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The properties and behaviours of unsaturated peat soil in Malaysia: A review

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Abstract: A detailed assessment of the properties and behaviour of unsaturated peat soils in Malaysia is presented, with a focus on their noteworthy attributes, including organic matter content of more than 75%, high moisture levels, low structural integrity, and high compressibility, ultimately resulting in substantial construction difficulties. The review assesses key characteristics of Malaysian peat soils, such as shear strength, unconfined compressive strength, specific gravity, moisture content, and compressibility, from the index properties perspective. The characteristics of Malaysia's peat soils are comparable to those found in typical peat soils globally. A significant discovery is the strong correlation between high moisture levels and organic content, which is associated with low shear strength and specific gravity, and increased compressibility of the soil. This paper fills a substantial omission in the existing research on the behaviour of Malaysian peat in unsaturated environments. Studies revealed that peat soil is significantly impacted by seasonal fluctuations, particularly during periods of heavy rainfall, which lead to a substantial decrease in shear strength and an increase in water infiltration, resulting in settlement, deformation, and slope instability. As depth increases, hydraulic conductivity is reduced due to the growing complexity of the pore structure, thereby hindering water flow. The review significantly improves comprehension of peat soil behaviour under unsaturated conditions, yielding valuable information for the construction industry and policymakers.

Keywords: Peat soil, unsaturated conditions, moisture content, water table, bearing capacity

BACKGROUND

Peat soil is an organic soil type characterized by more than 75% organic content. It forms through the slow decomposition of plant material under waterlogged conditions (Khanday *et al*., 2021). Peat, a spongy soil rich in organic matter and moisture, is globally widespread, occurring in all regions except deserts and the Arctic. Peatlands, covering an estimated 3–4% of the Earth's land area and spanning a global extent of roughly 500 million hectares, play a crucial role in carbon storage. They contain up to one-third of the world's soil carbon, exceeding the amount found in all of the world's forests combined by more than twice (UNEP, 2022). Figure 1 explains the peat formation process in a peatland area.

Figure 1 illustrates the formation of tropical peatlands over three stages. In Stage 1, which is shown in Figure 1(a), water from nearby rivers and rainfall collected in depressions, creating waterlogged and alluvial soils. During Stage 2, which is shown in Figure 1(b), marsh vegetation develops, and organic matter from leaf and tree litter accumulates, leading to slow decomposition due to poor aeration and anoxic conditions, resulting in a brownish-black water colour with a pH of 2.5-4.5. Stage 3, which is shown in Figure 1(c), marks the development of a fresh swamp forest. As alluvial deposition diminishes a peat layer forms over many years, accumulating at an estimated rate of 0.5-2 mm per year.

This study aims to provide a comprehensive review of the properties and behaviour of unsaturated peat soil, emphasising its implications for building. This paper addresses a significant gap in the literature by offering an in-depth review of the effect of unsaturated conditions on the most important characteristics of peat soil for construction. It delves into several peat soil topics, such as its general characteristics, classifications, and particular challenges associated with organic soil construction. In addition, this paper explores the effects of unsaturated conditions on soil strength, hydraulic conductivity, and moisture content, ultimately resulting in an improved understanding of how to regulate construction projects in regions where peat soil is prevalent.

PEAT SOIL IN MALAYSIA

Peat soil extends across more than 0.5 billion hectares, representing 4% of the Earth's terrestrial surface. The vast majority, exceeding 95%, is concentrated in the northern

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hemisphere, with Asia comprising 20.3% (36.9 million hectares). Canada possesses an extensive peatland area of 1,132,614 km², while Russia's peatland spans approximately 1,180,358 km². Table 1 lists the global distribution of wetlands by geographic area (Wahab *et al*., 2021).

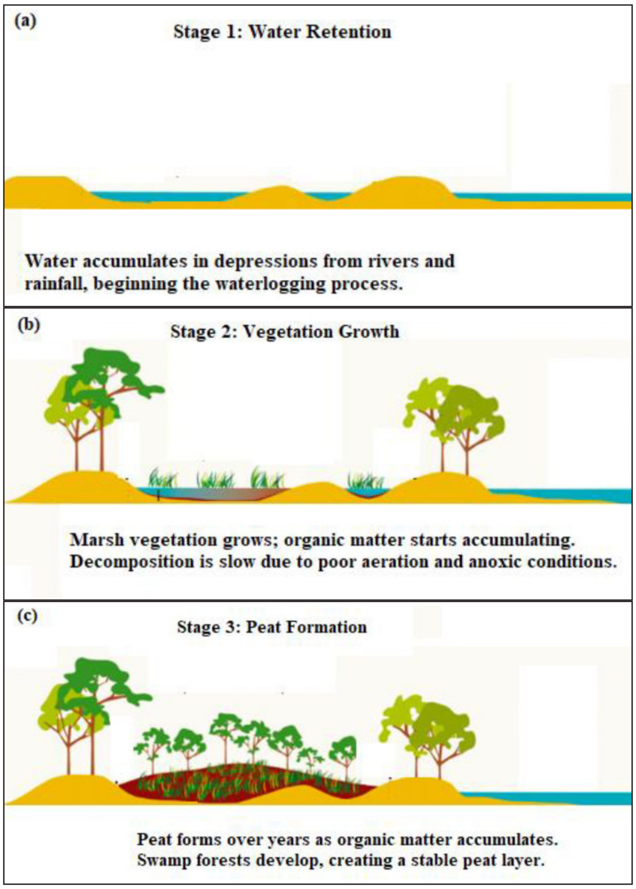


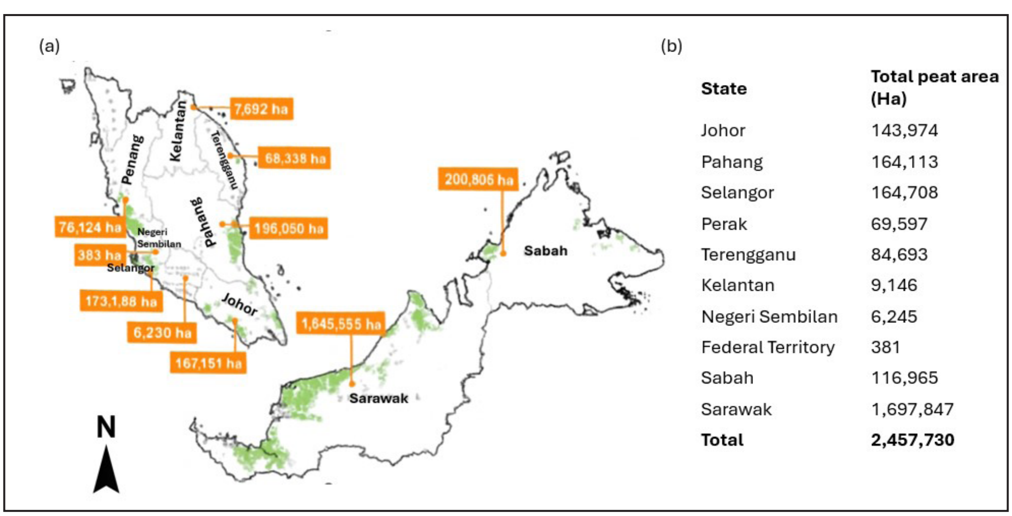
Figure 1: The formation of peat soil (a) Stage 1: water retention (b) Stage 2: vegetation growth and (c) Stage 3: peat formation (Modified from Wahab *et al*., 2019).

In Malaysia, peatlands are distributed across both highland and lowland regions within a tropical climates (Hajon *et al*., 2018). Lowland, or basin peat, is more prevalent, typically occurring in poorly drained depressions or basins near coastal areas. Common locations for these basin peats are the inner edges of mangrove swamps that border the shore (Lawson *et al*., 2022).

Malaysia ranks ninth globally in terms of extensive peat soil coverage. Peat soil occupies an estimated 2.56 million hectares, accounting for 7.74% of the nation's total land area. Over 60% of Malaysia's peatlands are currently utilized for agriculture purposes, with oil palm plantations constituting a significant portion of this land use. Sarawak is the Malaysian region with the largest peat soil coverage, spanning 1,645,585 hectares, which accounts for about 64.27% of the country's total peatland area (Irah *et al*., 2020). Figure 2 illustrates the distribution of peat soil regions in Malaysia.

Figure 2(a) shows that most of Malaysia's lands involve large peat deposits, with the maximum peat distribution areas in Sarawak. According to Talib *et al*. (2021), as shown in Figure 2(b), Sarawak has the largest peat soil distribution area, whereas Negeri Sembilan has the lowest coverage.

The substantial presence of peat soil in these regions poses significant challenges to construction projects due to its inherent weakness, making it unsuitable for supporting heavy construction loads (Warburton, 2020). The review revealed that despite extensive research on the properties of peat soil in Malaysia, a significant gap persists in understanding the Soil-Water Characteristic Curve (SWCC) and its associated behaviours under unsaturated conditions. Figure 3 provides land use maps of areas with large peat distribution in Malaysia.



State	Total peat area (Ha)
Johor	143,974
Pahang	164,113
Selangor	164,708
Perak	69,597
Terengganu	84,693
Kelantan	9,146
Negeri Sembilan	6,245
Federal Territory	381
Sabah	116,965
Sarawak	1,697,847
Total	**2,457,730**

Figure 2: (a) Malaysia's Peat Soil Distribution Map and (b) peat areas in Malaysia in (Ha) (Modified from Irah *et al*., 2020 and Talib *et al*., 2021).

Table 1: Global peat distribution (Wahab *et al*., 2021).

Continent	Countries	Total land area (km²)	Peatland area (km²)
North America	Canada	9,084,977	1,132,614
	USA	9,161,923	197,841
	Other	6,462,100	8866
	Total	24,709,000	1,339,321
Asia	Russia (Asian Part)	9,784,930	1,180,358
	Indonesia	1,811,569	148,331
	Malaysia	328,657	22,398
	China	9,326,410	136,963
	Other	23,327,434	135,132
	Total	44,579,000	1,623,182
Europe	Russia (European part)	6,592,812	185,809
	Sweden	410,335	60,819
	Finland	303,815	71,911
	UK	241,930	22,052
	Ireland	68,883	22,052
	Other	2,562,225	16,575
	Total	10,180,000	171,171
South America	Total	17,840,000	485,832
Africa	Total	30,370,000	187,061
Oceania	Total	7,692,024	68,636
Global	Total	148,647,000	4,232,369

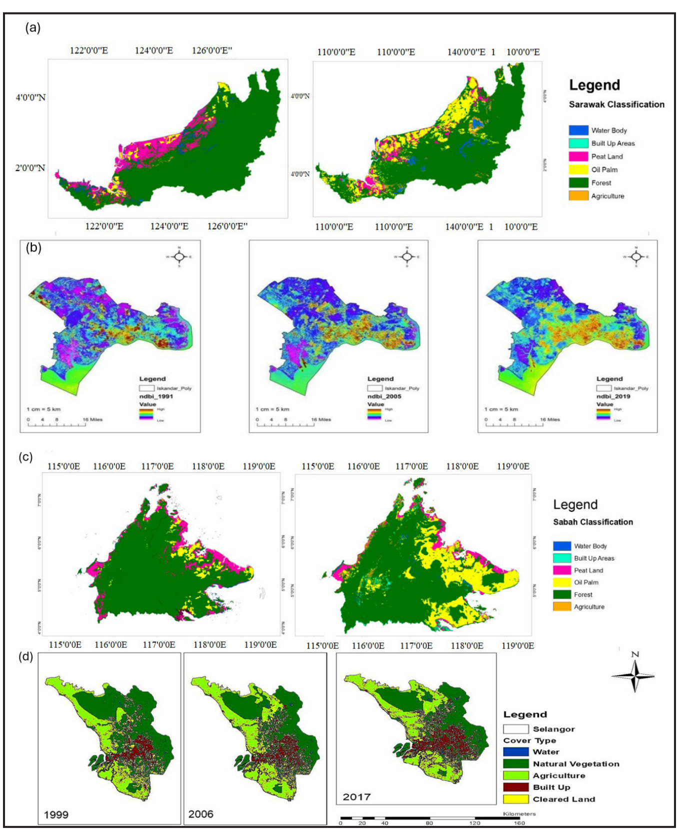


Figure 3: (a) Sarawak land use map in 1990 and 2018, (b) Johor land use map in 1991, 2005, and 2019, (c) Sabah land use map in 1990 and 2018, and (d) Selangor land use map in 1999, 2006, and 2017 (Modified from Jaafar, 2020, Yasin *et al*., 2022, Azari *et al*., 2022).

As depicted in Figure 2(b), Sarawak exhibits the most extensive distribution of peatlands in Malaysia, encompassing 1,697,847 hectares, according to Talib *et al.* (2021). Figure 3(a) further corroborates this observation, with maps from 1990 and 2018, sourced from Jaafar (2020), illustrating the widespread and consistent distribution of peatland across Sarawak, particularly within coastal and low-lying areas. This extensive peatland coverage presence severely limits to construction growth in these regions. The maps reveal that substantial areas remain covered by peatland, acting as a natural barrier to infrastructure development and constraining urban expansion in these locations for over three decades.

Yasin *et al*. (2022) assessed built-up areas and construction progress in Johor. Their findings, as shown in Figure 3(b), revealed a pattern of limited building development in 1991, 2005, and 2019, with extensive areas of Johor exhibiting minimal structural development. This discovery aligns with the findings of Talib *et al*. (2021), who reported that Johor possesses a substantial peatland area of 143,974 ha (Figure 2(b)). The presence of extensive peatlands significantly complicates construction activities, potentially explaining the observed slow pace of building growth throughout the analysed period.

Sabah, with 116,965 ha of peatland (Talib *et al*., 2021), provides further evidence of the influence of peat distribution on building development. The state exhibits a unique land-use pattern, characterized by a minimal built-up area as depicted in Figure 3(c) by Jaafar (2020). This discrepancy between the extensive peatland coverage and the limited built-up areas strongly suggests that peat significantly restricts development activities in Sabah.

Selangor, despite possessing a substantial peatland area in Peninsular Malaysia as per Talib *et al*. (2021), demonstrates limited growth in built-up areas between 1999 and 2017, as illustrated in Figure 3(d). This constrained expansion can be attributed to the presence of extensive peatlands, which pose significant challenges to construction and building operations.

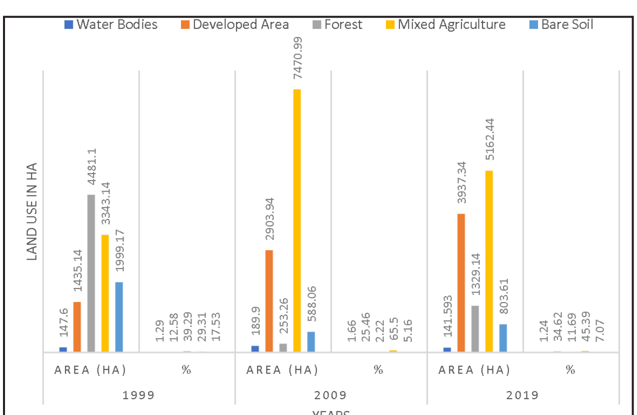


Figure 4: Land use in Negeri Sembilan between 1999 and 2019 (Modified from Zain *et al*., 2021).

In contrast, Negeri Sembilan, with a comparatively lower peatland distribution of 6,245 ha (Talib *et al*., 2021), exhibits a more pronounced increase in land use between 1999 and 2019, as depicted in Figure 4. The reduced presence of peat soil in Negeri Sembilan has likely facilitated greater construction and development activities, contributing to the observed increase in land use.

Therefore, comprehensive investigation of peat soil characteristics and associated conditions is crucial for the development and implementation of effective stabilisation strategies.

PEAT SOIL CLASSIFICATION

Peat soil is typically a mushy, damp, loose surface deposit that is a natural part of peatland ecosystems (Szajdak *et al*., 2020). Peat forms when organic matter, mostly from plants, accumulates faster than it decomposes or becomes damp (Findlay, 2021). Peat is created in wet environments, and waterlogging is necessary for its continued development (Kilpeläinen *et al*., 2023). To maintain organic soil carbon content and prolong peat accumulation, soil must be wet (Stirling *et al*., 2020). Figure 5 shows the fluctuations in water table depth for the eastern coast of Peninsular Malaysia between 2002 and 2004.

To minimize peat oxidation and subsequent carbon dioxide (CO_2) emission, maintaining a water table depth of 20–30 cm below the peat surface or higher is crucial. As shown in Figure 5, the peat bog remained inundated throughout the rainy months of the study period, with flood levels exceeding 50 cm on several occasions. The water table consistently exceeded 20 cm for the majority of the study period except of a drought in April 2004, during which it fell below 30 cm (Wetlands International-Malaysia, 2010).

The colour of peat, composed of decomposed organic and mineral materials, is brownish-black and mostly involves plant remnants like leaves and branches (Hewitt *et al*., 2021). Peat is formed when sedges, trees, mosses, and other plants that thrive in marshes and damp areas without oxygen partially decompose and disintegrate (Drobnik & Stebel, 2020). Peat's primary constituent of peat is organic matter,

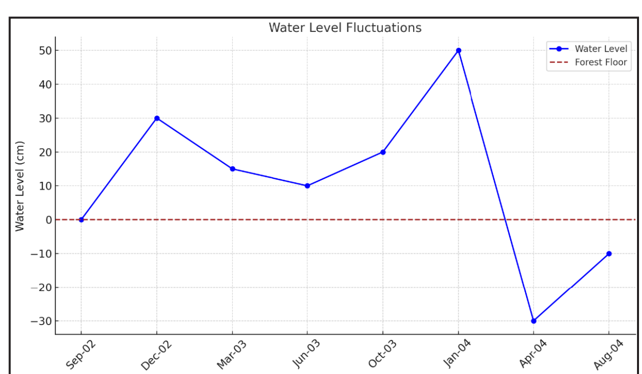


Figure 5: Water table in an undisturbed peat forest in Pahang, Peninsular Malaysia (Modified from Wetlands International-Malaysia, 2010).

Table 2: Peat soil classification based on ASTM standards (Sutejo *et al*., 2017).

	Fabric	Peat with >67% fibres
Fibre Content (ASTM, 2014)	Hemic	Peat with between 33% and 67% fibres
	Sapric	Peat with less than 33% fibres
Ash Content (ASTM, 2014)	Low Ash	Peat with less than 5% ash
	Medium Ash	Peat with 5%–15% ash
	High Ash	Peat containing more than 15% ash
Acidity (ASTM, 2022)	Highly Acidic	Peat with a pH below 4.5
	Moderately Acidic	Peat with a pH between 4.5 and 5.5
	Slightly Acidic	Peat with a pH >5.5 and 7

making it pliable and compressible. Due to this feature, peat differs from other inorganic soil types, e.g., sandy, silty, and clayey soils composed only of inorganic mineral composites, in their unique geotechnical characteristics (Saida *et al*., 2023). According to Sutejo *et al*. (2017), peat can be classified based on three characteristics (as shown in Table 2): fibre content, ash content, and peat acidity.

Furthermore, the fibre content is the most common classification method; in this system, peat soil is categorised based on humification levels. For instance, fibrous or fabric peat (Ptf) corresponds to the humification range of H1–H3, which is as shown in Figure 6(a), hemic or moderately decomposed peats (Pth) fall within the H4–H6 range, which is as shown in Figure 6(b), and capric or amorphous peat (Pta) fall within the H7–H10 range, which is as shown in Figure 6(c) (Mohd *et al*., 2019). This classification depends on identifying peat in the field using the von Post scale, as illustrated in Figure 6 (Mohd *et al*., 2019).

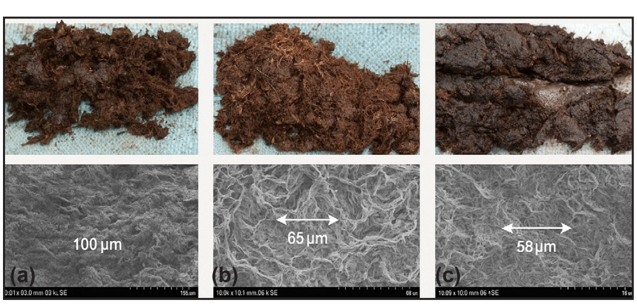


Figure 6: Field-Emission Scanning Electron Microscope (FESEM) image of peat (a) Fibric: Fibrous (> 67% fibers); least decomposed, (b) Hemic: Semi-fibrous (between 33% and 67% fibers); intermediate decomposed and (c) Sapric: Amorphous (< 33% fibers); most decomposed (Modified from Mohd *et al*., 2019).

The Extended Malaysian Soil Classification System typically employs a three step process to classify peat soils based on their organic content, as illustrated in Figure 7.

PEAT SOIL CHARACTERISTICS

Peat soils exhibit limited load-bearing capacity, necessitating a thorough understanding of their unique characteristics. Comprehending the properties of peat soils is crucial when considering their use in construction (Mohamad *et al*., 2022). Table 3 summarises the key indices and mechanical properties of peat soil from several recent studies.

Moisture content

Peat soil exhibits a characteristically high moisture content, directly attributable to its composition. The high organic matter content, predominantly composed of plant remains, plays a critical role in enhancing the soil's moisture retention capacity (Szajdak *et al*., 2020). This organic matter creates a porous soil structure, facilitating extensive water retention. Consequently, peat soil typically exhibits high moisture content values (Wu *et al*., 2020). The moisture content plays a crucial role in soil's compressibility. Under external pressure or load, water is expelled from the soil structure, initiating consolidation and compaction. As a result, pore spaces decrease, leading to an increase in soil density and reduced volume (Johari *et al*., 2020). Peat soils in Malaysia vary greatly in their water content values. In Johor, the water content varies from 230.8% to 913.2%, with the highest values observed at Medan Sari and Pontian. Selangor exhibits a moisture content range between 200% and 700%, reaching 598.5% around Klang. Sarawak displays exceptionally high moisture content, with values as high as 2193% reported in Sibu. In contrast, Sabah exhibits a moderate moisture content range, fluctuating between 461.7% and 687% in locations such as Klias and Lumadan. Finally, the moisture content in Pahang ranges between 362.1% and

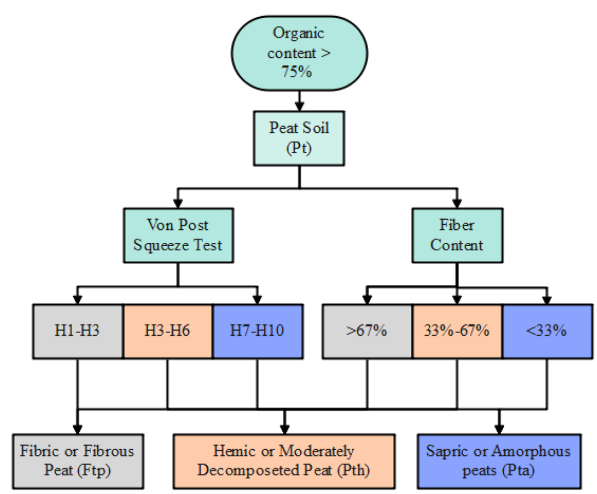


Figure 7: Flowchart of the peat classification, modified from (Modified from Mohd *et al*., 2019).

Table 3: Physical properties of peat soil in different locations in Malaysia.

Property	Location		Sample depth (m)	Value	Reference
Moisture content (weight %)	Johor	Parit Lapis Kadir	0.3	476.8	(Wahab *et al*., 2020)
		Parit Nipah Darat, the 'Saith' of the Darat	0.3-1.0	499.6	(Wahab *et al*., 2018)
		Parit Haji Ali	0.3	586.26	(Wahab *et al*., 2021)
		Parit Nipah	0.3	502.59	
		Teluk Kerang	0.5- 1	230.8	(Yacob & Som, 2020)
		Parit Nipah	1	741	(Talib *et al*., 2021)
		Parit Nipah	4	839.7	(Basri *et al*., 2021)
		Medan Sari	1.5	913.2	
		Pontian	3	898.9	
		Pontian	0.5	546.4	(Wahab *et al*., 2023)
	Selangor	Klang	0.5- 1	598.5	(Radwan *et al*., 2021)
		Banting	0- 0.5	200-700	(Shah *et al*., 2020)
	Sarawak	Sibu	0.5- 2.0	986.44	(Saffaee *et al*., 2023)
		Sibu	0.5- 2.0	1071.6	
		Sibu	0.5- 2.0	985.4	
		Sibu	3	2193	(Mahmood *et al*., 2020)
		-	0.5	646.45	(Makinda *et al*., 2018)
		Kampung Meranek	0.1- 1.50	1118.2	(Mahyan *et al*., 2022)
		Sri Aman	0.5- 2.88	900-1400	(M.Sa'don *et al*., 2021)
		Saratok	0.5- 3.0	747.4	(Jeffary *et al*., 2021)
	Sabah	Klias	0.3- 0.8	674	(Sapar *et al*., 2020)
			1.5	687	(Talib *et al*., 2021)
			-	572.5	(Bin Mohamad *et al*., 2023)
		Lumadan	0.3- 0.8	630.4	(Sapar *et al*., 2020)
		-	-	461.7	(Zainorabidin & Bin Mohamad, 2017)
	Pahang	Kampung Bahru	0.2- 0.6	601.9	(Wahab *et al*., 2022)
		Pekan	0.5- 1	362.1	(Duraisamy *et al*., 2020)
		Gebeng	-	614	(Al Jaber *et al*., 2024)
		Kampung Lancing	0.2- 0.6	537.1	(Wahab *et al*., 2022)
			0.2- 0.6	635.3	
Fibre content (%)	Pahang	Penor	-	40.5	(Zainorabidin & Mansor, 2016)
	Sarawak	Matang	-	45.6	(Sa'don *et al*., 2014)
		Sibu	0.5- 2.0	63.6	(Saffaee *et al*., 2023)
			0.5- 2.0	64.6	
			0.5- 2.0	51	
		Lumadan	0.3- 0.8	61.3	(Sapar *et al*., 2020)
	Johor	Pontian	3	47.6	(Basri *et al*., 2021)
Organic Content (%)	Sabah	Klias	0.3- 0.8	99.4	(Sapar *et al*., 2020)
			0.0- 1.5	98.9	(Talib *et al*., 2021)
		Kampung Meranek	0.1- 1.50	95.5	(Mahyan *et al*., 2022)
	Pahang	Kampung Bahru	0.2- 0.6	97.8	(Wahab *et al*., 2022)
		Kampung Lancing	0.2- 0.6	95.9	
			0.2- 0.6	98.5	
		Penor	0.5	80.3	(Zainorabidin & Bin Mohamad, 2015)
	Sarawak	Sibu	0.5- 2.0	91.6	(Saffaee *et al*., 2023)
			0.5- 2.0	90	
			0.5- 2.0	90.2	
		Kampung Meranek	0.1- 1.5	75.9	(Mahyan *et al*., 2022)
		Matang	0.4- 0.8	81-86	(Raghunandan & Sriraam, 2017)
		Sri Aman	0.5- 2.88	99-95	(M.Sa'don *et al*., 2021)

Table 3: *Continued.*

Property	Location		Sample depth (m)	Value	Reference
Organic Content (%)	Johor	Johore		80-96	(Raghunandan & Sriraam, 2017)
		Pontian	0.5- 1	90	(Yacob & Som, 2020)
			3	81.8	(Basri *et al*., 2021)
		Medan Sari	1.5	96.8	
	Selangor	Banting		79-94	(Raghunandan & Sriraam, 2017)
Specific Gravity	Sabah	Klias	0.3- 0.8	1.2	(Sapar *et al*., 2020)
			0.0- 1.5	1.7	(Talib *et al*., 2021)
		Lumadan	0.3- 0.8	1.6	(Sapar *et al*., 2020)
	Sarawak	Sibu	0.5- 2.0	1.2	(Saffaee *et al*., 2023)
			0.5- 2.0	1.1	
			0.5- 2.0	1.2	
			3	1.1- 1.3	(Mahmood *et al*., 2020)
	Johor	Medan Sari	1.5	1.2	(Basri *et al*., 2021)
		Pontian	-	1.2	(Wahab *et al*., 2021)
			-	1	(Mazlan *et al*., 2023)
			3	1.3	(Basri *et al*., 2021)
	Selangor	Klang	0.5- 1	1.2	(Radwan *et al*., 2021)
Liquid limit (%)	Sarawak	Sibu	0.5- 2.0	283.5	(Saffaee *et al*., 2023)
			0.5- 2.0	343.1	
			0.5- 2.0	371	
	Pahang	Kampung Bahru	0.2- 0.6	142.4	(Wahab *et al*., 2022)
		Kampung Lancing	0.2- 0.6	152.5	
			0.2- 0.6	137.6	
	Sabah	Klias	0.3- 0.8	171	(Sapar *et al*., 2020)
		Lumadan	0.3- 0.8	158	
		Klias		205	(Bin Mohamad *et al*., 2023)
	Johor	Pontain	-	230	(Mazlan *et al*., 2023)
Shear Strength (kPa)	Johor	Batu Pahat	0.3	10.7	(Wahab *et al*., 2020)
		Parit Haji Ali	0.3- 1.0	8.8	(Wahab *et al*., 2018)
		Pontian	-	9- 24.6	(Zainorabidin & Mansor, 2016)
			0.1- 0.2	8	(Kamaruidzaman *et al*., 2019)
		Parit Nipah	0.3- 1.0	9.9	(Mahmod *et al*., 2016)
	Sarawak	Sri Aman	0.5- 2.88	6	(M.Sa'don *et al*., 2021)
	Pahang	Kampung Bahru	0.2- 0.6	7.5	(Wahab *et al*., 2022)
		Kampung Lancing	0.2- 0.6	8.2	
			0.2- 0.6	7.2	
		Penor	-	11.5	(Zainorabidin & Mansor, 2016)
Unconfined compressive strength (UCS) (kPa)	Johor	Pontian	-	8.7	(Wahab *et al*., 2021)
			0.1- 0.2	10	(Kamaruidzaman *et al*., 2019)
	Selangor	Sabak	4- 5	9	(Che Mamat & Ramli, 2023)
Compressibility index (Cc)	Sarawak	Kampung	1	5.4	(Amuda *et al*., 2018)
			1	5.5	
			1	5.5	
	Selangor	Klang	-	1.2	(Mohamed Jais *et al*., 2019)
			-	1.3	
			-	1.2	
	Johor	Pontian	0.1- 0.2	3.8	(Kamaruidzaman *et al*., 2019)

635.3%, highlighting the significant spatial variability in different hydrological conditions across different regions.

Organic and fiber contents

The geotechnical properties of peat soil are significantly influenced by the organic content, primarily composed of plant remnants. High organic matter contents result in a high fibre content within the soil (Szajdak *et al*., 2020). These fibres form a complex, interconnected network within the soil matrix, contributing to increased porosity and water retention (Khanday *et al*., 2021). The fibrous nature of peat soil renders it susceptible to significant deformation and settlement under pressure, as the fibres can entangle and reorient, resulting in significant deformation and settlement over time (Johari *et al*., 2020). According to Chmielewska (2023), fibre content significantly affects the geotechnical qualities of soil, particularly peat. Particularly emphasizing its impact on parameters such as the secondary compression index, constrained modulus, and compression index, as determined through odometer testing. Results show that different peat types exhibit different properties. For example, fabric peat, characterized by a higher water and organic content and larger void ratios, exhibited lower bulk and particle densities compared to hemic and capric peat types, while simultaneously demonstrating higher compressibility (Chmielewska, 2023). This emphasizes the importance of fibre content in determining the geotechnical behaviour of peat soils. As shown in Table 3, the fibre content of peat soil in Malaysia differs depending on the area. Sarawak, with fibre content values reaching 64.6% in Sibu, generally exhibits the highest fibre content. In contrast, Pahang displays the lowest fibre content values, averaging around 40.5%. Johor exhibits a fibre content of 47.6% in Pontian, while Sabah exhibits a fibre content of 61.3%.

On the other hand, the organic content is highest in Sabah, Klias, with up to 99.4%, followed by Sarawak and Pahang, which have comparatively high organic content levels, as high as 91.6% in Sibu and 97.8% in Kampung Bahru, respectively. In Johor, organic content between 80% and 96%, with a maximum value of 96.8% recorded in Medan Sari. Selangor demonstrates a similar range, with organic content values varying from 79% to 94%, reaching a maximum of 94% in Banting.

Specific gravity

Specific gravity, defined as the ratio of the mass of soil solids to the mass of an equivalent volume of water, is a fundamental index property closely related to the soil's mineralogy and chemical composition (Larouci *et al*., 2021). This parameter provides information into the soil's suitability as a construction material, with higher specific gravity generally indicating greater strength for applications such as roads and foundation support (Ogbuchukwu *et al*., 2019). Moreover, specific gravity serves as a crucial input for calculating other important soil properties, including void ratio, porosity, degree of saturation (Pham *et al*., 2020).

Sharma & Shrivastava (2023) demonstrated a positive correlation between specific gravity and shear strength parameters, including cohesiveness and the angle of shear resistance. Similarly, Adeke *et al*. (2021) noticed a corresponding increase in the California bearing ratio (CBR), showing the increase in the subgrade materials strength used in road buildings, corresponding to specific gravity values.

Peat soils, characterized by high organic matter and pore space content, typically exhibits low specific gravity values (Paul & Hussain, 2020). This low specific gravity is translated to a lower unit weight per volume, rendering peat soils exhibit increased susceptibility to settlement and deformation under applied loads (Mazlan *et al*., 2023). Moreover, the low specific gravity negatively impacts the soil's capacity to support structures or maintain stability, necessitating specialized considerations when working with peat soil in construction or civil engineering projects (Sa'don *et al*., 2021).

As summarized in Table 3, specific gravity values are relatively consistent ranges across different peat soil deposits in Malaysia. In Sabah, specific gravity values range between 1.2 and 1.7, although higher values may be observed at greater depths in Klias. In Sibu, Sarawak has specific gravity values ranging from 1.1 to 1.3 across different depths. The values of Medan Sari and Pontian in Johor ranged from 1.0 to 1.3. Finally, in Selangor, specific gravity values at depths of 0.5 to 1 m typically range around 1.2.

Liquid limit

The soil's liquid limit (LL) of soil represents the moisture content at which the soil transitions from a plastic state to a liquid-like state when subjected to standardized laboratory testing. This critical parameter defines the boundary between plastic and liquid soil behaviour. Specifically, the LL corresponds to the moisture content at which the soil can no longer maintain its shape and begins to flow exhibits liquid-like characteristics (Pham *et al*., 2021). The LL significantly influences soil classification, behaviour, and suitability for construction projects, especially when evaluating soil susceptibility to moisture changes and its potential for deformation under varying conditions (O'Kelly, 2016).

According to O'Kelly (2016), the applicability of the Atterberg limit concept to peat soils faces challenges, especially regarding the LL test. The LL values were significantly affected by the scale and reinforcement effects of the peat fibres, particularly in the less humified peat material.

The liquid limit (LL) of peat soil is primarily influenced by several factors, including fibre content, humification level, and silt and clay within the soil matrix (Khanday *et al*., 2021). An increase in organic content significantly influences the liquid limit. In tropical climates, the LL of peat soils typically ranges from 200 to 600%, while bog peats exhibit significantly higher LL values, ranging from 800 to 1500% (Paul *et al*., 2018). The liquid limit of tropical peat soil in Malaysia typically falls within the range of 130% to 400% (Sate Ahmad *et al*., 2021).

As shown in Table 3, peat soils with higher liquid limit values are more likely to experience severe settlement under applied load, owing to their increased moisture content and increased compressibility index. The LL values in Pahang are relatively lower, with 142.4% in Kampung Bahru. In contrast, Sarawak displays exceptionally high LL values, reaching up to 371% in Sibu, as shown in Table 3. Similarly, Sabah exhibits LL values ranging between 158 and 230%. Regions characterized by high LL values are often characterised by low shear strength, unconfined compressive strength (UCS), and consequently, low bearing capacity to support structures. The high liquid limits of peat soils often become unstable, making them susceptible to deformation and posing significant challenges for construction activities.

Shear strength

Soil shear strength represents the internal resistance of a soil mass to failure per unit area and sliding along its internal plane within it (Veers *et al*., 2022). It quantifies the soil's ability to resist movement and sliding along internal planes. Shear strength is characterized by two primary components: cohesion and the internal friction angle. Cohesion represents the intrinsic molecular attraction within a substance, which contributes to its ability to resist shear stress and maintain structural integrity even without external forces (Stefanow & Dudziński, 2021). Meanwhile, the internal friction angle characterizes the resistance to sliding between soil particles, influenced by factors such as particle roughness and interlocking (Amiri *et al*., 2019). These parameters are crucial for assessing the stability of slopes, foundations, and various geotechnical structures (Nebeokike *et al*., 2020).

Wahab *et al*. (2022) emphasized the significance of soil shear strength a fundamental mechanical property for evaluating slope and foundation stability under various loading conditions. High moisture content and the presence of minerals immediately affect peat soil's shear strength. Furthermore, variations in fibre content across different peat types (e.g. capric, hemic, and fabric peat) contribute to spatial variability in shear strength, with fabric peat typically has a higher shear strength compared to hemic and capric peat.

Additionally, Arisya *et al*. (2022), dealing with poor peat soil poses several challenges, primarily due to their low shear strength. Inadequate shear strength can lead to instability issues, including erosions of ditches and drains. Moreover, during periods of intense rainfall, increased soil moisture can further reduce shear strength, increasing the susceptibility of soil layers to sliding and slope failures.

As summarized in Table 3, shear strength values indicate significant spatial variability across different peat soil deposits in Malaysia. The same soil with comparable shear strength, Batu Pahat in Johor demonstrates a range of 10.7 kPa, whereas at Parit Haji Ali exhibits a lower shear strength of 8.8 kPa within the depth range of 0.3 to 1.0 m. The maximum variation was observed at Pontian, ranging from 9 to 24.6 kPa. Sarawak, Sri Aman exhibits relatively lower shear strength, with a maximum value of 6 kPa within the depth range of 0.5 to 2.88 meters. Penor sample has the highest shear strength in Pahang, which is 11.5 kPa. The shear strength of Kampung Bahru and Kampung Lancing varies between 7.2 and 8.2 kPa.

Unconfined compressive strength (UCS)

Unconfined Compressive Strength (UCS), representing the maximum resistance to compression without lateral constriction, is a critical parameter in geotechnical engineering. It serves as a fundamental parameter for soil classification, assisting engineers in classifying soil types based on their strength characteristics (Jeremias & Cripps, 2023). Moreover, UCS results significantly influence construction planning, including the selection of designing foundation types, retaining walls, and embankments designs. In addition, UCS plays an important role in slope stability analysis, providing insights into potential failure modes and facilitating the design of stable slopes. The UCS impacts construction planning, material selection, and quality control during construction, as well as facilitating the predictive modelling of soil behaviour under varied stress circumstances and ensuring the safety and lifespan of infrastructure projects (Park *et al*., 2022). Peat soils are characterised by low UCS values. This inherent weakness renders the implementation of reinforcement or stabilization techniques to ensure the suitability of peat soils for construction purposes (Elangbam & Kalita, 2024).

Table 3 shows the considerable regional variations in the UCS of peat soil deposits in Malaysia. In Johor, at Pontian, the UCS was measured at 8.7 kPa with a slight increase to 10 kPa at depths of 0.1 – 0.2 meters. In Selangor, at Sabak, the UCS at a depth of 4-5 meters was measured to be 9 kPa. These measurements indicate that the compressive strength of peat soil in these regions is generally low.

Compressibility

The high moisture content and organic matter content of peat soil render it highly compressible. When subjected to external loading, the soil undergoes consolidation as water is expelled from the soil structure. This process leads to a reduction in pore space volume, resulting in an increase in soil density and a decrease in overall volume (Zhang *et al*., 2020; Johari *et al*., 2020). Furthermore, the fibrous nature of peat soil exacerbates its compressibility. The interconnected network of fibres within the soil matrix can undergo significant rearrangement and compaction under pressure, leading to a substantial settlement over time (Warburton, 2020). This combination of factors, including high moisture content, high organic content, and fibrous structure, results in peat soils with poor shear strength, limited load-bearing capacity, and a high susceptibility to moisture fluctuations. These characteristics contribute to increased instability, erosion susceptibility, and a heightened risk of subsidence (Berbar, 2020). Table 3 data demonstrate a strong correlation exists between high moisture content and compressibility of peat soils. Locations with higher moisture content typically exhibits higher compressibility index values, which indicates a greater potential for soil settlement under applied load.

According to Johari *et al*. (2020), peat compressibility unfolds in four stages:

- Initial compression: The loading of peat results in a large decrease in volume. The first compression directly reacts to the external force acting on the peat material. This is the first reaction to the applied force, resulting in a rapid drop in volume.
- Primary Consolidation: After initial compression. This step involves the progressive water evacuation from the peat pile caused by the applied load. As the excess water drains, the peat eventually settles, resulting in a further drop in volume. Primary consolidation is a time-dependent process, with settlement rates slowing as water is discharged.
- Secondary compression occurs when peat is subjected to persistent loading after primary consolidation. Secondary compression results from continually rearranging and realigning soil particles inside the soil structure. This sluggish process may last longer, causing more compaction and volume loss.
- Tertiary Compression: Some peat soils undergo a third stage after primary and secondary compression. This phase occurs when soil is subjected to long-term sustained loading. Tertiary compression refers to the slow and progressive restructuring of soil particles within the peat framework. Although less evident than in the primary and secondary phases, tertiary compression leads to additional compaction and volume reduction. This stage emphasizes peat's constant flexibility under sustained stress, demonstrating its continued proclivity for deformation and compaction.

These findings highlight the importance of considering the compressibility of peat soil during all stages of construction, particularly in peat areas characterized by high moisture content and low shear strength. These soil properties significantly influence the stability and long-term durability of structures built on peatlands.

CHALLENGES OF CONSTRUCTION ON PEAT SOILS

Peat soils are characterized by extremely high natural moisture content, leading to elevated void ratios. The void ratio, defined as the ratio of the volume of voids to the volume of solids, varies considerably depending on the peat type (Paul *et al*., 2021; Almsedeen *et al*., 2022). The void ratio can be as high as 25 in fibrous peat and as low as 2 in amorphous peat (ElMouchi *et al.*, 2021). The void ratio is strongly correlated with both water and organic content (Word *et al*., 2022). ElMouchi *et al*. (2021) found a linear relationship between water content and void ratio, consistent with theoretical predictions based on phase diagram calculations. Accordingly, peat soil's loose and highly compressible structure enables a significant increase in water-holding ability, contributing to its high permeability, ranging between 10^{-5} and 10^{-7} m/s (Bulliard *et al*., 2024).

Furthermore, the high-water content in soil significantly impacts the mechanical behaviour of peat soils by reducing effective stress, Effective stress, defined as the net stress transmitted through the soil skeleton, is diminished by the presence of pore water pressure and contributes to soil strength and stability (Huang *et al*., 2022). This pore water pressure comprises both hydrostatic pressure (due to water weight) and excess pore pressure (induced by fast fluctuations in water content), which arises from rapid fluctuations in water content (Faloye *et al*., 2021). The change from negative suction pressure, characteristics of unsaturated soils, to positive pressure hydrostatic pressures significantly affects the soil's stress state, potentially compromising its stability and load-bearing capacity (Zeng *et al*., 2023).

In unsaturated peat soils, especially partially dry peat, are held together by negative pore water pressures, often known as soil suction (McCarter *et al*., 2020). This suction creates apparent cohesion in the soil, increasing its shear strength and bearing capacity (Amir *et al*., 2020). Nonetheless, the soil becomes saturated when the water content increases and the negative pore water pressures change to positive hydrostatic pressures (Faloye *et al*., 2021).

Furthermore, the rise in pore water pressure due to excessive water content, such as during heavy rainfall or rapid flooding, can lead to the development of high pore pressures, exceeding hydrostatic pressure (Johnston *et al*., 2021). Excessive pore pressures are positive pore water pressures exceeding hydrostatic pressure and are commonly associated with undrained loading conditions. This reduces effective stress and can lead to a rapid loss of soil strength, known as liquefaction, which can cause significant damage to structures erected on peat soils because the ground loses its capacity to support imposed loads (Chakraborty & Sawant, 2022).

Variations in soil suction due to changes in moisture content substantially affect the essential characteristics and bearing capacity of peat soils (Wang *et al*., 2020). In unsaturated peat soils, negative pore water pressure (soil suction) increases the obvious cohesiveness and shear strength (Pandya & Sachan, 2020). However, inundation events increase moisture content and pore water pressure, resulting in a larger void ratio and a decrease in bearing capacity (Ma *et al*., 2023). In contrast, drying-induced consolidation increases soil suction and effective stress improving bearing capacity by lowering the void ratio (Ying *et al*., 2022). Moisture-induced changes affect Atterberg limits (liquid, plastic, and plasticity index) and soil permeability. Increasing moisture content typically leads to an increase in liquid limits and plasticity indices, making the soil more compressible and susceptible to deformation. Concurrently, increased moisture content can also lead to an increase in soil permeability (Karumanchi *et al*., 2020).

The resulting low bearing capacity leads to several issues, including settlement, subsidence, and structural collapse (Almsedeen *et al*., 2024). Moisture content, specific gravity, decomposition degree, and organic content significantly influence these properties (Dettmann *et al*., 2021). Shear strength is a vital soil characteristic determining the potential for deformation or failure in organic soils. This weakness in shear strength depends on several factors, including water content, humidity, organic matter content, decomposition level, and mineral content. Notably, heightened water content and increased decomposition are consistently correlated with diminished shear strength (Wang & Li, 2023).

In construction projects situated on peat soils, ground level experiences settlement due to various factors, such as natural compression of the underlying peat soil. This settlement can necessitate continual adjustments by adding more fill to maintain desired ground levels or counteract subsidence (Warburton, 2020). Furthermore, when embankments are constructed on peat soil, the underlying foundation soils undergo a process of consolidation. Consolidation is a natural process in which the peat soil gradually compresses under the weight of an embankment or any imposed load. Consequently, the original embankment crest may experience subsidence or settling, potentially compromising its structural integrity and stability. This phenomenon poses a significant engineering problem, particularly in projects involving infrastructure or construction on peat soils (Abdulkareem & Hassan, 2019; Abdel-Rahman, 2020; Simon, 2023).

UNSATURATED PEAT SOIL CONDITIONS

Unsaturated soil is characterized by the presence of both water and air within the voids between soil particles, occurring above the water table. The distinctions between the medium and shaping techniques contribute to the soil's unique structure and stress state (Khalili *et al*., 2022). Unsaturated soil involves a three-part structure consisting of a solid phase composed of soil particles and specialised bio-cementitious materials, a liquid phase containing water and aqueous solutions, and a gas phase comprising components like air and water vapour (Li *et al*., 2023). The unsaturated soil is divided into four categories: fully connected, incompletely connected, internally connected, and entirely closed, depending on the pore structure and the degree of water saturation (Huo *et al*., 2021). The reduction in gas connectivity with increasing water content can significantly impact pore air pressure and subsequently influence effective stress within the soil mass (Zhang *et al*., 2023).

The presence of both air and water within the pore spaces creates a complex stress state within unsaturated soils. Soil suction, arising from the tendency of water to evaporate from the soil surface, plays a crucial role in governing soil behavior. As water content increases and the soil approaches saturation, soil suction diminishes, leading to a reduction in effective stress and a corresponding increase in soil compressibility. Unsaturated soils exhibit distinct behavior compared to saturated soils due to the complex interplay of air and water within the pore spaces. This multiphase system significantly influences key soil properties, including moisture content, permeability, shear strength, and bearing capacity (Pham *et al*., 2023). The composition of the soil medium, including particle size distribution, mineralogy, and organic matter content, further influences these properties and contributes to the observed variability in unsaturated soil behavior.

Peat soil water characteristic curve (SWCC)

Unsaturated soil mechanics influence soil permeability, shear strength, volume change capacity, pore size distribution, water content and various suction levels (Fredlund & Fredlund, 2020). The soil water characteristics curve (SWCC) is essential for assessing unsaturated soil properties and elucidating the relationship between soil water retention capacity and suction (Hedayati *et al*., 2020).

The Soil Water Characteristic Curve (SWCC) graphically illustrates the relationship between soil water content (volumetric or gravimetric) and soil matric suction. Because of its highly porous and organic nature, peat soil exhibits remarkable water retention properties as reflected by its high starting values for gravimetric water content, w, volumetric water content, θw, and degree of saturation, S in the SWCC (Rezanezhad *et al*., 2016). Both w and θw decrease rapidly with increasing matric suction, indicating rapid drainage of water from the highly massive pores that are typical of peat (Kämäräinen *et al*., 2020). The water retention ability of peat is manifested in its thin, fibrous pore structure by the degree of saturation, remaining comparatively high under higher suction (Mohamad Tarmizi, 2014; Kurnain, 2016). According to Sutejo *et al*. (2018), an experimental study

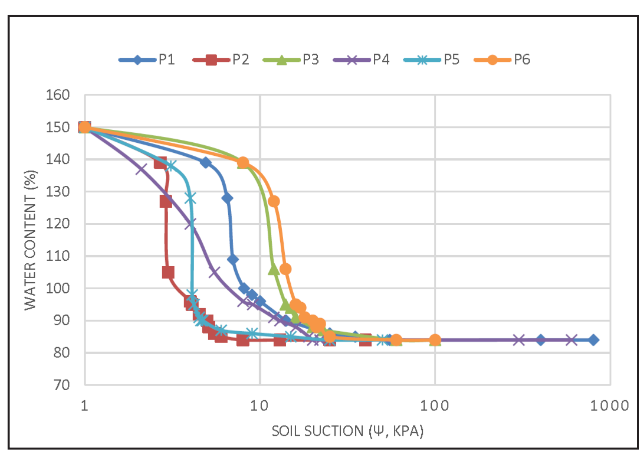


Figure 8: SWCC for different peat soils (Modified from Sutejo *et al*., 2018).

focused on Malaysia's peat soil regarding its SWCC and water retention characteristics. The fibrous peat tested using the filter paper method had a high-water content of 294.30% and pH of 3.0; the suction values, ranging from 3.2432 to 17.5230 kPa, showed lower retention than other soil types. In Figure 8, the SWCC of the six peat soil samples shows a sharply decreasing water content curve with increased suction.

The SWCC of unsaturated peat soil, shown in Figure 8, depicts the stages of desaturation while emphasising peat's distinct behaviour due to its high organic content and porosity. Initially, peat has a high saturated moisture content, but as the matrix suction develops, air enters at relatively low suction values, causing rapid desaturation in the transition zone; this is followed by the stability of moisture content in the unsaturated zone (McCarter *et al*., 2020). During these stages, peat soils in Malaysia undergo considerable volume changes, such as shrinkage and decreased strength, requiring careful technical and environmental management to deal with issues such as settlement, stability, and carbon emissions (Yassin *et al*., 2020).

According to Sutejo *et al*. (2019), a study of SWCC of peat soil under both drying and wetting cycles, recognizing the unique water retention behaviour. The highly porous and fibrous structure of peat facilitates rapid water drainage during drying, resulting in a steep decline in volumetric water content with increasing matric suction. This rapid drainage is indicative of the presence of large pores within the peat soil. During the wetting cycle, the SWCC exhibits hysteresis, with the suction values tracing a different path compared to the drying cycle, indicating partial water entrapment within smaller pores. This hysteresis phenomenon, along with the steep drying curve, highlights the complex water retention and release properties of peat soils, which are strongly influenced by their unique structural characteristics and organic composition. Figure 9 illustrates the SWCC for several peat samples, where P denotes the baseline soil suction, and W1 to W9 represent various measurement stages of soil suction and water content along the SWCC.

To further investigate these findings, the experimental data were compared to the van Genuchten and Fredlund-Xing models, as described by Niu *et al*. (2023), which provide insight into the soil behaviour at different matric

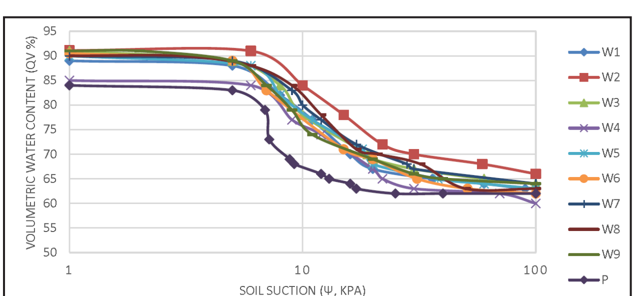


Figure 9: SWCC for peat soil (Modified from Sutejo *et al*., 2019).

suction levels. This result shows that the saturation degree decreases as the matric suction increases, resulting in residual water content. This suggests that air starts replacing water in soil pores at lower suction levels, consistent with the observation that finer soils with more organic content, such as peat soil, retain water more efficiently at lower suction levels (Panagea *et al*., 2021).

However, although peat soil characteristics have been studied extensively in Malaysia, more studies are needed on the SWCC of peat soil and related aspects under unsaturated conditions. The following sections discuss peat soil characteristics in Malaysia, including moisture content, swelling and shrinkage, hydraulic conductivity, strength fluctuations, embankment and slope stability, volume changes, and compressibility under unsaturated soil conditions.

Peat soil moisture content under unsaturated soil conditions

Peat soils, renowned for their high organic matter content, ranging from 75.9 to 99.4 % in Malaysia, as shown in Table 3, exhibit essential moisture dynamics within the unsaturated zone, which is critical for construction applications (Rezanezhad *et al*., 2016). The unsaturated zone, located above the groundwater table, comprises a mixture of air and water within the soil pores (Dahan, 2020). Seasonal fluctuations in hydrological conditions significantly impact moisture content within the unsaturated zone (Sate Ahmad *et al*., 2021). During spring, a shallow groundwater table near the surface causes the soil to nearly saturate within this unsaturated zone, resulting in minimal air content (Ojoawo & Adagunodo, 2023). Conversely, periods with higher drainage, rising groundwater levels increase the air content in the unsaturated zone (Li *et al*., 2020). Furthermore, dry periods, despite the inherently high moisture content of peat soils, can result in a significant reduction in water content within the unsaturated zone (Stirling *et al*., 2020).

According to Eyo *et al*. (2022), moisture variations within the unsaturated zone significantly affect soil behaviour and moisture-holding abilities, which affect other soil characteristics. Besides, Malaysia's seasonal shifts can cause the water table to fluctuate by 1.25 meters (Ledger *et al*. 2023). For instance, the water table can drop as deep as 71 cm below the surface at smallholder oil palm sites, leading to peat surface oscillations of up to 6.1 cm. These fluctuations significantly affect the mechanical properties of peat soils, including their subsidence rates and moisture retention capacity. For example, the elastic deformation of peat soil under unsaturated conditions is closely related to the change of water content within the unsaturated zone.

The compaction and consolidation processes of peat soil in Malaysia significantly influence its moisture content, especially under unsaturated conditions (Samuel & Evers, 2024). Such cases of compaction occur above the water table because a decrease in pore water pressure increases the effective stress on the peat matrix and shrinks the soil as moisture is lost from the pores (Ledger *et al*., 2023). It is most pronounced during drought when the water table falls and leaves the peat in the unsaturated zone (Mahdiyasa *et al*., 2023). In Malaysia peat soil deformations, such fluctuations can be seasonal, with the water table falling considerably during the dry season (Imran *et al*., 2023). Consolidation beneath the water table occurs due to the weight of the overlying unsaturated peat, which exerts pressure on the underlying saturated peat. This pressure drives the expulsion of water from the saturated layer, leading to a reduction in moisture content and a corresponding decrease in soil volume (Nababan, 2021). The moisture content of peat soil in the unsaturated zone is significantly impacted by seasonal shifts, with fluctuations in air and water content within soil pores, which can affect the soil's behaviour and moisture-holding abilities and significantly impact on other soil characteristics.

Swelling and shrinkage of peat soil under unsaturated conditions

According to Verbeke *et al*. (2022), peat, categorized by its significant organic matter content, often exhibits noticeable shifts in land elevation. These changes are driven by two primary factors. The first is the irreversible and prolonged subsidence caused by the bio-oxidation of organic matter, particularly pronounced in drained wetlands. This process results in subsidence rates of several centimetres per year, especially in temperate and tropical climates (Peng *et al*., 2021). Conversely, reversible displacements primarily occur due to changes in moisture content during drying/wetting or freeze/thaw cycles (Lahoori *et al*., 2021). Drier periods in the unsaturated zone generate significant matrix suction, leading to increased bulk density and a reduction in pore volume due to soil shrinkage (Zhao, 2023). Simultaneously, lowering the water table causes saturated peat compression as the effective stresses intensify (Warburton, 2020). The degree of shrinkage and swelling varies depending on the ratio between the unsaturated and saturated zones, with volume changes occurring in the unsaturated zone being notably higher (Seidel *et al*., 2023).

Experimental evidence from Malaysian peat soil shows high compressibility, causing volumetric changes up to 10 times larger than swelling clay soils (Zhao & Jommi, 2022; Mousavi & Ghayoomi, 2021). Owing to moisture content changes, these displacements can reach up to 0.1 m in fibrous and poorly decomposed wetlands but are relatively small (around 0.01 m) in amorphous organic soils (Zanello *et al*., 2011). This phenomenon is typical when an unsaturated zone coincides with a shallow layer that experiences swelling/shrinking deformations comparable to irreversible subsidence rates due to long-term organic matter oxidation (Zhao & Jommi, 2022).

Furthermore, Malaysian peat soils exhibit massive swelling and shrinkage with seasonal changes in moisture (Raghunandan & Sriraam, 2017). During the wet season, the soil receives more rainfall, which easily infiltrates the soil. This, in turn, causes peat to swell because of the absorbing action of peat. During the dry season, the peat shrinks due to the reduction in moisture content. Accordingly, when the water table rises following rainfall, the peat expands; on the contrary, if the water table drops during dry periods, the peat undergoes shrinkage (Zanello *et al*., 2011).

In general, there are three distinct phases during the drying process of peat soil (Parra-Gómez *et al*., 2023). The initial phase, termed near-normal shrinkage, occurs when soil volume decreases with moisture loss, maintaining the peat matrix close to saturation (Seidel *et al*., 2023). Subsequently, subnormal shrinkage occurs as moisture loss surpasses volume change, causing soil to become definitively unsaturated. This phase involves air infiltration into larger pores, whereas the smaller pores within the organic fibres remain water-filled (Weghorst, 2022). Finally, super-normal shrinkage emerges when volume reduction exceeds moisture loss. In this case, even smaller pores dry out, causing the matrix to collapse to its minimum volume as the moisture content approaches zero (Weghorst, 2022).

Peat soils in Malaysia have expansive and shrinkage cycles induced by seasonal fluctuations in the moisture content (Imran *et al*., 2023). These volumetric changes are closely linked to variations in the water table, which rise during wet periods and decline during dry periods. As the water table rises, peat soils tend to swell due to increased water absorption. Conversely, during periods of declining water table, peat soils undergo shrinkage as they lose moisture (Zanello *et al*., 2011).

Hence, the depth of the water table is an important factor influencing peat soil swelling and shrinkage under unsaturated conditions (Liu *et al*., 2020). As the water table rises, peat becomes saturated and expands. On the other hand, when the water table is lowered, the soil loses water and shrinks (Seidel *et al*., 2023). These types of cycles might be very observable in peatlands in Malaysia, for instance, where large seasonal changes in water table depths can produce such changes in physical structure (Girkin *et al*., 2022).

Peat soil hydraulic conductivity under unsaturated conditions

According to Gharedaghloo & Price (2017), the hydraulic conductivity of unsaturated peat soil is regulated not only by pore size and shape but also by gas occupancy within the active porosity. Stachowicz (2022) explained that the complex and multi-scale pore structure of peat significantly influences its hydraulic activity, making it challenging to directly infer unsaturated hydraulic properties from saturated conditions. Usowicz & Lipiec (2020) underlined that water transport through unsaturated peat depends on the fractal nature of the pore distribution, which is quantified by the soil's fractal dimension.

Understanding the flow dynamics through unsaturated peat requires a complex interplay of factors. Furthermore, apart from the pressure head gradient, the flow rate of unsaturated peat is heavily dependent on its hydraulic conductivity. This property, determined by water content, pore structure, distribution, size, and geometry, significantly influences the ability of peat to transmit water (McCarter *et al*., 2020).

Rezanezhad *et al*. (2010) observed that, at a constant pressure head of 40 cm, both water content and air-filled porosity exhibited minimal variation with depth within the studied peat profile. This suggests that the observed decline in unsaturated hydraulic conductivity with depth was primarily attributed to an increase in tortuosity. Deeper layers of peat likely exhibited smaller pore sizes and altered pore geometry, leading to increased tortuosity and consequently, reduced hydraulic conductivity. The hydraulic conductivity of peat soils varies depending on the pore structure, moisture content, and organic composition. Generally, hydraulic conductivity in Malaysia ranges from 10^{-6} to 10^{-3} cm/s, with higher values observed for less decomposed peats of fibric composition and lower values in highly decomposed peats with smaller pore spaces (Firdaus *et al*., 2012).

Malaysian peat soils, such as those in the Sebangau catchment area, exhibit very different hydraulic conductivity behaviour under unsaturated conditions (Takahashi *et al*., 2021). Unsaturated hydraulic conductivity decreases significantly with depth because of increased tortuosity associated with smaller pore sizes and more complex pore geometry in deeper layers of peat (Rezanezhad *et al*., 2010). Understanding this behaviour is critical for elucidating water flow through peat soils, critically during periods when rain is scanty and there is a drop in the water table. Studies have suggested that hydraulic conductivity in unsaturated zones of tropical peatlands is one factor largely controlled by the physical structure of the peat. Furthermore, because of the hydraulic conductivity of the peat at deeper layers, water transmission becomes slower. This reduced conductivity affects soils' capability to retain water and thereby impairing the storage of water in peat and the total peatland hydrology (Sajarwan *et al*., 2021).

Peat soil volume changes and compressibility

According to Engman (2022), peat soil's behaviour in unsaturated conditions depends significantly on water table alterations and the inherent physical characteristics of the peat. Variations in the water table in Malaysian peat soils permit variations of effective stress to act on them, causing compressions or expansion (Amuda *et al*., 2018). According to Table 3, peat in Malaysia is highly compressible, with compressibility index (Cc) values ranging from 1.2 to 5.5, indicating a strong deformation potential. These fluctuations show that peat soils can sink significantly under stress, resulting in issues for construction and long-term stability. Higher Cc values indicate more vulnerability to compression, highlighting the importance of rigorous geotechnical evaluation in peatland environments (Mohammadi & Hayley, 2024). Higher effective stress causes peat compression as the water table descends, reducing saturated hydraulic conductivity and enhancing moisture retention. This restricts lateral drainage and further water loss (Waddington *et al*., 2014). Conversely, rising water tables prompt peat expansion, reducing moisture retention and potentially escalating water loss through drainage and evapotranspiration (Helsel *et al*., 2020).

The compressibility of peat primarily arises from decomposition levels, typically increasing with depth and reducing compressibility in deeper layers (Rezanezhad *et al*., 2016). Although termed "peat volume change," this phenomenon manifests through vertical shrinkage and compression of peat, visibly altering soil surface levels. Drainage-induced soil exhibits lowered surface positions due to shrinkage above the water table and compression below it, with the latter often playing a more significant role. This occurrence, prevalent in extensively drained soils, indicates that the increased soil weight above the water table compresses the peat below as the water table diminishes (Engman, 2022). However, in natural soil with shallow unsaturated zones, the impact on peat volume is minimal (McCarter *et al*., 2020).

In addition, fluctuations in atmospheric pressure can influence soil surface changes. However, when the unsaturated zone gains dominance and alters the elastic storability definitions, the thicker unsaturated zone diminishes the water support to the peat matrix, causing collapse and compression in the unsaturated layer and below. This dynamic indicates that changes in soil surface position induced by shifts in pore water pressure in the unsaturated zone are not correlated with absolute water level modifications (Engman, 2022).

Peat soil in Malaysia exhibits high volume changes and compressibility under unsaturated states (Mohamad *et al*., 2021). These properties are due to the high organic content, low density, and high void ratio. Under unsaturated conditions, peat dehydrates and shrinks to reduce the volume; it would swell upon rewetting. These volume changes depend on negative pore water pressure, or soil suction, which controls soil compressibility and structure (Teplitsky, 2024). According to the studies of Ledger *et al*. (2023) and Kasbi *et al*. (2021), Malaysian peat could be subjected to high compression upon even small effective stress changes, especially with fluctuating moisture conditions.

Peat soil strength variations under unsaturated soil conditions

Peat soils, rich in organic matter and typically composed of decomposed plant residues, exhibit remarkable sensitivity to moisture alterations, a characteristic that profoundly impacts their mechanical properties (Holthusen *et al*., 2020). Within the unsaturated zone, soils respond dynamically to fluctuations in moisture levels, a pivotal factor that directly influences their strength and stability (Yang *et al*., 2019). As moisture levels fluctuate, organic soils undergo transformative changes in their load-bearing capacity and shear (Sate Ahmad *et al*., 2021). When these soils experience dryness, their structural integrity may weaken, potentially compromising their ability to support construction loads. Conversely, increased moisture content can reduce shear strength, raising concerns regarding soil suitability for sustaining construction activities and structures (Gui *et al*., 2021).

Peat soils unsaturated zone has a highly variable moisture content, which affects the strength and behaviour of the soil (McCarter *et al*., 2020). The upper portion of soil becomes unsaturated and contains both water and air in its pores when drainage lowers the water table (Kacimov *et al*., 2020). Higher water retention capacity results from increased capacity due to increased bulk density. This may decrease soil water content, affecting unsaturated hydraulic conductivity and soil's ability to retain water. The moisture content of an unsaturated zone may trigger peat soils to expand and contract, compromising the soil's strength and structural stability (Jones *et al*., 2020).

Peat soils in Malaysia, especially in coastal areas, demonstrate significant variation in strength under unsaturated conditions due to wet and dry cycles (Daud *et al*., 2021). During rainy seasons, peat normally swells since it absorbs water inside and causes strength loss. Conversely, it shrinks during dry periods when moisture content decreases, which increases soil stiffness and strength to some degree (Tang *et al*., 2020). However, due to their high moisture retention capacity and organic content, Malaysian peat soils exhibit relatively low unconfined compressive strength values, often below 100 kPa in their natural state, compared to mineral soils (Shah *et al*., 2020). These variations in strength are majorly developed through seasonal fluctuations in the water table, which affect the degree of saturation and, thus, the mechanical behaviour of peat soils. The following sections review the effect of strength variation of unsaturated peat in Malaysia on two important aspects, including embankment stability and slope stability.

Embankment stability

The effect of unsaturated conditions on peat soil characteristics is most noticeable in embankment foundations built from soft soils rich in peat particles. These soils have poor permeability and shear strength but high plasticity and compressibility. During heavy rainfall events, considerable water infiltration into the embankment soil material reduces matric suction, lowering the shear strength of compacted soil (Nobahar *et al*., 2020). This rapid reduction in shear strength can cause slope failure, crack development, scouring, and landslides (Gratchev *et al*., 2019). The degree of precipitation penetration into the unsaturated zone was greatly influenced by rainfall intensity. This infiltration process advances owing to variations in moisture content and suction effects, eventually leading to infrastructure breakdown. This failure is frequently referred to as shear displacement, which indicates a change in the performance of the embankment or detectable movement in the road pavement (Ellithy & Stark, 2020).

The stability of the embankment on unsaturated peat soils is very challenging in Malaysia because of its high compressibility and low shear strength (Mohamad *et al*., 2021). Due to the seasonal changes effect on the water table levels in Malaysia, the fluctuating moisture content in unsaturated peat potentially heightens instability and yields large settlements and deformation under load (Basri, 2023). This can significantly damage the integrity of the embankment, particularly during dry seasons when the soil shrinks and its load-bearing capacity is lowered (Gowthaman *et al*., 2018).

For example, according to Ellithy & Stark (2020), unsaturated soil mechanics principles were applied to analyse the failure of an interstate connecting-ramp embankment during its construction phase. Investigations into the embankment failure uncovered significant insights into the behaviour of the peat layer situated within the unsaturated zone between the elevation of 295 m and 300 m, as shown in Figure 10.

Figure 10 illustrates that the calculated Factor of Safety (FOS) was 0.99, which closely matches the observed failure start at a relatively low embankment height of only 4.0 m. Table 4 summarizes the total and saturated unit weights, undrained shear strengths, and total and effective friction angles for the studied layers, including the peat layer.

Notably, the peat layer exhibited specific properties within this unsaturated zone, with total and saturated unit weights of 11.8 kN/m³. This layer's undrained shear strength (c_0) was calculated at 36 kPa, while the total stress or effective friction angles (ϕ_0) registered at 0°. However, the low shear strength and friction angle of 0° suggest a potential vulnerability to mechanical stress, highlighting the propensity for reduced stability under unsaturated conditions (Ellithy & Stark, 2020).

Slope stability

The predicted increase in precipitation associated with global climate transitions may result in more frequent slope

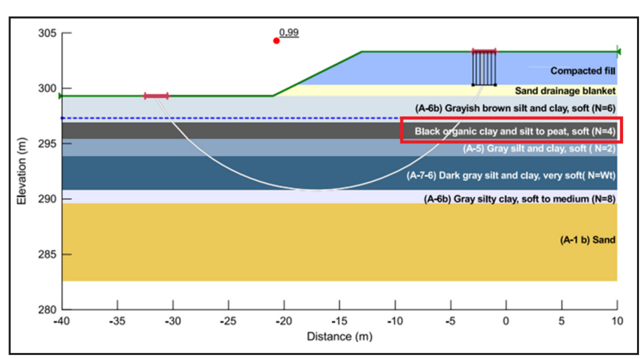


Figure 10: Soil layers involved in the studied embankment (Modified from Ellithy & Stark, 2020).

Table 4: Slope stability characteristics of the studied layers (Ellithy & Stark, 2020).

Soil Type	Total and Saturated unit weights (kN/m³)	Undrained shear strength or c' (kPa)	Total (φ) stress of effective (φ') friction angels (degrees)
Compacted fill	21.2	71.8 or 14.4	φ = 0, φ'=33
Sand drainage blanket	18.6	0	φ'=33
(A6-b) grey/brown silt and clay	17.3	36	φ = 0
Black organic clay and silt to peat	11.8	12	φ = 0
(A-5) grey silt and clay	17.3	12	φ = 0
(A-7-6) dark grey silt and clay	15.7	9.6	φ = 0
(A-6b) grey silty clay	18.1	48	φ = 0

collapses caused by rainfall (Gariano & Guzzetti, 2016). Kamal *et al*. (2022) discovered that soil slopes with peat layers collapse more frequently during rainy seasons but are resilient during dry years. Low shear strength is noted in the unsaturated peat zone above the groundwater level along these slopes during heavy rainfall in Malaysia (Wahab *et al*., 2021). Rainfall infiltration significantly influences matric suction within the unsaturated zone, leading to a reduction in shear strength and consequently increasing the vulnerability of slopes to failure (Rahardjo *et al*., 2019). This phenomenon of increased slope instability during wet seasons is particularly prevalent in tropical regions, such as Malaysia, characterized by frequent and intense rainfall events and extensive peatland coverage (Rahardjo *et al*., 2018).

As illustrated by Rahardjo *et al*. (2019), the mechanisms of slope failure in unsaturated inorganic soils can be extended to peat soils by considering their distinct properties. Peat soils, characterised by their high organic matter content and low shear strength, respond dynamically to moisture changes, significantly influencing their stability during rainfall.

Rainwater infiltrates peat soil after heavy rainfall, lowering matric suction and, as a result, causing effective soil stress. This decrease in effective stress reduces shear strength, which increases the probability of slope collapse (Ashrafullah, 2023). The infiltration process can also worsen existing tension cracks in the soil, allowing greater water penetration and further weakening soil stability (Luo and Ma, 2024). The high water retention capacity of peat soils extends the period in which the soil is saturated after rainfall, allowing them to retain low shear strength for longer periods (Warburton, 2020). Furthermore, the low permeability of peat soils hinders the rapid dissipation of excess pore water pressure generated during heavy rainfall events. This delayed drainage prolongs the period of reduced soil strength and increases the risk of slope failure even after rainfall has ceased (Li *et al*., 2020; Rasheed & Moghal, 2022).

This prolonged saturation period can lead to ongoing instability and an increased risk of slope failure, particularly in tropical climates with excessive rainfall (Dhanai *et al*., 2022; Nazrien Ng *et al*., 2022). The extended period of elevated pore water pressures contributes to ongoing instability and an increased likelihood of slope failure even after the cessation of rainfall (Rosly *et al*., 2022).

In general, peat soils' very compressible nature and poor shear strength, particularly under extended rains, make embankments and slopes in peat-rich parts of Malaysia more unstable (Md Isa, 2019). Also, the sudden saturation of soil in case of heavy rainfall leads to the loss of matric suction drastically reducing the shear strength and developing a high risk of embankment instability and slope collapses (Naseer, 2023). Accordingly, this behaviour underlines the importance of understanding suction dynamics and the SWCC in unsaturated peat soils to improve geotechnical stability in these regions.

CONCLUSION

This paper comprehensively reviews the characteristics and behaviour of unsaturated peat soils in Malaysia. The peat soil, with a high organic content of more than 75%, is characterised by high moisture content, poor strength, and susceptibility to settlement and compressibility. Accordingly, challenging the construction in this type of soil.

The review encompassed several key index properties of peat soil from various locations in Malaysia. Results showed that the shear strength, unconfined compressive strength, specific gravity, moisture content, fibre content, organic content, and compressibility index of Malaysian peat soils fall within the normal range of peat soils worldwide. Also, it was obtained that locations rich with peat soils commonly have low utilization of land cover due to the inherent fragility of this type of soil. Furthermore, the analysis revealed strong correlation between several keys properties. For instance, higher moisture and organic content are related to lower specific gravity, shear strength, and UCS values, concomitantly increasing the soil compressibility.

Furthermore, this review focuses on the behaviour of peat soils under unsaturated conditions. The review revealed that despite extensive research on the properties of peat soil in Malaysia, a significant gap persists in understanding the Soil-Water Characteristic Curve (SWCC) and its associated behaviours under unsaturated conditions. Therefore, key characteristics of peat soil in Malaysia were reviewed in undersaturated conditions, including moisture content, swelling and shrinkage, hydraulic conductivity, strength variations, stability of embankments and slopes, volume changes, and compressibility, especially in unsaturated conditions.

Results revealed that seasonal changes are one of the major factors affecting peat soils under unsaturated soil conditions, including their swelling and shrinkage, as well as their general stability, especially in the tropical environment in Malaysia. It was found that the hydraulic conductivity of peat declines with depth as the intricacy of its pore structure increases, making it harder for water to pass through the soil. Furthermore, peat soil's moisture content significantly impacts its strength under unsaturated circumstances; increased moisture content lowers the soil's shear strength, making it more susceptible to settlement and deformation, especially during the rainy season when water penetration rises. This demonstrates the intricate connection between the mechanical stability, water movement, and the structural properties of peat.

Furthermore, unsaturated peat soils in Malaysia are particularly prone to slope instability and embankment failure during heavy rainfall periods when the shear strength is reduced and its water content increased. This underlines the importance of considering the specific behaviour of peat soil during rainy seasons when changes in effective stresses due to fluctuating water tables directly impact the stability of slopes and embankments.

This study provides a comprehensive review of the characteristics and behavior of unsaturated peat soils in Malaysia, addressing a critical knowledge gap in this field. The findings of this study offer valuable insights for various stakeholders. For the construction industry, this research provides a foundation for developing effective soil stabilization techniques and mitigating the challenges associated with constructing on peatlands. For policymakers, this study underscores the need for updated geotechnical guidelines that specifically address the unique challenges posed by unsaturated peat soils. Finally, this research provides a valuable dataset and insights for researchers to further refine and enhance predictive models for the behavior of unsaturated peat soils under various environmental and loading conditions.

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MMSAJ contributes to gathering the literature review sources and writing the review manuscript. NM contributes to editing, reviewing and providing funding.

COMPETING INTERESTS

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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