanical integrity, solution viscosity, and functional porosity for the resulting composite [15].

Based on these studies, the concentration of 0.5 to 2.0% chitosan and 10% constant expanded perlite is selected to optimize the mechanical strength and maintain workability. Higher concentration can lead to negative performance trade-offs. Based on a study by Sujatha *et al.* [12], it indicates that chitosan can enhance mechanical properties >2%. A study by Barleany *et al.* [14] found that adding 0.25% wt% to 0.5% chitosan yielded the best mechanical strength at 28 days. Expanded perlite is a lightweight aggregate used to reduce the density, but it negatively impacts the strength of the mechanical properties in addedd excess. While expanded perlite reduces the weight of the materials, it reduces the mechanical strength. A study by Rithani & Kumar [13] showed that a 10 wt% replacement of sand with expanded perlite provides the best balance in compressive strength and improves density without compromising the structure. In summary, 0.5% - 2.0% chitosan and 10% expanded perlite keep the mixture weight and enough porosity without causing severe strength loss.

The procedure in this study used ASTM standards [43], to obtain reliability and comparability of findings based on the recommendations shown. A total of 17 samples were produced to obtain the results in this study. In sample preparation, the quantities of chitosan and expanded perlite (based on Table 1) were thoroughly mixed with 5 kg of peat soil to ensure uniform distribution of additives. Curing periods starting from 0, 7, 14, and 28 days were chosen to evaluate the effect of curing time on strength growth, with all tests conducted under undrained conditions. The (CBR) test (62 blows from a 4.50 kg hammer) was performed using a constant penetration rate of 1.25 mm/min. The CBR values and the resulting load-penetration curves were automatically generated using the CBR-Utes Software, providing full results for the samples. Chitosan and expanded perlite, which were used in this study, act as sustainable and eco-friendly soil stabilization systems. According to Ngasotter *et al.* [31] and Ekwue & Stone [32], chitosan acts as an adhesive, covering the soil particles and fills voids, creating a stable, interconnected framework, while expanded perlite acts as alighweight, porous structural matrix, enhancing the

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overall soil structure and providing a medium for chitosan to bind, thus preventing the soft nature of soils. The combination of chitosan and expanded perlite creates a highly porous and providing a better interlock mechanism between soil particles. The shear strength increases over time (curing) as the chitosan gel dries and becomes a more rigid binder, particularly in air-curing conditions. While it improves the CBR, the chitosan-expanded perlite-treated soil exhibits higher CBR values, with an increase in unsoaked CBR and an increase in soaked CBR for soil, especially at an optimal dosage.

3. Results and Discussions

This section presents and discusses the experimental results from the laboratory work to determine the behavior of the composition samples. Table 2 shows the parameters that were tested in this research. The parameters are critical to monitor the natural soil properties and also to follow as a benchmark for the reflective behavior of soil performance.

Table 2 *Parameters of the physical properties of peat soil and their results*

Parameters	Values
Moisture Content (%)	501
Specific Gravity	1.11
Degree of Decomposition	Sapric (H7)
Fiber Content (%)	21.07
Organic Content (%)	98.64
Optimum moisture content (OMC, %)	142
Maximum Dry Density (MDD, kg/m^3)	160

In this study, the results obtained from laboratory tests showed that 501% moisture content was obtained from the samples, which is very high for peat soil, where the moisture range of peat soil is between 200% and 2000% and it is used as the range referred to in Malaysian peat soil research. The moisture content of peat soil in Parit Nipah, Johor, is between 150% and 700%. However, if the peat soil moisture results are 545% for undisturbed samples and 328% for reconstituted samples, this depends on the location of the soil taken [44], [45]. The reading of 501% is due to the natural characteristics of peat soil. This is because the material in the peat soil contains organic matter that is partially decomposed with a very fibrous and porous configuration [46]. It forms a large internal void area that can accommodate a large amount of water through capillary absorption and adsorption to organic particles [47] if it is not drained sufficiently with high groundwater levels, which leads to continuous water saturation. This situation is usually found in low-lying areas in Parit Nipah. In this study, the observations found that humic substances and plant residues present in peat soil increase the soil's ability to retain and store water, which is a major factor contributing to the very high humidity levels.

The Von Post scale shows that the visual observation of peat soil in this study is categorized as H7. It shows that the peat soil sample has sapric properties with highly decomposed plant material. Peat has a decomposition stage where half of the peat seeps through the fingers. The material is dark in color, thick, and mostly shapeless. The specific gravity reading of peat soil was obtained as 1.11. This is among the factors of its significant organic matter and minimal mineral decomposition, which indicates that the specific gravity value of peat soil is low. The specific gravity range of peat soil is in the range of 1.07 and 1.85 for peat soil located in Johor and Peninsular Malaysia [48]. The Von Post scale indicates a highly decomposed (sapric) condition (H7). It is due to prolonged biological activity occurring in an aqueous and anaerobic environment, facilitating the process of gradual decomposition of plant material over time [49]. In addition, the continuous saturation process restricts oxygen access. It slows down the complete mineralization process and gradually becomes fine organic waste [50]. The long decomposition process leads to the loss of plant form. In addition, the creation of undifferentiated organic matter may contribute to the sapric properties described [51]. Therefore, the specific gravity reading of 1.11 is relatively low because organic matter has a much lower particle density than mineral soils, resulting in a decrease in solid density [52].

The fiber concentration value of peat is recorded as 21.07% (sapric) because it has less than 33% fiber. Usually, dark brown to black in color, it decomposes extensively. In addition, the material is very moist and amorphous. Sapric peat is identified by its capacity to store large quantities of water [53]. According to ASTM D1997 [54], peat is categorized according to fiber content into fibric (>67%), hemic (33–67%), and sapric (<33%). If the peat fiber content is 21.07%, it indicates that the peat is in a later stage of decomposition, which is typical of sapric peat. It is due to the prolonged microbial decomposition of plants growing in a constantly watery environment. This also occurs because the initial fibrous components, such as roots, stems, and leaves, have gradually broken down into smaller organic fragments. Apart from that, at the same time, the biological and chemical properties that react also reduce the number of fibers present and change their nature into amorphous organic matter and humic substances. As a result, the peat exhibits a reduced fiber framework but an increased capacity to retain water due to the high surface area and porous microstructure of the decomposed organic matrix, which explains both the low fiber content and the high moisture retention observed in this study.

The results also indicated that the soil is highly decomposed (sapric) with a low fiber content and very high organic matter, characteristic of tropical peatlands. The 98.64% value for organic content suggests a highly pure organic material, often found in deep peat layers. Previous studies in Parit Nipah, Johor, Malaysia, have shown that the organic content of the peat soil in this area typically falls in the range of 78% to 95% or 90% to 98%. The decomposition level for these sites is generally classified in the H5-H6 range (hemic to sapric) on the von Post scale, with a moisture content of over 500% and a high fiber content of up to 67% [55]. Furthermore, according to Wahab *et al.* [56], findings for Parit Nipah peat soil include organic content (78.77% - 95.44%), fiber content (40.97% - 63.77%), degree of humification [H5-H6 (moderately to highly decomposed)], and physical properties (high compressibility, low bearing capacity, and high moisture content). The high value of 98.64% indicates that the organic content is consistent with the very high organic matter in the peat soil of Parit Nipah.

Fig. 2 illustrates the compaction characteristics of the peat soil, where the optimum moisture content (OMC) was determined to be 142% and the corresponding maximum dry density (MDD) was 160 kg/m^3, reflecting the highly porous and lightweight nature of the organic soil matrix. The results of the compaction test were found to be with high optimum moisture content (OMC = 142%) and low maximum dry density (MDD = 160 kg/m^3), which can be attributed to the influence of physical properties (decomposed organic matter, fibrous residues, interconnected voids) carried by the peat soil.

Lee & Yip [57] reported that organic particles have a high capacity to absorb water and a strong attraction to moisture. Therefore, a significant amount of water is required to lubricate the particles and facilitate their rearrangement during the compaction process, resulting in a high optimum moisture content (OMC). However, despite the high moisture content, the soil is unable to achieve high density because organic matter has low particle density and poor packing efficiency compared to mineral soils. Additionally, the compressible and elastic behavior of peat causes rebound after compaction, preventing effective reduction of void ratio and leading to the observed low MDD. These characteristics collectively justify the unusually high OMC and low MDD values reported in this study.

Fig. 3 and Fig. 4 show a graph of the California Bearing Ratio (CBR) test on treated peat soil. The following findings were observed at 0-day curing under unsoaked conditions at the top vs. bottom CBR values: the bottom samples exhibited higher CBR values compared to the top samples across all tested mixtures. This is commonly attributed to the higher density of the soil at the bottom of the compaction mold compared to the top. Regarding the effect of chitosan content, contrary to expectations of increased strength, higher percentages of chitosan resulted in reduced strength, indicating that increased stabilizer content did not improve the load-bearing resistance in this specific, early-stage (0-day) scenario. This suggests that for immediate, unsoaked, 0-day conditions, a lower stabilizer or alternative preparation methods might be necessary to achieve higher initial resistance in peat soil.

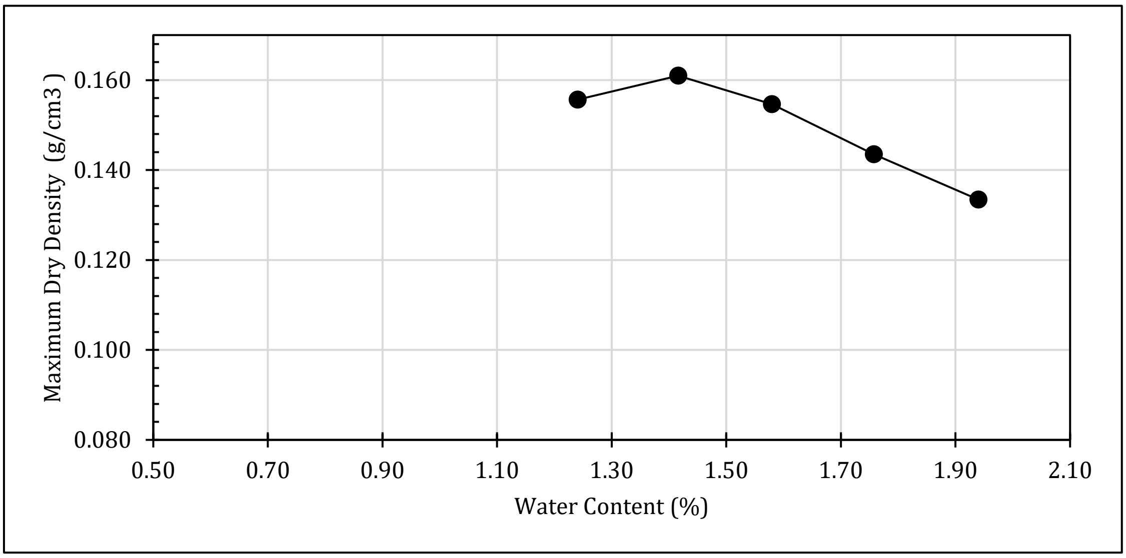

Fig. 2 *Result of compaction test for CBR*

The observed CBR results at 0 days of curing, in which the bottom samples in Fig. 4 exhibited higher load-bearing capacity than the top samples in Fig. 3, can be attributed to differences in compaction density and moisture distribution within the specimens. Deeper soil layers typically experience more confinement and a denser particle arrangement during the compaction process. This is because enhanced interparticle contact and stiffness are produced at higher initial CBR values. On the other hand, the upper layers, which have more space, facilitate the retention of a larger void ratio and are more prone to deformation under load, resulting in a decrease in measured strength. At the same time, the reduction in strength observed at high chitosan levels at 0 days may be due to insufficient interaction and limited time for the biopolymer to establish a functional binding network between soil particles; immediately after mixing, excess chitosan may also retain water and increase pore pressure, temporarily affecting the soil matrix. This is supported by Tapia *et al.* [58], where their study showed that the stabilization process is time-dependent, requiring curing to facilitate effective bonding between the polymer and the soil, thus maximizing the load-bearing capacity of the peat soil.

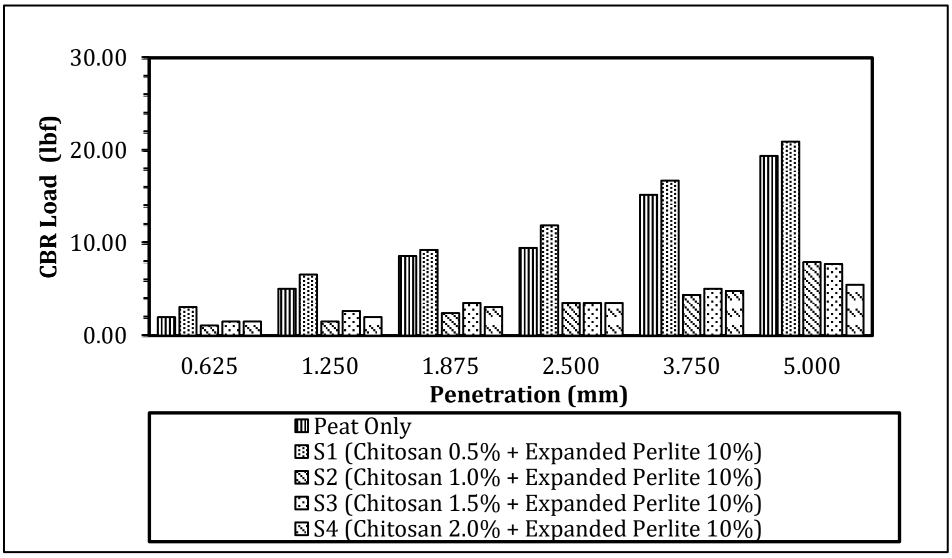

Fig. 3 *CBR load at 0-day curing for top sample*

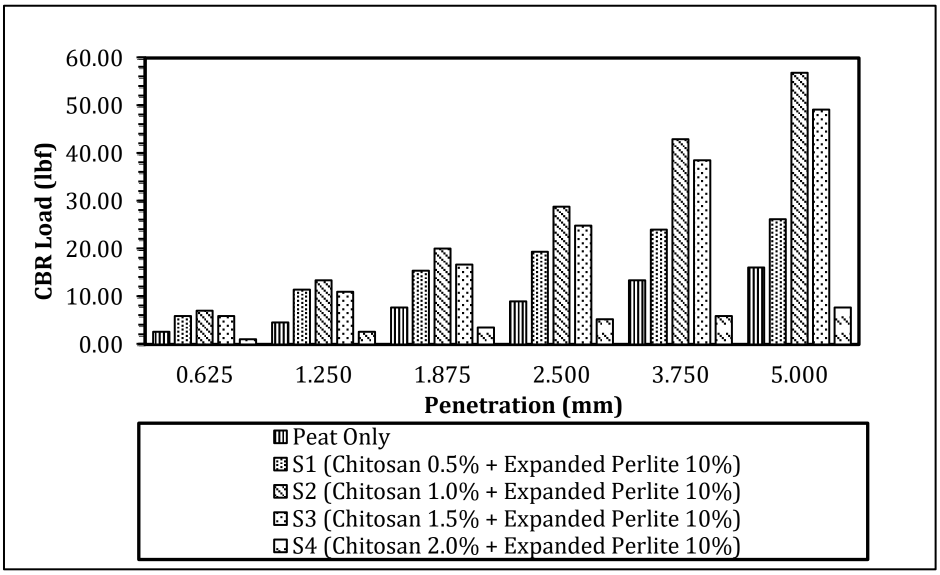

Fig. 4 *CBR load at 0-day curing for bottom sample*

Fig. 5 and Fig. 6 show the relationship between CBR load (lbf) and penetration (mm) for the specimens' peat soil top layer and bottom layer for 7 days of curing under unsoaked conditions. Fig. 6 shows the results for the lower sample. It shows that the results consistently exhibited higher load-bearing capacity across all penetration depths. As opposed to the top sample illustrated in Fig. 5, the effects were more significant in the lowest layer. The reason is that such curing and compaction processes promote the chemical reaction between chitosan-expanded perlite stabilizer and peat soil particles, increasing particle interlocking, structure bonding, void space reduction, structural integrity, and hence better mechanical performance. It is densified (confined and compressed) better than the sub-base. Compared to the bottom layer, it benefits from greater confinement and compression during compaction. It shows that it densifies the soil matrix and facilitates more efficient stress transfer under load.

Therefore, the performance shows the synergy between effective compaction and time-dependent curing. The CBR performance in the bottom sample highlights the important role of both procedural factors. The chemical stabilization improves the strength characteristics of weak peat soils [59].

The results in Fig. 6 after 7 days of curing for the bottom sample showed the combined effect of compaction and stabilization processes over time. Increased overburden and confining stress affect the bottommost layer of the specimen during compaction. Therefore, the reaction of the force changes the facilitating particle rearrangement. Therefore, the reaction of the force changes, facilitating particle rearrangement. It also reduces the void ratio and increases interparticle contact, leading to greater stiffness and initial density. But during the 7-day curing process, the chitosan-expanded perlite stabilizer slowly changes and interacts with the peat soil matrix. This is because the bonding process occupies the gaps to further improve the soil structure. The bottom layer actually gains more due to its denser arrangement. It promotes better chemical infiltration and stronger bonding between soil particles and both the stabilizer and filler. Even though the top layer is less dense, it still has the potential for increased voids and reduced particle interactions, and inhibits the immediate strength increase. Therefore, it illustrates the combined effect of density from compaction and chemical stabilization from curing on the mechanical properties of peat soils' impact during CBR performance between the top and bottom layers [60].

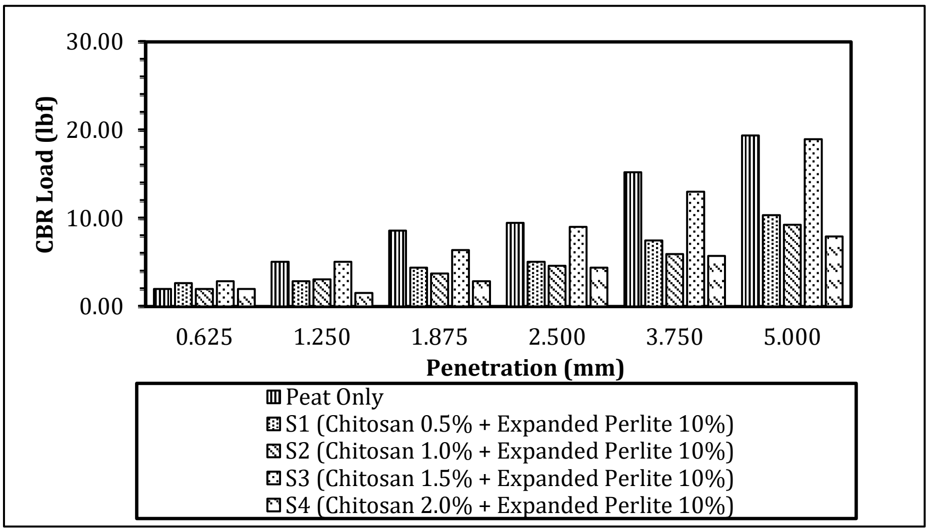

Fig. 5 *CBR load at 7-day curing for top sample*

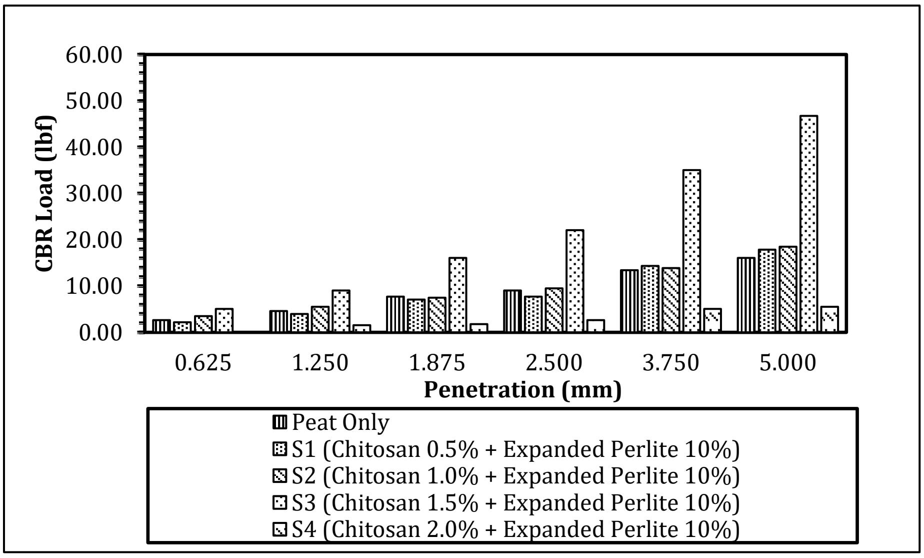

Fig. 6 *CBR load at 7-day curing for bottom sample*

For the 14-day curing in unsoaked conditions, Fig. 7 and Fig. 8 showed the CBR load (lbf) in relation to penetration (mm) for the upper and lower layers of the peat soil samples. The effect of curing on the mechanical properties of the stabilized peat soil at 0- and 7-day CBR tests showed a distinct and noteworthy rise. The bottom samples consistently showed greater CBR values compared to the top samples. The combined influence of better compaction, which increased particle density, and enhanced stress distribution in the lower layer was observed.

It indicates that the increasing chitosan levels past an ideal point result in decreased strength. Too much polymer could impede proper bonding or introduce more voids. Therefore, there is a need to emphasize the necessity of identifying the optimal stabilizer amount. It shows that the curing time and compaction efficiency are important in improving the load-bearing capacity of peat soils. As can be seen, the lower layer consistently performed. Its yield was better because the peat soil was a denser composition. It had better interaction with the materials, as the perlite stabilizer was developed with chitosan.

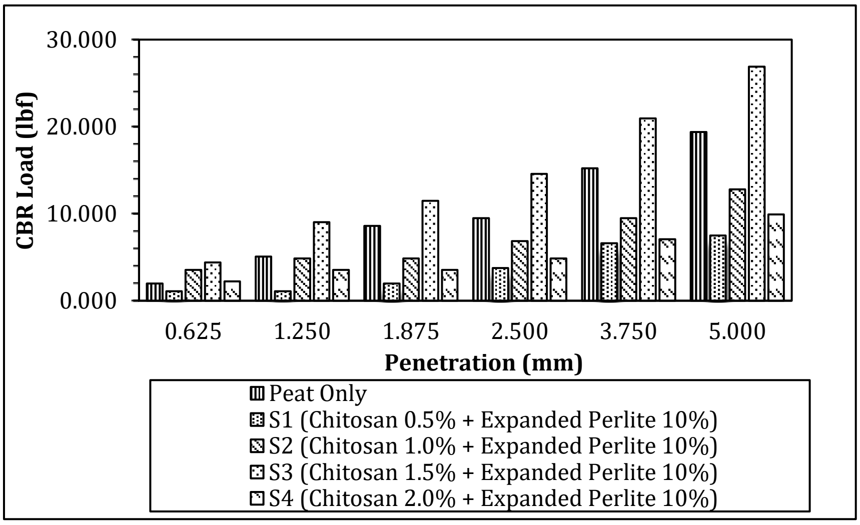

Fig. 7 *CBR load at 14-day curing for top sample*

After 14 days of curing, the CBR results showed an improvement. This is because the developed chitosan-perlite stabilizer factor combines with the peat soil particles. The chitosan material acts as a natural polymer binder during the stabilization period. It acts slowly to create a chemical and physical bond with the organic soil matrix. In addition to increasing particle cohesion, it also minimizes void space and increases stiffness. In Fig. 8, the results obtained were consistent. Fig. 8 shows a greater strength than the upper sample due to compaction during specimen preparation. Therefore, it provides a better confinement result and a denser packing in the lower layer. This process aims to provide more effective stabilizer workability and stronger particle bonding. Although chitosan increases, it shows a decrease in strength. Therefore, an ideal dosage combination exists; excess polymer should be present to allow water storage or cause uneven soil distribution, which affects the matrix instead of strengthening it. So, factors such as curing time, compaction effectiveness, and controlled stabilizer quantity are very important in improving the mechanical properties of peat soils [61].

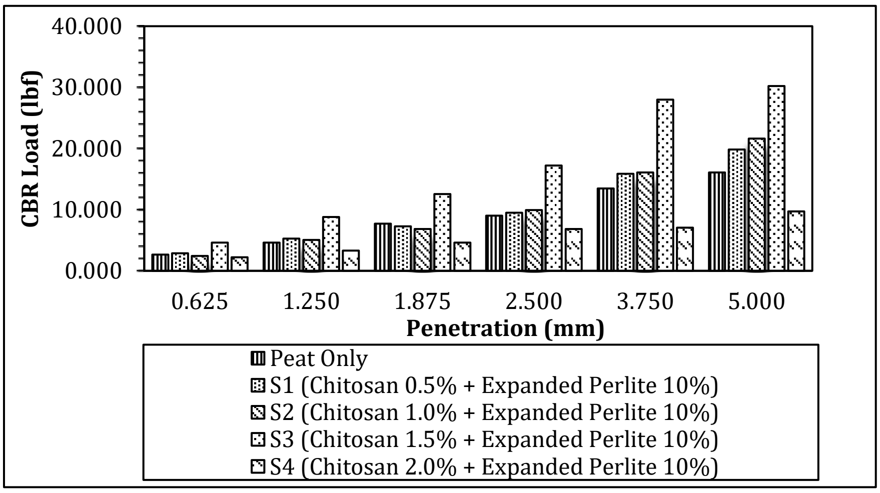

Fig. 8 CBR load at 14-day curing for bottom sample

Fig. 9 and Fig. 10 illustrate the relationship between CBR load (lbf) and penetration (mm) for the upper and lower layers of stabilized peat soil after 28 days of unsoaked curing. The value of CBR during this curing period was higher than that measured at the previous periods for stabilized peat soil. This demonstrated the continued strength development after some time. This improvement indicates that the curing treatment has the potential to increase physicochemical interactions among chitosan biopolymer, expanded perlite, and the soil matrix of peat. It shows the resulting particle adhesion, decreased voids, and a more cohesive and stable soil composition. In addition, the lower panels in Fig. 10 presents a sustained improvement in load-bearing capacity. This was particularly visible when the penetration depths increased, owing to higher compaction density and confinement during specimen preparation, which enabled more effective stress transfer and better resistance to deformation. That strength goes down as more chitosan is added, and it suggests that there is an optimal amount of stabilizer, and too much polymer can similarly disrupt the soil structure, increase its water retention, and prevent particle bonding. In determining the long-term mechanical behavior of stabilized peat soils, it has an effect on the results, emphasizing the joint impact of curing time, stabilizer interaction, and compaction efficiency.

Another reason could be that the CBR value at 28 days after curing of expanded stabilization had been enough for chitosan–expanded perlite to fully penetrate peat soil matrix and develop stronger bonding mechanisms. Chitosan polymer chains link with soil particles during the curing process. Now the expanded perlite is a lightweight filler that fills voids and increases mechanical interlocks to the denser soil matrix, for the lower samples in Fig. 10 by an amount that was always larger than the uppermost data points in Fig. 9 because of the enhanced compaction-induced confinement. It also demonstrates a better stabilizer penetration and bonding, thanks to an increased particle-contact area. Therefore, it improves the stress transfer and penetration resistance, but a decrease in strength indicates that at higher chitosan content, the excess polymer is present. This results in increased water holding, nonuniformity, and potential formation of soil zones, which may be weak as a consequence of disruption in particle stacking and particle-to-particle bonding. Thus, the influence of extended curing on long-term strength development of stabilized peat soil involved a combined contribution of keeping stabilization for a longer duration to facilitate stabilizer interaction and the impact of compaction efficiency.

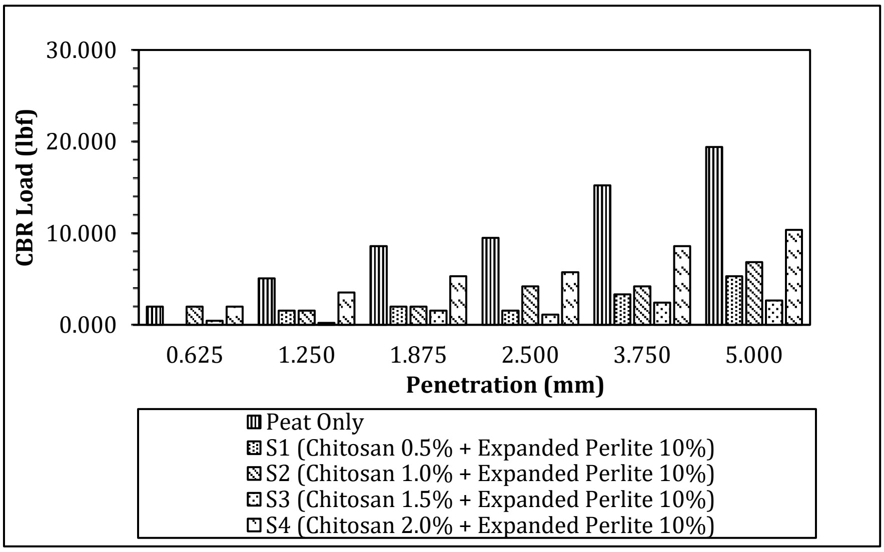

Fig. 9 *CBR load at 28-day curing for top sample*

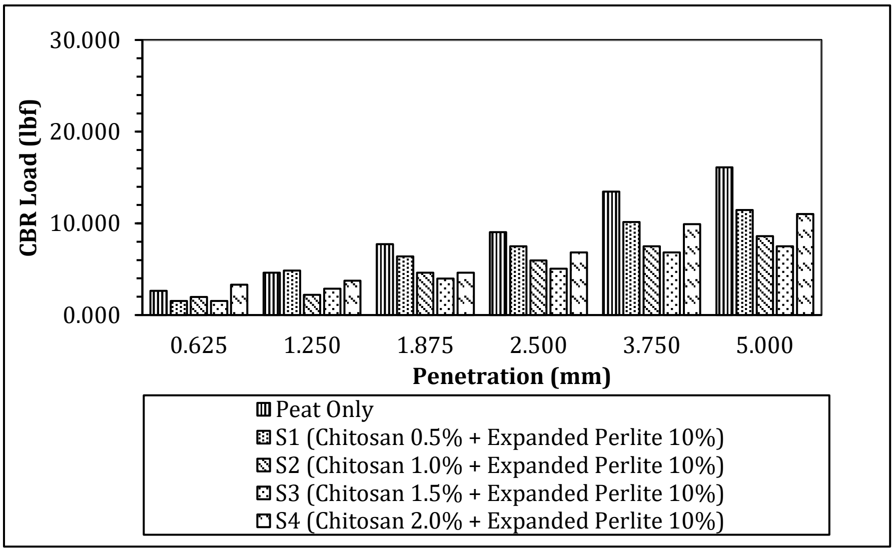

Fig. 10 *CBR load at 28-day curing for bottom sample*

Research findings demonstrated that the CBR value of peat soil is considerably affected by chitosan concentration, curing time, and depth of samples. For the uppermost layer results of 0-day curing date, CBR values recorded a propensity towards decreasing with increasing chitosan content (reduced from 20.95 lbf at 0.5% Chitosan to 5.51 lbf at 2.0%), revealing a lack of bonding without sufficient curing process taking place. However, with a curing period of 7 days, the CBR values increased and showed an effective trend after 1.0% chitosan and optimum behavior at 1.5% chitosan, then decreased again at 2.0%, suggesting an increase in chitosan content to have an effect on soil strength adversely. At the bottom layer, CBR values were fairly larger than the top layer for both curing periods. At 0-day curing, the CBR dropped between 26.24 lbf (0.5%) and a peak of 56.89 lbf (1.0%), then a dramatic decrease at higher chitosan contents was observed. While cured for 7 days, the bottom layer gave a CBR of 46.7 lbf (1.5%) chitosan, demonstrating the curing effect and an optimal dosage.

At 2.0% chitosan, CBR values decreased greatly for both curing regimes, signifying a reduction in particle friction and soil weakening. In general, the findings indicated that as moderate chitosan (1.0%-2.0%) is used in conjunction with 10% expanded perlite and a 7-day curing time, it would confer the most significant increase in strength. The comparison chart in Fig. 10 shows that the bottom performed better due to greater compaction and weight. The compressive strength of peat decreased, however, with the highest chitosan concentration. These observations are in agreement with a previous study, where biopolymers increased the soil strength by bonding particles together upon curing, but weakened the material when applied at their highest doses. The strength development trend is clearer after curing for 14 and 28 days. The CBR load increased with curing time, indicating that extended curing had a positive effect on the stabilized peat soil. After 14 days of curing, at the highest level, peak CBR load reached 26.90 lbf (1.5%), and demonstrated better bonding/interaction between chitosan, expanded perlite, and peat soil particles. At the bottom layer, the CBR load also increased to 30.220 lbf (1.5%) from 19.80 lbf (0.5%) when compared to the only load. The load decreases during other curing periods for an optimal blend of 2.0% chitosan. After 28 days of curing, the CBR loads of top and base layers were also above that of the only sample, which indicates the effect of long curing on strength increase. Shear strength of the top layer has actually increased with time, showing that bonding has developed over time, while the bottom layer had higher loads due to better compaction and confinement. Overall, extended curing enhanced load resistance and allowed stabilized peat soil to outperform untreated peat, despite a slight decrease at greater chitosan levels.

Fig. 11 shows a relationship between CBR load, chitosan, and expanded perlite for peat-only, 0, 7, 14, and 28 curing days for the top layer. Fig. 12 shows a relationship between CBR load, chitosan, and expanded perlite for peat-only, 0, 7, 14, and 28 curing days for the bottom. As a result, based on the CBR load for both the top and bottom layers, we can conclude that the bottom layer has a greater CBR load than the top layer, with the highest CBR load. According to past researchers, chitosan works better in soils with higher density, specifically the bottom layer that reacts strongly and achieves higher CBR values than the top layer [62], [63]. Normally, the top layer should have the highest value since it absorbs the most compaction energy. Still, in this case, the mixture of perlite and chitosan affected the soil structure and lowered compaction uniformity. The CBR at 5.0 mm penetration was also higher than at 2.5 mm, showing that the bottom part of the sample is stiffer or more complex because of particle rearrangement, and the additive material that mixes with peat soil showed behavior during compaction.

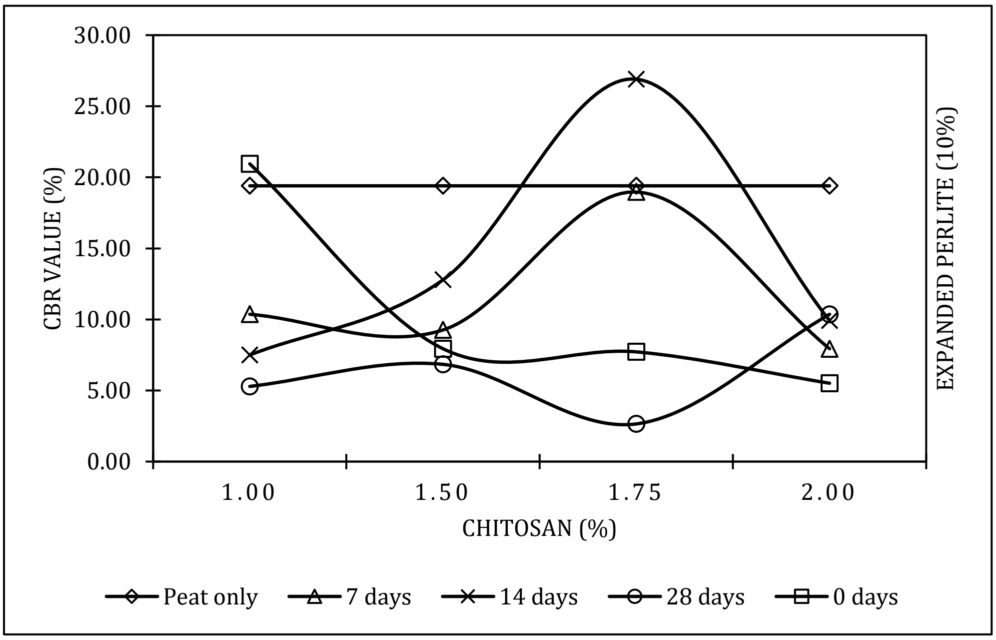

Fig. 11 *Relationship between CBR load (lbf), chitosan (%), and expanded perlite (10%) for peat-only, 0, 7, 14, and 28 curing days (top)*

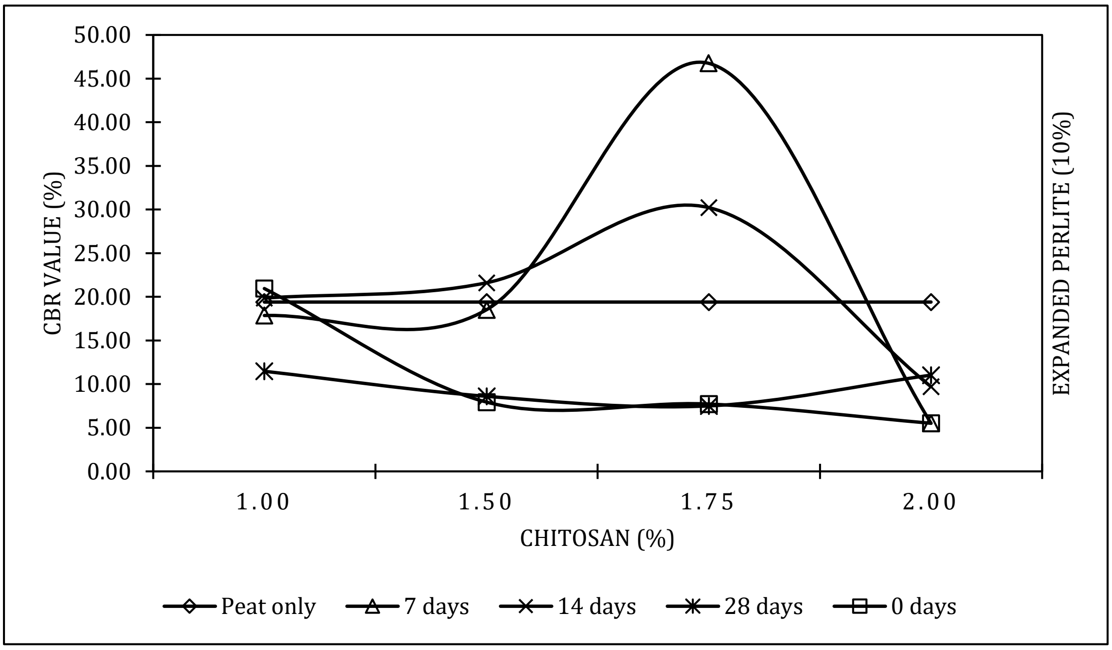

Fig. 12 *Relationship between CBR value (%), chitosan (%), and expanded perlite (10%) for peat-only, 0, 7, 14, and 28 curing days (bottom)*

Based on Fig. 11 and Fig. 12, this indicates that some disruption occurred during sample preparation, specifically during curing days. In addition, the CBR value at 0 and 7 days was higher than at 14 and 28 days. However, 0, 7, and 14 days of curing at the bottom layer are significantly higher than the untreated peat soil. This indicates that mixing the soil with chitosan and expanded perlite effectively increases the strength of the sample despite the slight reduction after curing.

The stabilization of peat soil using chitosan and expanded perlite presents the new outcomes of the synergistic process in the chemical bonding, performance of the microstructural, and also the improvement of the hydraulic conductivity. Chitosan acts as a stabilizing agent to form the chemical and physical materials with organic peat voids and particles. This reaction increases the interparticle cohesion, creating a stronger soil matrix. The interaction between chitosan and the peat soil can improve the microstructure. This presented a good result in a significant increase in cohesion and a reduction in the void ratio, leading to a denser soil fabric. Expanded perlite gives a function as a lightweight filler that fills up the internal voids. This indicates that the load distribution is improved across the peat soil layers, which can directly reduce deformation and settlement under vertical stress. Furthermore, the expanded perlite can incorporation in the drainage characteristics of the peat, especially in accelerating the consolidation process. Meanwhile, the chitosan component ensures the peat soil retains its structural integrity whenever it's under high moisture conditions and saturation [62], [63].

As the results show that the trend in CBR values with increasing chitosan content and curing time is primarily driven by the cationic, adhesive, and hydrophobic properties of chitosan, creating a stable condition and reinforced soil matrix. The chitosan interacts with the surface of the peat soil particles and forms strong electrostatic bonds. Furthermore, it acts as an adhesive, binding soil particles together and increasing the cohesion of the mixture. The chitosan acts as filler, therefore its cover the soil particles and the voids, which creates a denser structure. This was reducing the porosity and significantly enhancing the load-bearing capacity (CBR). Chitosan allowed the acid to dissolve, forming a gel, but curing allows the mixture to dry. As the curing increases, the moisture content decreases because the chitosan gel dehydrates and changes to a brittle, strong, and water-insoluble binding matrix. The strength was continuously increased up to 14 – 28 days. Some higher chitosan content shows strength reduction in some curing periods because it's due to the issues of molecular agglomeration, insufficient matrix adhesive, and hygroscopic nature. In the results, it is clearly shown that the results of 1.5% chitosan show better performance. Therefore, it is suggested that 1.5% chitosan is the percentage that provides the optimum performance mixture.

4. Conclusion

The conclusion of this study shows that this research outcomes present that the peat at Parit Nipah, Johor has an extremely high moisture content (MC = 501%), low specific gravity (Gs = 1.11), very high organic content (OC = 98.64%), moderate fiber content (FC = 21.07%), and a significant level of decomposition (H7), which together contribute to poor compaction properties (MDD = 160 kg/m^3, OMC = 142%) and a very weak untreated bearing capacity (CBR = 16.10 lbf). Chitosan and expanded perlite for stabilizing peat soil show the CBR loads rising to a peak of 56.89 lbf at 0 days and 46.75 lbf at 7 days, reaching optimal enhancement at 14 days of curing. This study demonstrated that 1.5% chitosan and 10% expanded perlite significantly enhance the CBR values. The results indicate that the optimum mixture consists of 1.5% chitosan, which achieved 2 – 3%. Furthermore, a 7-day curing period using CBR was identified as the ideal approach, yielding 1.5% chitosan with higher strength than the peat-only control sample.

Based on research by Putra & Yudhistira [62] and Ibrahim *et al.* [63], the stabilization of CBR performance is observed with higher dosages (4%) and longer curing periods. It is shown that 20% materials treatment increased the unsoaked CBR from 2.86% to 10.47%. It means that this demonstrates a strong particle adhesion and structural strengthening within the soil matrix. At 28 days, a slightly improvement in strength was observed. It is hypothesized that a time-dependent stabilization process, such as moisture adsorption and biopolymer progressive degradation, is at play. The lower layer, however, presented a higher increase in strength, indicating that compaction and curing influenced load resistance. However, as in the case of Sample 4 (S4), an increasing number of additives did not provide a further improvement in strength and thus indicates that an optimal stabilizer amount is necessary. Thus, the findings indicate chitosan–expanded perlite can be a potential and sustainable stabilizer that enhances the load-carrying capacity of peat soil to serve as an appropriate material for subgrade and foundation treatments, while also considering eco-effectiveness in comparison to commonly used dust-based soft soil construction materials. Therefore, it can apply to the subgrade and embankment stabilization, pavement, geotechnical and environmental applications, which, in areas with deep, compressible peat, the mixture can be used for soil exchange or filling. The blend of expanded perlite significantly reduces the overall density, decreasing the load on the foundation and limiting settlement.

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Conflict of Interest

The authors declare no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm their contribution as follows: ***study conception and design****: Zeety Md Yusof;* ***literature review and data compilation****: Zeety Md Yusof, Nurul Aida Asri, Mohamad Afiq Let;* ***critical evaluation and interpretation of findings****: Zeety Md Yusof, Nurul Aida Asri;* ***manuscript writing (original draft and technical editing)****: Zeety Md Yusof, Leow Chee Sin, Paulus Pramono Rahardjo, Mohamad Afiq Let. All authors read and approved the final manuscript.*

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