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Sustainable Stabilization of Peat Soil Using Hydrated and Expanded Perlite

Zeety Md Yusof[1,2], Mohamad Afiq Let[1*], Putera Agung Maha Agung[3], Leow Chee Sin[4]

[1] *Faculty of Civil Engineering and Built Environment,*
Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Batu Pahat, Johor Darul Ta'zim, MALAYSIA
[2] *Research Centre for Soft Soil (RECESS), Institute for Integrated Engineering (IIE),*
Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Batu Pahat, Johor Darul Ta'zim, MALAYSIA
[3] *State Polytechnic of Jakarta, Department of Civil Engineering,*
Kampus Baru UI Depok 16425 West Java, INDONESIA
[4] *Foundation and Geotechnical Specialist, Design Department,*
Geohan Sdn. Bhd., 60000, Kuala Lumpur, MALAYSIA

*Corresponding Author: gf240037@student.uthm.edu.my

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Abstract

Peat soil, due to its weak engineering properties, poses significant challenges in geotechnical applications. This review critically examines the potential of using sustainable stabilizers, specifically hydrated lime (HL) and expanded perlite (EP), for peat soil stabilization. Studies published in 2020 - 2025, along with selected earlier works, were analyzed to evaluate the effectiveness and performance in enhancing peat soil properties, particularly through Unconfined Compressive Strength (UCS) tests. Impressive UCS improvements were reported, such as a 13,553.2% increase with quarry dust (QD) and ordinary Portland cement (OPC). However, not all studies included microstructural analysis; those that did utilized Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray (EDX) to observe bond formation and structural changes in stabilized peat. The review concludes that HL and EP show promise as sustainable alternatives for stabilizing peat, though challenges remain regarding their long-term performance and the potential benefits of combining both stabilizers. Further research is needed to optimize their dosage, durability, and environmental impact under field conditions.

1. Introduction

This review adopts a narrative synthesis approach to critically evaluate recent advancements in peat soil stabilization techniques. The literature search focused on the studies published between 2020 and 2025. Earlier works prior to this range were only incorporated when relevant to provide a comprehensive overview. Key terms, including "peat," "sustainable soil stabilization," "hydrated lime," and "expanded perlite," were used to identify studies that align with the scope of interest. The search was conducted using major academic databases such as Scopus, ScienceDirect, MDPI and IOP. The inclusion criteria were based on soil type, stabilizer dosage, curing, and testing methodologies employed. Only peer-reviewed publications were considered to ensure the reliability and academic rigor. While no formal quality appraisal was conducted, significant emphasis was placed on the experimental robustness, methodological transparency, and the practical relevance of the findings in real-world applications of peat soil stabilization. This review aims to determine whether hydrated lime (HL) and expanded perlite (EP) can serve as effective and sustainable alternatives for stabilizing peat soil.

2. Background of Peat Soil

Peat is primarily formed in wetlands where plant material accumulates in a waterlogged environment with low oxygen. This anaerobic degradation causes partial decomposition of plant organs like roots, branches, trunks, and leaves. Water stagnation reduces microbial activity, allowing the organic material to accumulate and convert into peat. As this plant material decomposes, it creates humic compounds, which serve as native binders. These humic materials affect the compacting of accumulated organic matter, forming thick peat layers typical of peatlands [1]. The distinctive properties of peat are its high fiber content, which includes partially fossilized plant fibers such as stems, leaves, and roots. The degree of prevalence and its state of preservation are also very important for the classification of peat. Huat et al. [2] stated that peat is generally divided into fibric peat (>66% fiber, least decomposed), hemic peat (33 – 66% fiber, moderately decomposed), and sapric peat (<33% fiber, highly decomposed). This classification reflects the degree of preservation of plant material and directly affects peat's engineering properties. Fiber content also influences water-holding capacity and mechanical strength. Peat with higher fiber content generally keeps its structure better and is less prone to compaction. Meanwhile, peat with lower fiber content has a low Unconfined Compressive Strength (UCS), often below 50 kPa, which does not make it suitable for a load-bearing application [3]. Additionally, peat's organic content, which generally exceeds 75%, contributes to its compressibility and low bulk density. These combined properties, along with low inorganic content, show why peat is considered one of the weakest soils in engineering practice [1],[4].

As shown in Fig. 1, the physical structure of peat is heterogeneous, consisting primarily of organic bodies and pores. The organic bodies are solid parts derived from decomposing plants, while the pores may be filled with water or air, depending on the saturation level. This compound structure significantly influences the geotechnical behavior of peat, such as low CBR values and its tendency for high settlements under loading conditions, often observed in consolidation and compressibility tests [5],[6].

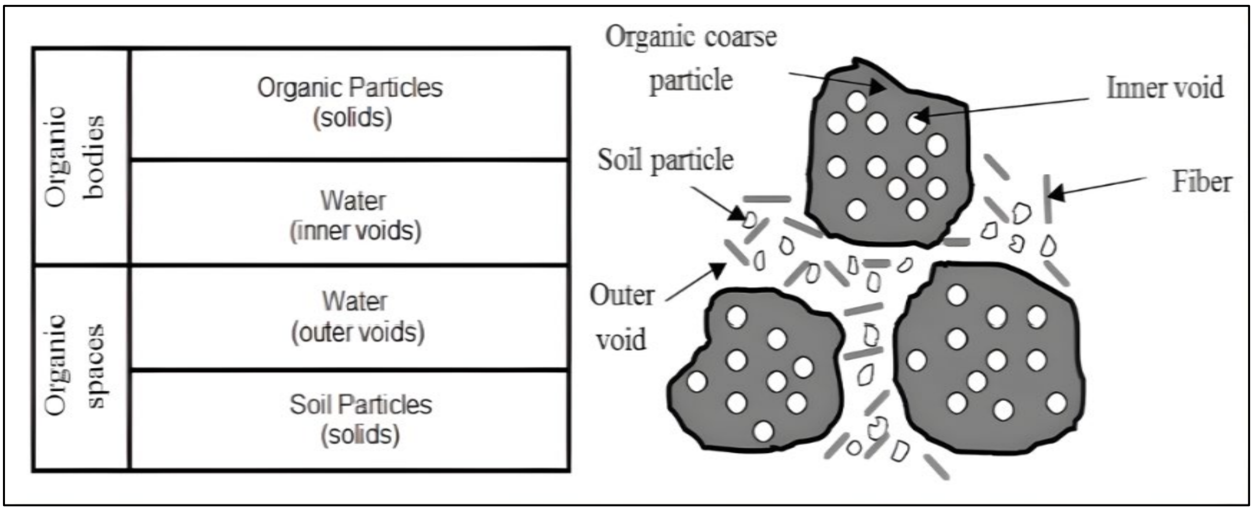

Fig. 1 *Idealized structure of the soil peat [5], [6]*

2.1 Peat Soil Distribution

Peat soil is found in different types of environments with varying geographical characteristics and occupies nearly all types of environments on the Earth, except for arid deserts and extremely cold Arctic regions. World peatlands are estimated to cover approximately 1 billion acres in total, or about 4.5% of the world's land surface [7]. Peat is primarily located in areas with high rainfall and poor drainage, both of which are conditions that favor peat accumulation [8]. Malaysia, located in Southeast Asia, ranks as the ninth largest country globally in terms of peatland coverage, according to a global peatland area report [9]. In Malaysia, peatlands are not only ecologically significant, but they also have economic importance. The reason is that more than 60% of the peatlands have been converted to agricultural land, particularly for the oil palm industry. The distribution of peat soils throughout the country is uneven, with Sarawak having the largest area, followed by Sabah and Johor.

Globally, recent mapping efforts such as PEATMAP have refined earlier estimates of peatland distribution, identifying a total global peatland area of approximately 4.23 million km^2 (2.84% of Earth's land area). A revision that highlights previous underestimations in tropical regions, including Southeast Asia [10], suggests that Asia accounts for nearly 38.4% of the world's total peatland area. Specifically, Malaysia's peatlands occupy approximately 22,400 km^2, representing around 83.9% of earlier national estimates [10]. In the regional context, Southeast Asia contains about 24 million hectares of peatlands or 40% of the world's tropical peatlands, with Malaysia contributing about 2.6 million hectares [11],[12]. These tropical peatlands, predominantly ombrogenous in nature, are mostly found in coastal lowlands where high rainfall and poor drainage promote peat formation. Smaller inland deposits occur in Tasek Bera and Cameron Highlands in Pahang [12].

However, due to extensive land conversion, especially for oil palm and acacia plantations, Malaysia and its neighboring countries have lost a significant portion of their original peat swamp forests. In fact, regional studies show that over half of Southeast Asia's peatlands have been degraded or converted since 1990 [13]**.** This widespread transformation has major implications for carbon storage, hydrology, and land stability, emphasizing the importance of effective peatland conservation and soil stabilization measures. This extensive presence of peat across Malaysia highlights both the potential and the challenges associated with its use in land development, making effective soil stabilization strategies critically important [8].

Fig. 2 shows the national distribution of peatland in Malaysia, with Table 1 providing a more detailed breakdown of peatland areas according to the individual states. Based on the tabulated information, no data is recorded for Kedah, Perlis, Pulau Pinang, Melaka, Kuala Lumpur, and Labuan. In total, Malaysia's peatland area spans approximately 2,559,341 hectares, underscoring the need for localized management strategies tailored to the specific distribution and utilization of peat soils [12],[10].

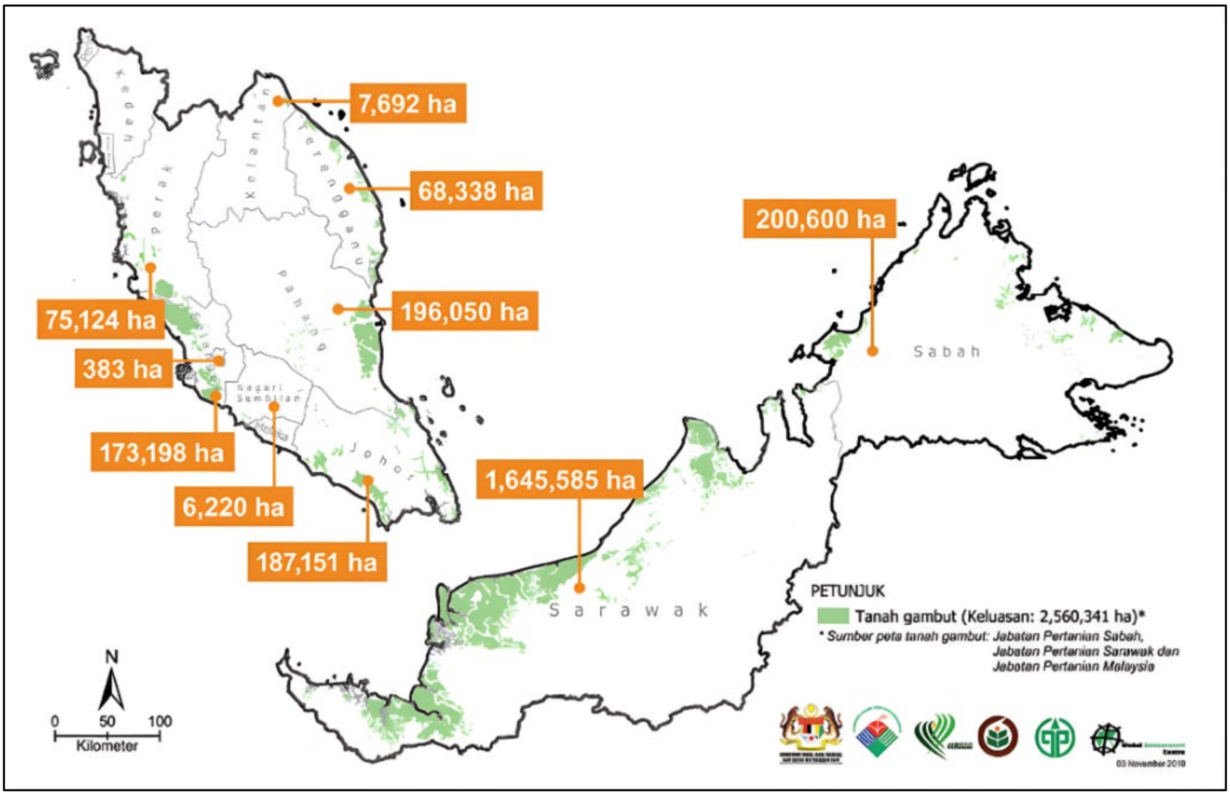

Fig. 2 *Distribution of peat soil in Malaysia [8]*

Table 1 *Estimated peatland area by state for Malaysia (refer to fig. 2)*

No.	State	Peatland area (ha)
1	Sarawak	1,645,585
2	Sabah	200,600
3	Pahang	196,050
4	Johor	187,151
5	Selangor	173,198
6	Perak	75,124
7	Terengganu	68,338
8	Kelantan	7,692
9	Negeri Sembilan	5,220
5	Wilayah Persekutuan Putrajaya	383
11	Kedah	N/A
12	Perlis	N/A
13	Pulau Pinang	N/A
14	Melaka	N/A
15	Wilayah Persekutuan Kuala Lumpur	N/A
16	Wilayah Persekutuan Labuan	N/A
	Total	2,559,341

2.2 Peat Soil as a Challenging Soil and Stabilization Requirement

Geotechnical engineers face significant challenges when building infrastructures on soft ground areas [14]. To mitigate the issues, many engineers have traditionally tried to avoid such sites. However, with rapid development, the utilization of soft ground is now unavoidable. Peat soil is classified as a challenging soil due to its weak engineering properties, including low shear strength, low bearing capacity, and high moisture content, which render it unsuitable for supporting structural loads. Peat exhibits an exceptionally high moisture content, typically ranging from 500 to 2,000%, coupled with high permeability and considerable water retention capacity [15].

These characteristics contribute to excessive compressibility and substantial long-term settlement, making it highly unsuitable as a foundation material. Additionally, the high water content complicates drainage and leads to unpredictable soil movements. Studies by Pakir et al. [16] and Huat et al. [17] have shown that peat soil typically has a low pH, ranging between 3 and 4.15, which is harmful to both construction materials and plant growth. Such soil creates an acidic environment that accelerates the corrosion of foundations and infrastructure.

According to L. Pei et al. [18], peat also has low bearing gravity due to its high organic content, resulting in less dense soil material and reduced load-bearing capacity. Furthermore, the significant variation in peat behavior, driven by its fiber content and degree of decomposition or humification, makes it difficult to predict its engineering properties. High fiber content often leads to excessive water retention, complicating standard engineering tests. Recent studies by Sutarno & Mohamad [19] quantified the common engineering characteristics of untreated peat soil, reporting very low shear strength (5–20 kPa), high compressibility (0.9–1.5), and moisture content exceeding 100%. In particular, the organic content reached 96%, with a pH of about 2.3 and specific gravity near 1.47, confirming the weak, acidic, and highly compressible nature of Malaysian peat. Such properties justify the critical need for stabilization prior to construction applications.

Based on these findings, peat is now classified as a challenging issue. Hence, specialized strategies are essential to resolve the problems of uneven settlement and enhance the soil's stability. According to Correia et al. [20], soil stabilization is necessary when traditional methods like preloading or geogrid reinforcement are unfeasible. Md Zahri & Zainorabidin [21] emphasized that peat soil stabilization is crucial due to its low undrained shear strength, high compressibility, and susceptibility to shrinkage when drying occurs. Effective stabilization methods are required to improve peat soil's performance for safe and stable infrastructure development.

3. Soil Stabilization Methods

Various techniques have been developed and practiced for soil improvement and stabilization, including simple methods such as soil cutting and filling, and drainage. Further advanced techniques include adding other types of materials, chemically stabilizing it, and using mechanical, hydraulic, electrical, or thermal methods [20],[21],[22]. These stabilization strategies are generally classified into physical and chemical approaches. Physical stabilization modifies the physical properties of the soil and comprises electric and thermal processes, such as electrokinetic stabilization, vitrification, and heating, that induce marked physical transformations. These methods also include mechanical and hydraulic techniques, such as pattern confining, soil nailing, embankment piling, stone columning, preloading, staged construction, displacement, and replacement, which aim to enhance soil stability through compaction, dewatering, and reinforcement. For instance, stone column installation has been widely applied to improve the bearing capacity and reduce settlement of soft soil, where parameters such as column spacing, diameter, and material properties significantly influence performance [23].

Chemical stabilization, in contrast, refers to the mixing of soil with regulatory agents that react with the soil, including cement, lime, bituminous materials, resins, blast furnace slag, fly ash, and similar materials. These reactive agents stimulate reactions in the deep, medium, or shallow layers of the soil, resulting in enhanced strength, stability, and performance. For example, Taib et al. [24] demonstrated that the chemical stabilization of amorphous peat using cement and fly ash at different water additive ratios improved compressive strength and reduced water sensitivity, highlighting the effectiveness of chemical binders in improving highly organic soils. Similarly, the application of biochar and other industrial byproducts has gained attention in recent years. According to Hov et al. [25], the combination of biochar with cement yielded up to an 80% increase in UCS of peat samples, whereas industrial byproducts showed limited chemical compatibility with organic soils. Fig. 3 systematically categorizes various soil stabilization methods.

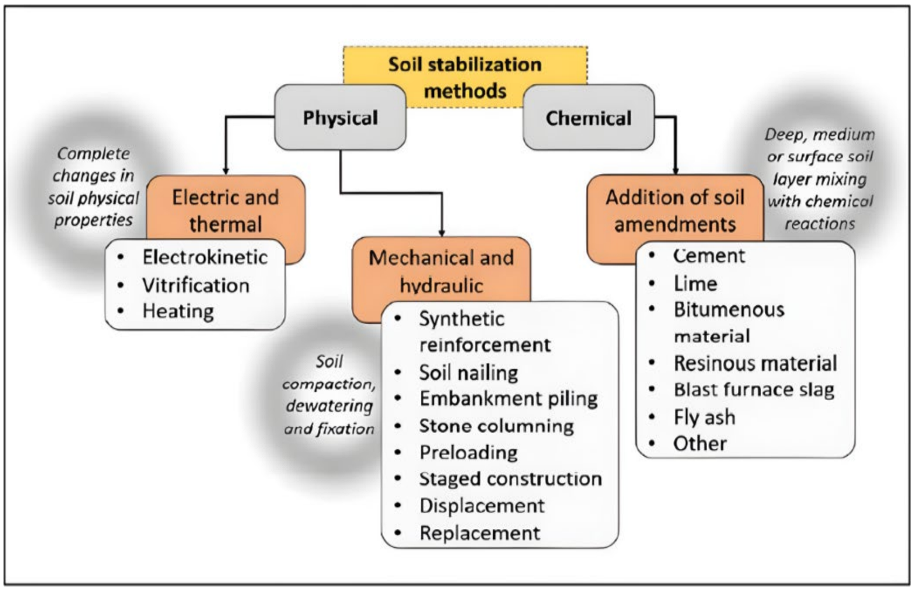

Fig. 3 *Categorization of soil stabilization methods: physical and chemical approaches [26]*

3.1 Sustainable Peat Soil Stabilizations

In recent studies, the use of new and environmentally friendly materials to solve some issues related to peat soil has been investigated. These approaches are slowly being considered as sustainable alternatives to traditional or conventional stabilizers. This section reviews some of the studies conducted on different stabilizers applied for the sustainable stabilization of peat. Among the most popular are natural biopolymers like xanthan gum, synthetics like GeoPolySoilS, and agro–industrial byproducts like rice husk ash (RHA), sugarcane bagasse ash (SCBA), and coir fiber ash (CFA). Silica fume (SF), eggshell powder (ESP), demolished crushed waste (DCW), scrapped tire waste (STW), quarry dust (QD), and electrokinetic stabilization (EKS) are also studied for their suitability in peat soil stabilization. These are intended not only to enhance the strength of soil but to be environmentally friendly as well.

This study aims to investigate regionally suitable alternative stabilizers using locally available waste materials. It also seeks to address the lack of microstructural studies and long-term performance data for relevant stabilizers. To date, the performance of peat stabilizers has been investigated in several geotechnical tests, primarily UCS, with some works revealing impressive results regarding the soil strength, such as an increase in UCS up to 13,580% when using SF & OPC. Although only some studies include microstructural analysis, those that do utilize techniques such as Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray (EDX) to gain valuable insight into the formation of bonds and the overall structure of the stabilized peat soil. These analyses have proven to be essential in understanding the mechanisms behind the stabilization process and the durability of the treated peat soil over time.

Table 2 presents details of the analysis of environmental impact and the method/testing applied for each study. Table 3 compares the improvements in soil properties for each stabilizer along with the geotechnical performance data. The microstructural analysis of the peat soil into which the stabilizers work, presented in Table 4, describes the changes in the structure of the peat soil by the chemical adsorption at the molecular level. This information is critical in evaluating the function of each stabilizer on the internal structure of peat soil and on the long-term performance. In addition, Fig. 4 demonstrates a comparison between the UCS increase for the stabilized peat soil to substantiate the reinforcing potential of each stabilizer over the peat soil strength.

Table 2 *Environmental impact and methodology of peat soil stabilization using various stabilizers*

Year	Author	Stabilizer	Environmental Impact	Methodology
2025	H. Sulaiman [27]	Xanthan Gum	Very low (biopolymer)	Xanthan gum mixed in peat at 2%, 4% concentrations, tested for moisture content and compaction
2024	I. Bagus et al. [28]	GeoPolySoilS	Low (biopolymer, eco-friendly)	GeoPolySoilS mixed with peat, tested for UCS and CBR
2023	M. Abu Talib et al. [29]	RHA	Moderate (eco-friendly)	RHA mixed with peat and cement, tested for UCS and SEM-EDX
2023	N. Jumien et al. [30]	QD & OPC	High (Cement-related)	QD mixed with cement for stabilization of peat, tested for UCS
2023	A. Rashid et al. [31]	CFA + OPC	Moderate (Cement use)	CFA mixed with cement, tested for compaction and UCS
2021	A. Ahmad et al. [32]	SF + OPC	High (Cement-related)	SF mixed with cement and peat, tested for UCS and CBR
2021	H. Nor et al. [33]	SCBA	Moderate (agricultural waste)	SCBA mixed with cement, tested for UCS and SEM-EDX
2021	A. Ahmad [34]	DCW + STW	Low (recycling material)	Concrete waste and tires mixed into peat, tested for strength improvement
2020	A. Mahmood et al. [35]	ESP	Low (natural byproduct)	ESP mixed with peat in varying ratios, tested for CBR and UCS
2020	A. Wahab et al. [36]	EKS	Low (energy-efficient)	Electrodes applied with a voltage gradient to peat, tested for shear strength

Table 3 *Comparison of soil property enhancements with different stabilizers*

Year	Author	Stabilizer	Peat Properties Before Stabilization	Peat Properties After Stabilization	Curing time for optimal performance	Increment/ Improvement
2025	H. Sulaiman [27]	Xanthan Gum	High Moisture content = 135.42%	39.5% moisture content	N/A	95.92% moisture reduced
2024	I. Bagus et al. [28]	GeoPolySoilS	UCS = 13 kPa	161 kPa at 14% GeopolySoils (uncured) 95.62 kPa at 20% GeoPolysoilS.	28 days	635.5%
2023	M. Abu Talib et al. [29]	RHA	UCS Not specified (assume 5-20 kPa)	262 kN/m^2 at 5% RHA	28 days	Up to 13,580%
2023	N. Jumien et al. [30]	QD & OPC	UCS = 47 kPa	684 kN/m^2 at 5% QD	28 days	13,553.2%
2023	A. Rashid et al. [31]	CFA & OPC	UCS = 55 kPa	200 kPa at 20% OPC replacement	28 days	263.6%
2021	A. Ahmad et al. [32]	SF & OPC	UCS = 42.94 kPa	1063.94 kPa at 20% SF	28 days	2377.7%
2021	H. Nor et al. [33]	SCBA	UCS = 16 kPa	278 kPa at 5% SCBA	28 days	1337.5%

Year	Author	Stabilizer	Peat Properties Before Stabilization	Peat Properties After Stabilization	Curing time for optimal performance	Increment/ Improvement
2021	A. Ahmad [34]	DCW & STW	UCS = Not specified (assume 5-20 kPa)	774 kPa 15% cement and 10% STW.	N/A	Up to 15,380%
2020	A. Mahmood et al. [35]	ESP	Low CBR value (around 0.782%)	28 - 38 times at 20% ESP mix.	28 days	28 - 38 times
2020	A. Wahab et al. [36]	EKS	UCS = 10.7 kPa	64 kPa applied voltage 110 V with applied load of 50 kg	3 hours (operational period)	498.1%

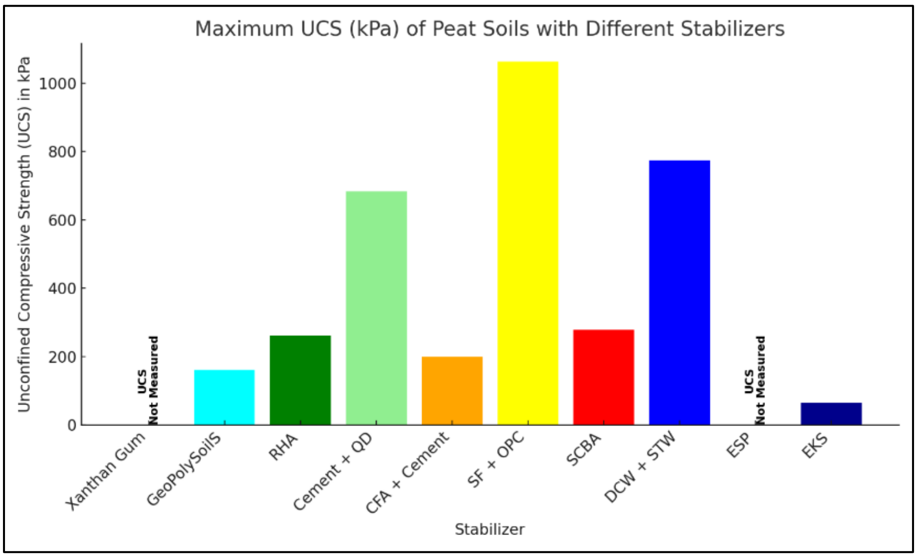

Fig 4. *Comparison of the Highest UCS Values Obtained After 28 Days of Curing for Stabilized Peat Soil*

Table 4 *Microstructural analysis of peat soil stabilized with different stabilizers*

Year	Author	Stabilizer	Microstructural Analysis (SEM/EDX)
2025	H. Sulaiman [27]	Xanthan Gum	N/A
2024	I. Bagus et al. [28]	GeoPolySoilS	N/A
2023	M. Abu Talib et al. [29]	RHA	SEM and EDX confirmed the presence of calcium, showing significant improvements in soil strength
2023	N. Jumien et al. [30]	QD & OPC	SEM and EDX tests to assess strength gain mechanisms, confirming an increase in calcium and a decrease in carbon
2023	A. Rashid et al. [31]	CFA & OPC	SEM and EDX were used to analyze the microstructure, showing a densification of the soil structure, with reduced porosity and an increase in calcium content.
2021	A. Ahmad et al. [32]	SF & OPC	SEM was used to observe the microstructural changes, showing reduced porosity and increased calcium content, enhancing strength
2021	H. Nor et al. [33]	SCBA	SEM analysis showed improvements in microstructure with SCBA, filling voids, and increasing strength
2021	A. Ahmad [34]	DCW & STW	N/A

Year	Author	Stabilizer	Microstructural Analysis (SEM/EDX)
2020	A. Mahmood et al. [35]	ESP	N/A
2020	A. Wahab et al. [36]	EKS	N/A

4. Hydrated Lime (HL) Properties

Table 5 summarizes the physical and chemical properties of HL, as reported in previous studies, which collectively illustrate its influence on material performance and reactivity. Abdul-Hussain [37] and Abdalla Sahih [38] emphasized that physical parameters, such as fineness, hydration time, temperature, surface area, specific gravity, and particle size distribution, are critical indicators of HL quality. Finer lime particles with greater specific surface area generally exhibit higher reactivity, while hydration time and temperature govern the rate and completeness of slaking, all of which affect the consistency and stability of the hydrated product. These parameters ultimately determine the uniformity, workability and suitability of HL for geotechnical and construction applications [37],[38].

Chemically, HL typically contains a major proportion of calcium oxide (CaO) along with magnesium oxide (MgO), silicon dioxide (SiO_2), and minor oxides such as aluminum oxide (Al_2O_3) and iron oxide (Fe_2O_3). A higher CaO content contributes to long-term stability and reduced volumetric expansion. The relative proportions of SiO_2 and other minor oxides influence the potential for secondary phase formation, such as calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H), which enhance bonding in stabilized soils [39]. Therefore, both physical and chemical characteristics of HL play a decisive role in determining its reactivity, consistency, and overall performance in soil stabilization.

Table 5 *Physical and chemical properties of HL*

Category	Property	Findings	
		Abdul-Hussain [37]	Abdalla & Salih [38]
Physical Properties	Fineness remaining on sieve 90 micron	4%	N/A
	Percent Passing Sieve No. 200	N/A	98%
	Specific Gravity	N/A	2.78
	Surface Area	N/A	398 m^2/kg
	Temperature of Hydration	75°C	N/A
	Time of Hydration	11 minutes	N/A
Chemical Properties	Al_2O_3 (Aluminum Oxide)	4	0.72
	CaO (Calcium Oxide)	N/A	56.1
	Fe_2O_3 (Iron (III) Oxide)	4	0.12
	MgO (Magnesium Oxide)	0.8	0.13
	SiO_2 (Silicon Dioxide)	4	1.38
	SO_3 (Sulfur Trioxide)	N/A	1.38
	LOI (Loss on Ignition)	N/A	40.6
	CaO + MgO	87.99	N/A
	IR (Insoluble Residue)	0.81	N/A
	CO_2 (Carbon Dioxide)	1.89	N/A

4.1 Hydrated Lime (HL) as Traditional Soil Stabilizer and Understanding the Pozzolanic Reaction

HL has been widely used as a traditional soil stabilizer since the early 1920s, primarily due to its ability to modify the physical and mechanical properties of problematic soils [26],[40]. Produced by the hydration of quicklime, HL can be easily mixed with soil to initiate a series of reactions with the native siliceous and aluminious minerals. These interactions lead to a structural rearrangement and enhanced mechanical properties of the treated soil.

The fundamental mechanism governing this improvement is the pozzolanic reaction, whereby calcium ions (Ca^{2+}) released from HL react with reactive silica (SiO_2) and alumina (Al_2O_3) present in the soil to form calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H) compounds. These cementitious gels act as binding agents that fill pore spaces and bond soil particles together [26],[41]. The rate and efficiency of these reactions are influenced by lime fineness, specific calcium content, and the kinetics of gel formation [37],[42].

Subsequent studies have shown that these reactions contribute to significant improvements in compressive strength, stiffness, and durability while reducing soil plasticity, compressibility, and swelling potential [38],[43],[44],[39]. Overall, the literature underscores HL's long-standing effectiveness as a sustainable and technically reliable material for the stabilization of soft and organic soils, including peat.

4.2 Effectiveness of Hydrated Lime (HL) in Peat Soil Stabilization

Studies consistently show that HL improves the engineering properties of peat soil. However, the extent of improvement is strongly influenced by dosage, curing duration, and material properties. Previously, Yusof et al. [45] conducted a comprehensive investigation of various HL-pond ash (PA) mixtures and curing durations up to 150 days, reporting that certain combinations, such as 12% HL with 20% PA, produced substantial strength gains under extended soaking, whereas other mixtures exhibited diminishing returns beyond specific dosage and curing thresholds. This study also included microstructural analysis, confirming that the effectiveness of HL is highly context-dependent, influenced by dosage, binder combination, and soaking duration. Consistent with these findings, Yusof et al. [46] later demonstrated that a mixture of 9% HL with 10% PA achieved the highest maximum dry density (MDD), indicating an optimum lime threshold beyond which additional HL yields limited improvements.

Abdul-Hussain [37] further emphasized the importance of lime fineness and hydration conditions, noting that finer particles and elevated hydration temperatures accelerate pozzolanic reactions and promote early strength development. Similarly, Nikoorkar et al. [47] showed that the UCS of peat increases with higher HL dosage and lower curing periods, with significant gains observed even after 90 days. These observations highlight that curing duration plays a decisive role as lime-stabilized soils continue to gain strength over extended periods, sometimes for 2 to 3 months or longer [46],[47]. Overall, while HL provides long-term enhancement of peat soil properties, its efficiency remains strongly context-sensitive, depending on particle properties, curing conditions, and potential synergies with supplementary binders.

Recent advances in soil stabilization emphasize the effectiveness of hybrid binders that integrate HL with materials such as POFA, fly ash, or lightweight fillers like EP. These blends address multiple challenges associated with peat, including excessive moisture, low density, and chemical incompatibility. By combining alkali activation with pozzolanic reactivity, hybrid systems generate denser microstructures and accelerate strength development, while reducing lime demand and improving sustainability. Laboratory findings also demonstrate that incorporating supplementary materials can enhance workability, reduce settlement, and increase resistance to acidic and saturated field conditions [48].

5. Expanded Perlite (EP) Properties

Table 6 presents the main physical properties of EP to demonstrate its suitability for use as a soil stabilizing agent. EP has a very low weight compared to common stabilizing additives, attributed to its lightweight and highly porous network structure [49]. This structure enhances soil aeration, reduces bulk density, and improves water retention, which is particularly beneficial for problematic soils such as peat. The high porosity and water absorption capacity further contribute to moisture retention and improved consistency of stabilized soils [50].

In addition to its lightweight characteristics, EP exhibits excellent thermal performance and stability. Its low thermal conductivity and controlled thermal expansion ensure strong resistance to temperature variations [49]. The material is also non-combustible and heat-resistant, providing reliable fireproof properties for engineering applications [51]. Furthermore, EP demonstrates good sound-absorption performance, providing additional acoustic benefits in construction and insulation. Overall, with its combination of low density, high porosity, superior thermal performance, and fire resistance, EP represents a sustainable and effective material for soil conditioning and stabilization works [49].

Table 6 *Physical properties of EP* [49]

Property	Finding
Colour	White
Specific Gravity	55 - 300
Apparent density	30 - 250
Melting Point	1300
Thermal conductivity	0.04
Thermal expansion	$4\times10^{-6} \sim 11\times10^{-6}$
Fire Resistance	Fireproof
Sound absorption	0.6

EP is primarily composed of silica (SiO_2) and alumina (Al_2O_3), with lower proportions of alkali and alkaline earth oxides such as K_2O, Na_2O, CaO, and Fe_2O_3, and slight contents of MgO and TiO_2 [52]. Recent compositional assessments confirm that SiO_2 and Al_2O_3 are the dominant constituents, while oxides such as Na_2O, K_2O, CaO, Fe_2O_3, and MgO occur in smaller but significant amounts [53]. Additionally, variability in these oxide proportions has been shown to influence expansion efficiency, thermal performance, and suitability for end-use applications, particularly when the material is sourced from deposits of different geological origins [54].

As highlighted by Chatterjee [55], loss on ignition (LOI) is another critical characteristic of EP, as it reflects both the quantity of water retained within its structure and the extent of expansion and dimensional change during heating. This property is essential in applications such as soil amendment, lightweight fillers, and insulation. The thermal performance of EP is also affected by trace oxides such as SO_3 and CO_2, underscoring the importance of understanding its full chemical profile.

Since perlite is a naturally occurring volcanic glass, its oxide composition varies depending on its geographic source. Table 7 presents representative compositions from regions such as Morocco, China, and Turkey, along with ranges reported in recent material characterization studies. Recognizing these compositional variations is crucial, as even slight differences in oxide content can significantly influence the engineering performance of EP in stabilization and construction applications.

Table 7 *Typical range of chemical compositions of perlite and EP*

Oxide	Perlite	EP		
	[55]	[55]	[53]	[54]
SiO_2	68-76.5 %	74-77	70-75	65-80
Al_2O_3	10-15 %	12-15	12-15	7.5-18
Na_2O	2.8-4.5 %	5.0-8.0	3-4	2-5
K_2O	3.2-5.7 %	N/A	3-5	1.4-5.5
Fe_2O_3	0.5-2.5 %	1.1-1.6	0.5-2	0.5-3.66
CaO	0.5-2.0 %	1.3-1.7	0.5-1.5	0.5-3.66
MgO	0.1-1.5 %	0.1-0.7	0.2-0.7	0.1-1.5
LOI/Bound Water/H_2O	2.9-5 %	N/A	2-6	3-5

5.1 Effectiveness of Expanded Perlite (EP) in Soil and Concrete Stabilization

EP, as a soil and concrete stabilizer, is a versatile material; its stabilization performance depends on the amount used. EP can stabilize collapsible soil by enhancing stronger particle interlocking, increasing the number of ions bound to particle surfaces, and reducing particle dispersion. Khodabandeh et al. [56] proved that EP dosage levels, ranging from 2 - 8%, significantly improved the soil strength and decreased with usage levels surpassing 6 – 8%. The granular nature of EP allows for interparticulate bonding and results in high shear strength and material stability, particularly beneficial in access-limited construction areas with difficult-to-compact conditions, such as underground utility areas [57]. By measuring zeta potential, it was found that particle repulsion can be enhanced with increasing EP content, resulting in a more stable and uniform soil structure [58]. Field simulations under varying moisture conditions to simulate in situ conditions also confirm EP's performance as a stabilizing agent in soil [59],[60].

In addition, Shahadha et al. [61] reported that the exceptionally high porosity of EP (≈ 88%), consisting of ~28 % water porosity and ~60 % air capacity, allows it to retain moisture while maintaining aeration balance [62]. This property not only improves soil water-holding capacity but also reduces bulk density and enhances cation

(Ca^{2+}, Na^{+}) exchange, promoting better aggregation and structural stability [63]. Such characteristics are advantageous for peat or other highly compressible soils, as they sustain adequate moisture during curing and support chemical interaction with calcium-based stabilizers such as HL.

In conclusion, EP is inert and acts as an internal curing agent, improving hydration and compressive strength. Liu et al. [64] reported a 13% increase in 90-day compressive strength with the addition of 30% EP. The high porosity of EP makes it possible for continual hydration, which is a requirement to obtain the early strength. SEM analysis shows that EP can promote the formation of C–S–H and AFt, which, in turn, fill microcracks and improve the ITZ, resulting in a more stable microstructure. EP, in both soil and concrete, enhances material properties; however, the mechanisms that impact them differ: in soil, flow is reduced and particle interlocking is improved, whereas in concrete, it accelerates hydration and crack healing.

6. Conclusion

This paper highlights that Hydrated lime (HL) and expanded perlite (EP) are potential sustainable stabilizers for peat soil. HL improves strength and moisture resistance through pozzolanic reactions, while EP enhances microstructure, internal curing, and soil workability. Studies reviewed in this paper reported significant mechanical improvement, with the unconfined compressive strength (UCS) increasing by 13,553.2% for quarry dust (QD) and ordinary portland cement (OPC) and 2,377.7% for silica fume (SF) and OPC, indicating the strong potential of alternative stabilizers. Although comparable quantitative data for HL and (EP) are limited, their combined use is expected to yield similar or greater improvements due to synergetic hydration and microstructural effects. However, challenges still exist, including the possibility that peat diversity (fiber/ash content) may affect results, that lime carbonation can reduce effectiveness in acidic conditions, and that EP may segregate during compaction. The effects of leachate and pH also need to be tracked for environmental concerns. Until today, it remains unclear whether combinations of HL-EP can effectively stabilize peat soil, leaving a significant research gap. Future studies should focus on optimizing HL-EP dosage, long-term durability under tropical field conditions, and life-cycle sustainability assessments.

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Conflict of Interest

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

Author Contribution

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

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