Available online at www.CivileJournal.org

Civil Engineering Journal

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

Vol. 11, No. 05, May, 2025

Assessment of Primary and Secondary Compression Parameters of Tropical Fibrous Peat Using Improved-CRS Consolidation Test

Ayu Prativi [1*], Noor Endah Mochtar [1], Indrasurya B. Mochtar [1]

[1] *Department of Civil Engineering, Institut Teknologi Sepuluh Nopember, 60117, Surabaya, Indonesia.*

Received 01 January 2025; Revised 09 March 2025; Accepted 14 April 2025; Published 01 May 2025

Abstract

Predicting the long-term compression behavior of peat using conventional Oedometer tests is challenging. This soil exhibits an unusual compression curve shape under conventional load-increment tests. Meanwhile, conducting the conventional single-load test can disrupt specimens due to its sudden load. Alternatively, a constant rate of strain (CRS) test provides a rapid consolidation method by gradually loading the specimen at a small constant strain rate. However, the inability of the conventional CRS test apparatus to measure compression under a constant load limits its applicability in providing the secondary compression curve, which is essential for predicting the long-term compression in peat. To address this issue, an improved-CRS test apparatus was developed to measure compression under a constant load. Tropical fibrous peat was collected from Palangkaraya, Indonesia. The compression curves obtained from the CRS test, which are comparable to those from the conventional Oedometer test, were used to suggest appropriate strain rate ranges for conducting CRS tests on tropical fibrous peat. The results show that the improved-CRS consolidation test provides accurate primary and secondary compression parameters of tropical fibrous peat by using appropriate strain rates, which were categorized based on the coarse fiber content (C_{Fc}).

Keywords: Coarse Fibers; Coefficient of Consolidation; Constant Rate of Strain (CRS) Consolidation Test; Fiber Content; Primary Compression; Secondary Compression; Tropical Fibrous Peat.

1. Introduction

Peatlands in Indonesia cover approximately 87% of Southeast Asia's tropical peatland area, distributed across Sumatra, Kalimantan, Papua, and Sulawesi, with a total area of 13.43 million hectares [1–3]. Peat is an organic soil composed of accumulated, decomposed, and fragmented plant material (at various degrees of decomposition), with organic content larger than 75% [4, 5]. In tropical regions, the average rate of peat accumulation ranges from 4 to 5 mm/year (can reach up to 5–10 mm/year at some sites), which is higher than the rate of peat accumulation in temperate and cold regions (less than 1 mm/year) [6]. In contrast, peat decomposes more slowly in tropical regions than in temperate and cold climates.

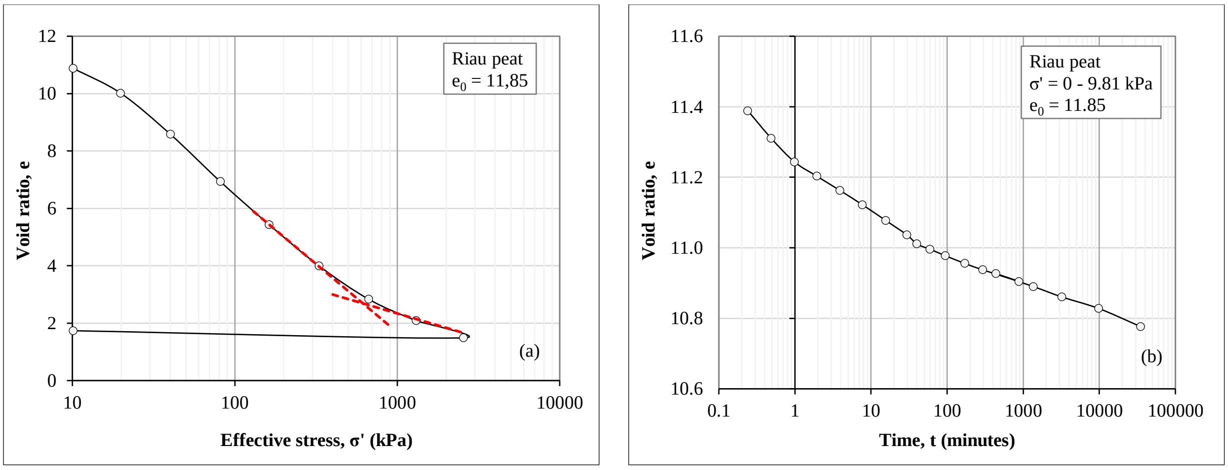
The slow decomposition rate of tropical peat is due to the high lignin content in woody materials, which are the dominant parent materials of tropical fibrous peat [3, 7]. Compared to Sphagnum peat, moss found in temperate and cold regions, the lignin content in woody materials is significantly higher [8, 9]. According to MacFarlane and Radforth [10], peat in tropical regions is often classified as fibrous peat (F_c > 20%). Based on ASTM D 4427 [5], it is further categorized as sapric (fiber content, F_c < 33%), hemic (33% ≤ F_c ≤ 67%), or fibric (F_c > 67%). Coarse fibers (fibers retained on sieve no. 8), such as roots and stems, are common components of tropical fibrous peat [3, 6, 11–16]. These

* Corresponding author: ayuprativi@gmail.com

http://dx.doi.org/10.28991/CEJ-2025-011-05-03

materials are stiffer than the coarse fibers found in Sphagnum peat moss [3, 17]. Consequently, the characteristics of tropical fibrous peat (woody peat) differ significantly from those of temperate and cold region peat (Sphagnum peat moss). Peat is a problematic soil due to its low bearing capacity and high compressibility. Generally, peat soil undergoes a short period of primary compression, followed by significant secondary compression [18]. Primary compression occurs as the pore water is expelled from the macropores. Subsequently, secondary compression occurs as the pore water drains out from the micropores into the macropores [19, 20]. The compression behavior of peat is totally different from that of inorganic soils; thus, a comprehensive understanding of the long-term compression behavior of peat is crucial to mitigate the risk of excessive compression in the field [21].

The compression curves obtained from conventional load-increment tests for peat vary significantly due to its fiber characteristics [16, 22]. For tropical fibrous peat, the void ratio (e) vs. logarithmic effective stress (σ’) curves obtained in these tests often consist of two distinct linear segments (as shown in Figure 1-a), while the void ratio (e) vs. logarithmic time (t) curves may deviate from the typical S-shape curve observed in clay (as shown in Figure 1-b) [23, 24]. Moreover, the coarse fiber content (C_{Fc}) in tropical fibrous peat can lead to a nearly linear e vs. log t curve (as shown in Figure 2), indicating apparent fiber reinforcement [15, 16]. Consequently, the Terzaghi consolidation theory is not fully applicable to peat, particularly tropical fibrous peat.



(a) (b)

Figure 1. Compression behavior of tropical fibrous peat in Riau (F_c = 45.83% and C_{Fc} = 34.5%): a. (e) vs. log σ’; b. (e) vs. log (t) [25]

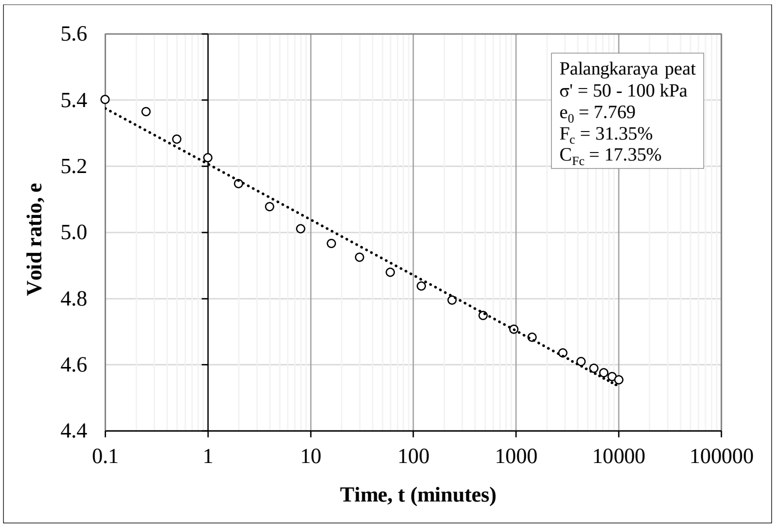


Figure 2. Influence of apparent fiber reinforcement on (e) vs. log (t) curves under load-increment test

To address these issues, the conventional single-load consolidation test serves as an alternative method to represent the e vs. log t curves of tropical fibrous peat [26]. Using this consolidation method, the compression parameter of peat can be determined with the Gibson & Lo [27] model, which was first introduced by Edil & Dhowian [21]. However, this test is typically time-consuming and costly, requiring five days to establish the time-compression relationship under a single load. Moreover, applying a significant load at once can cause a sudden impact that potentially disrupts the specimen due to an undrained condition.

To avoid sudden impact loads, it is preferable to conduct consolidation tests on soft soils, such as peat, using a continuous loading method that begins with a very small stress or strain, rather than an abrupt load application [28]. Among continuous loading techniques, the Constant Rate of Strain (CRS) consolidation test is notably advantageous. The CRS test method was first introduced by Hamilton and Crawford [29] as a rapid method to determine pre-consolidation stress (σ'_{pc}) and the e vs. log σ' curve for clay. This method maintains a constant rate of vertical displacement (or constant strain rate) on the saturated specimen while continuously measuring and recording pore-water pressure, load, and displacement. As a result, the CRS test provides a comprehensive set of stress-compression data in about two days for clay [30] and within a few hours for peat [31].

Despite the advantages of the CRS test over the conventional Oedometer test, its application is limited, particularly for tropical fibrous peat, due to several factors outlined below:

- The CRS test requires a minimum excess pore-water pressure to develop at the bottom of tested specimen to ensure consistent compression results [28, 31, 32]. Consequently, each soil type has a specific range of strain rates required to meet this condition, depending on its permeability. For cohesive soils, ASTM D4186 [33] suggests that the maximum ratio of excess pore-water pressure at the base of the specimen to the vertical total stress (u_b/σ) be maintained between 3% and 15% for reliable measurements. This limit can be achieved by applying a minimum strain rate of 0.167%/min (10%/h) for silt with high plasticity (MH), 0.017%/min (1%/h) for clay with low plasticity (CL), and 0.002%/min (0.1%/h) for clay with high plasticity (CH). Unfortunately, since the permeability of tropical fibrous peat varies significantly depending on its fiber content (i.e., sapric, hemic, and fibric) and coarse fiber content (C_{Fc}), the application of maximum u_b/σ limit suggested in ASTM D4186 [33] to obtain appropriate strain rate is not applicable to tropical fibrous peat.
- The presence of coarse fibers in tropical fibrous peat can lead to an apparent fiber reinforcement effect, resulting in unique compression behaviors [15, 16]. This behavior may complicate the analysis of CRS test results.
- The secondary compression index (C_α), an essential parameter for predicting long-term compression in tropical fibrous peat, cannot be directly obtained from the CRS test due to the inability of the test apparatus to maintain a constant load for establishing the secondary compression gradient [34]. Consequently, CRS tests on peat have mainly been conducted only to complement results obtained from conventional Oedometer tests [31, 35].

Based on the challenges discussed above, an improved-CRS test apparatus was developed that can measure vertical displacement under constant load. Using this improved-CRS test apparatus, therefore, the assessment of long-term compression behavior (primary and secondary compression) in the laboratory can be conducted in a short period without disrupting the specimen. Using this apparatus, this study aims to establish appropriate strain rates for tropical fibrous peat to assess accurate primary and secondary compression parameters. Undisturbed specimens, including reconstituted specimens (sapric, hemic, and fibric), were used to conduct improved-CRS consolidation tests and conventional Oedometer tests.

2. Research Methodology

Figure 3 illustrates the workflow diagram of the research methodology in this study. In general, there are three stages to reach the goal of this study, as detailed below:

- Material preparation (shown in the blue box);
- Consolidation test (shown in the green box);
- Data analysis (shown in the orange box).

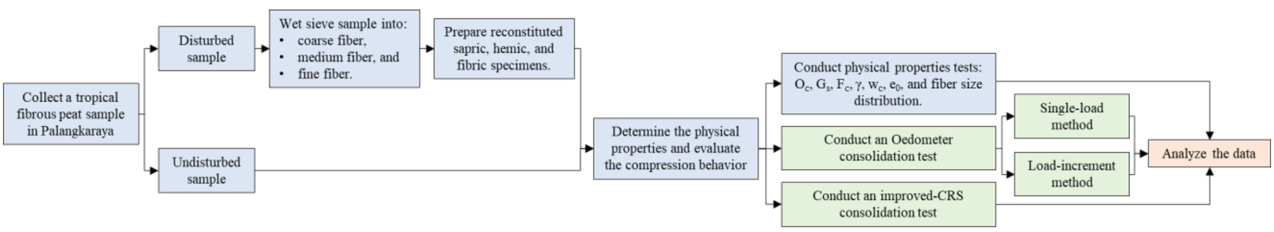


Figure 3. Workflow diagram of research methodology

2.1. Material Preparation

This study used tropical fibrous peat taken from Bereng Bengkel Village in Palangkaraya, Central Kalimantan, Indonesia. Figure 4 shows the documentation captured during sample collection. Samples of tropical fibrous peat, both undisturbed and disturbed, were collected from a depth of 1 meter beneath the peat surface. The undisturbed specimens were stored in sealed tubes to preserve their natural moisture content. The reconstituted specimens were made in the laboratory by sieving the disturbed sample using Standard Sieve No. 8 and No. 20 to segregate the peat into coarse fibers (retained on Sieve No. 8), medium fibers (retained on Sieve No. 20), and fine fibers (passing through Sieve No. 20). Subsequently, the reconstituted sapric, hemic, and fibric specimens, with different ranges of fiber content (F_c), were made using the following compositions:

- Reconstituted sapric specimen ($F_c < 33\%$) consists of fine fiber.
- Reconstituted hemic specimen ($33\% \leq F_c \leq 67\%$) consists of medium fiber.
- Reconstituted fibric specimen ($F_c > 67\%$) consists of medium and coarse fiber.

Figure 4. Tropical fibrous peat collection in Palangkaraya: a. surface stripping, b. disturbed sample collection

All reconstituted samples were encased in steel tubes and subjected to compression to achieve a unit weight (γ) comparable to that of the undisturbed specimens, approximately 10 kN/m³. The water content (w_c), organic content (O_c), and ash content (A_c) were assessed following ASTM D2974-20 [36]. The fiber content (F_c) was assessed following ASTM D1997-20 [37]. The specific gravity (G_s) and fiber size distribution were assessed following the Peat Testing Manual [38].

The physical properties of the undisturbed and reconstituted specimens, presented in Table 1, indicate that the reconstituted sapric, hemic, and fibric specimens meet the fiber content requirements specified in ASTM D4427 [5]. The foreign materials (≥ 2 cm), coarse fibers, and medium fibers after oven drying of the peat sample are shown in Figure 5. This visual observation indicates that the parent material of the studied peat predominantly consists of woody materials. According to ASTM D4427 [5], the undisturbed specimen is classified as sapric peat ($F_c < 33\%$) with low ash content ($A_c < 5\%$) and moderate water absorbency ($300\% < w_c < 800\%$).

Table 1. Physical properties of tropical fibrous peat studied

No.	Type of Sample	O_c (%)	A_c (%)	G_s	F_c (%)	γ (kN/m³)	w_c (%)	e_0	Fiber Size Distribution (%)			
									Foreign materials	Coarse	Medium	Fine
1	Undisturbed Peat	99.48	0.52		31.35	10.63	612.48	10.874	1.72	17.35	13.95	66.97
2	Reconstituted Peat											
	• *Sapric ($F_c < 33\%$)*	99.32	0.68	1.41	24.71	10.25	455.14	6.645	0.00	0.00	0.28	99.72
	• *Hemic ($33\% \leq F_c \leq 67\%$)*	99.31	0.69		47.52	10.15	468.44	6.912	0.00	27.78	10.94	61.28
	• *Fibric ($F_c > 67\%$)*	99.46	0.54		75.18	9.76	680.42	10.292	0.00	37.00	27.31	35.68

(a)

(b)

(c)

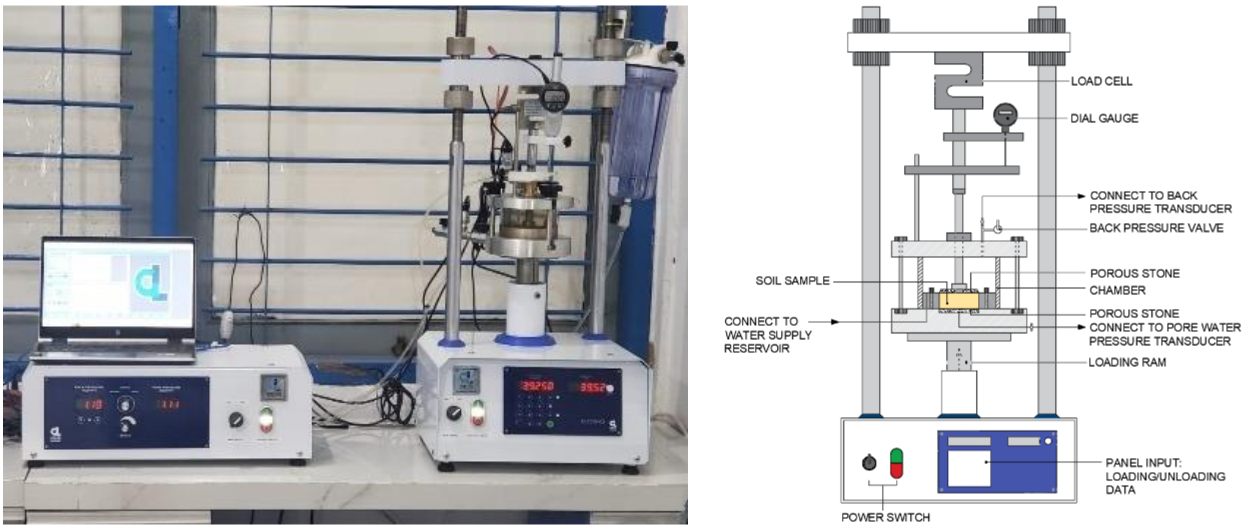
Figure 5. Oven-dried undisturbed sample after wet sieving analysis: (a). Foreign materials, (b). Coarse fibers, (c). Medium fibers

2.2. Consolidation Test

A series of conventional Oedometer test and improved-CRS consolidation tests were conducted on the undisturbed and reconstituted specimens. Conventional Oedometer tests, including the load-increment method and the single-load method, were conducted to validate the shape of the normalized void ratio (e/e_0) vs. log σ' and normalized void ratio (e/e_0) vs. log t curves obtained from the improved-CRS tests. The procedures for the load-increment method followed ASTM D2435 [39]. Each specimen was subjected to incremental loadings from 12.5 kPa to 200 kPa, with a load increment ratio (LIR) of 1. Meanwhile, single-load tests were conducted by applying a load of 200 kPa to the specimen, and compression was monitored over one week.

To determine the appropriate strain rates for each fiber content, at least four specimens with the same fiber content were subjected to different strain rates. Each specimen was subjected to a constant strain rate until it reached the final vertical total stress of 200 kPa. Subsequently, the specimen was subjected to a constant load for one day to obtain the secondary compression curve.

The schematic of the improved-CRS consolidation apparatus used in this study is illustrated in Figure 6. The specifications for the apparatus components, including the axial load transducer, back pressure transducer, pore water pressure transducer, and displacement gauge, are in accordance with ASTM D4186 [33]. The saturation process is conducted solely through the back pressure valve.



(a) (b)

Figure 6. Improved-CRS test apparatus: a). Photo, b). Schematic

Several improvements to the CRS test apparatus developed in this study (referred to as the improved-CRS) are detailed as follows:

- Allows setting the targeted vertical total stress value to facilitate the application of load comparable to that used in the field.
- Enables the setting of the targeted duration of the constant load.
- Automatically switches from loading at a constant strain rate to loading at a constant load mode once the targeted vertical total stress is reached.
- Automatically switches to unloading mode after the targeted constant load phase has been thoroughly monitored.

2.3. Data Analysis

Based on the data obtained from the improved-CRS consolidation test and the Oedometer test, several analytical steps were performed as follows:

1. Evaluate the effect of fiber content (F_c) and coarse fiber content (C_{Fc}) on the generation of u_b.
2. Assess the applicability of u_b/σ limit suggested in ASTM D 4186 for tropical fibrous peat.

3. Analyze the effect of constant strain rate to:
   - The gradient of primary compression curves,
   - The coefficient of consolidation (c_v), and
   - The gradient of secondary compression curves
4. Determine the appropriate strain rates for tropical fibrous peat.

By using the appropriate strain rate, accurate compression parameters such as primary compression index (C_c), coefficient of consolidation (C_v), and secondary compression index (C_α), can be directly obtained from the improved-CRS consolidation test.

3. Results and Discussion

The fiber characteristics of tropical fibrous peat play a significant role in the generation and dissipation of excess pore-water pressure during the loading phase of the CRS test. This behavior is quantitatively represented by excess pore-water pressure developed at the base of the specimen (u_b), calculated as the difference between pore-water pressure reading during load application to the specimen and the pore-water pressure reading before loading began. It should be noted that the excess pore-water pressure in the field is the difference between pore-water pressure developed after load application and hydrostatic pressure. In CRS test, the increase in the u_b value during loading at a constant strain rate is essential for determining the coefficient of consolidation (C_v). However, a significant increase in u_b over a short period indicates that the specimen is experiencing undrained conditions, leading to an inaccurate primary compression index (C_c). Since the tropical fibrous peat typically consists of coarse fibers (woody materials), which exhibit different characteristics compared to the coarse fiber found in Sphagnum moss peat, it is important to discuss:

- The effect of fiber content (F_c) and coarse fiber content (C_{Fc}) on the generation of u_b;
- The applicability of the maximum u_b/σ ratio between 3% and 15%, as outlined in ASTM D4186 [33], for determining an appropriate strain rate for tropical fibrous peat;
- The effect of strain rate on the gradient of primary compression curves;
- The effect of strain rate on coefficient of consolidation (C_v); and
- The effect of strain rate on the gradient of secondary compression curves.

3.1. Effect of Fiber Content (F_c) and Coarse Fiber Content (C_{Fc}) on The Generation of u_b

The excess pore water pressure at the base of the specimen (u_b) is used to calculate the effective stress (σ') and is a critical parameter for determining the coefficient of consolidation (C_v) values. The relationships between these parameters are defined by the following equations, according to ASTM D4186 [33]:

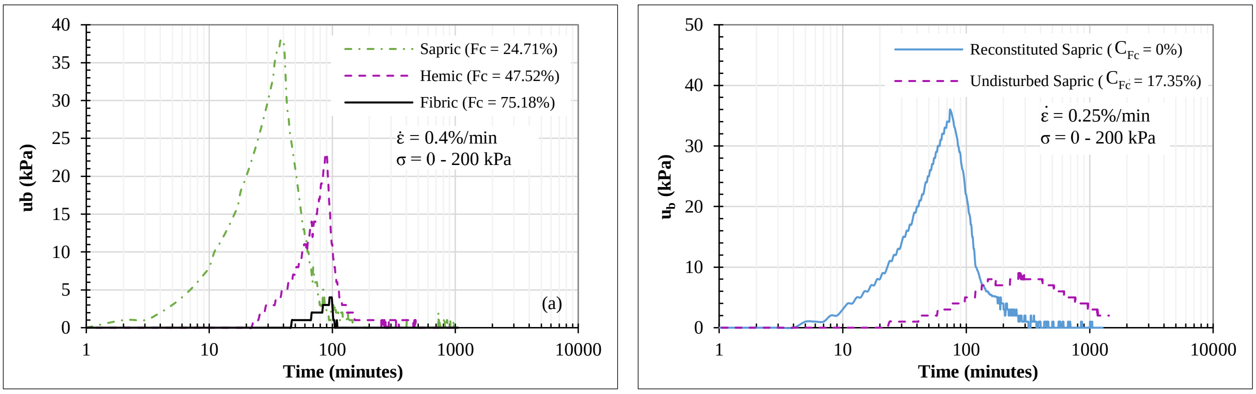
$$\sigma'_n = \left(\sigma_n^3 - 2\,\sigma_n^2\, u_{b,n} + \sigma_n\, {u_{b,n}}^2\right)^{1/3} \tag{1}$$

$$C_{v,n} = -\frac{H_n H_0 \log\left[\frac{\sigma_{n+1}}{\sigma_{n-1}}\right]}{2(t_{n+1}-t_{n-1})\log\left[1-\frac{u_{b,n}}{\sigma_n}\right]} \tag{2}$$

where σ is vertical total stress, u_b is the excess pore-water pressure at the base of the specimen, H is specimen height, H_0 is the initial specimen height, t is time, subscript n denotes the given time of data, subscript (n+1) denotes the next time of data, subscript (n–1) denotes the previous time of data.

A small u_b value is suggested during the CRS test to ensure uniform consolidation of the specimen and allow for an accurate determination of the coefficient of consolidation [31, 32]. It is important to note that reconstituted (sapric, hemic, and fibric) and undisturbed specimens, due to differences in their fiber content (F_c) and coarse fiber content (C_{Fc}), may exhibit varying responses to u_b. Consequently, each specimen type needs to be evaluated individually to account for the distinct variations in their response to u_b value.

Figure 7 shows the generated u_b values during the loading phase (both under constant strain rate and under constant load conditions) of tropical fibrous peat. Generally, the u_b value increases under constant strain rate loading until it reaches a peak, indicating that the specimen has reached the targeted vertical total stress of 200 kPa. Following this peak, the u_b value decreases as the specimen transitions to a constant load. The figure demonstrates that the applied strain rate ($\dot{\varepsilon}$), fiber content (F_c) and coarse fiber content (C_{Fc}) influence both the maximum u_b value and the time required to reach it.



(a) (b)

Figure 7. Excess pore-water pressure at base of the specimen (u_b) generated during the CRS test: a. At different fiber content (F_c), b. At different coarse fiber content (C_{Fc})

The influence of fiber content (F_c) on u_b generation is shown in Figure 7-a. The data indicate that higher F_c results in a lower maximum u_b value and extends the time required to reach the peak of u_b value. For example, when reconstituted specimens are loaded at a strain rate of 0.4%/min, the observed maximum u_b values are 38 kPa, 23 kPa, and 4 kPa for reconstituted sapric, hemic, and fibric specimens, respectively. These maximum values are attained within 40 minutes for reconstituted sapric, 90 minutes for reconstituted hemic, and 99 minutes for reconstituted fibric specimens. This behavior suggests that an increased F_c of 50.44% accelerates the dissipation of excess pore-water pressure at the top of the specimens during constant strain rate loading, reducing the u_b value up to 89.47% and doubling the time required to reach the maximum u_b value. Consequently, higher F_c requires a higher strain rate to achieve comparable u_b value.

Figure 7-b illustrates the influence of coarse fiber content (C_{Fc}) on the generation of u_b. The undisturbed (sapric) and reconstituted sapric specimens were loaded at a strain rate of 0.25%/min. Although both specimens are classified as sapric peat (F_c < 33%), the reconstituted specimen contains no coarse fiber (C_{Fc} = 0%), while the undisturbed specimen consists of 17.35% coarse fiber. The figure indicates that the presence of coarse fibers significantly reduces the ability of the specimens to generate u_b. Specifically, an increase of 17.35% in coarse fiber content in sapric peat reduces the maximum u_b value by approximately 77.78% compared to sapric peat without coarse fiber content. It also causes the maximum u_b value for the undisturbed specimen to be reached over a longer period than for reconstituted sapric specimen. This behavior suggests that the presence of coarse fibers has a greater influence on generating u_b than the fiber content alone. Therefore, it is recommended that the strain rate selection in CRS test be based on coarse fiber content (C_{Fc}).

3.2. Applicability of u_b/σ Limit Suggested in ASTM D 4186 for Tropical Fibrous Peat

As previously mentioned, the applied strain rate must fall within a maximum u_b/σ ratio in the range of 3% to 15% to obtain a consistent compression curve. The maximum u_b/σ values for undisturbed and reconstituted specimens are shown in Figure 8. The effect of fiber content (F_c), coarse fiber content (C_{Fc}), and strain rate ($\dot{\varepsilon}$) on u_b/σ is evaluated as follows:

- For the same values of F_c and C_{Fc}, the maximum u_b/σ tends to increase as the strain rate applied to load the specimens increases. The specimen's ability to develop u_b/σ is comparable to its ability to generate u_b.
- An increase in F_c and C_{Fc} values leads to a decrease in the maximum u_b/σ, even when the specimens are loaded at the same strain rate. For example, when the specimens are loaded at strain rate of 0.4%/min, the maximum u_b/σ for sapric (F_c = 24.71%, C_{Fc} = 0%) is 46%, while the maximum u_b/σ for fibric (F_c = 75.15%, C_{Fc} = 37%) is 2.1%. Thus, an increase of 50.44% in fiber content and 37% in coarse fiber content results in a significant decrease of 43.9% in u_b/σ.
- Specimens with higher F_c and C_{Fc} values require higher strain rates to achieve the same maximum u_b/σ. For example, a maximum u_b/σ of approximately 24% is achieved when strain rates of 0.03%/min, 1.5%/min, and 4.0%/min are applied to load the sapric, hemic, and fibric specimens, respectively.

In general, achieving the suggested maximum u_b/σ range of 3% to 15% for tropical fibrous peat requires the application of slower strain rates. However, this would diminish the advantages of the CRS test as a rapid consolidation method. Therefore, the suggested maximum u_b/σ ratio for cohesive soils is not applicable to tropical fibrous peat. Consequently, the appropriate strain rates for tropical fibrous peat should be determined by comparing the consistency of compression curves between improved-CRS consolidation tests and conventional consolidation tests.

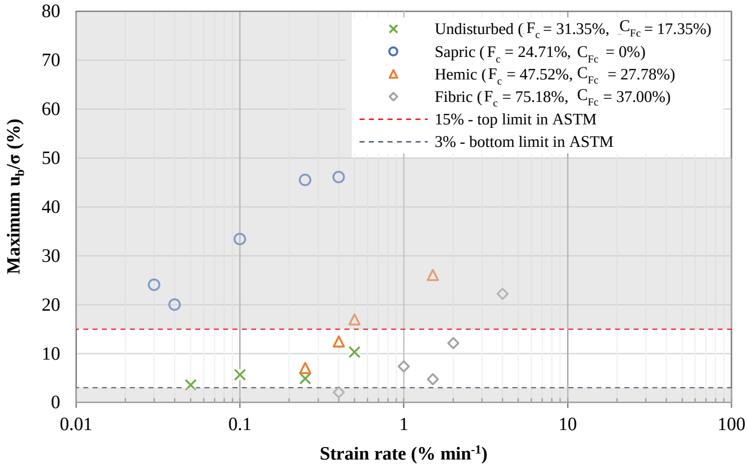


Figure 8. The influence strain rates on maximum ub/σ values of tropical fibrous peat studied

3.3. Effect of Strain Rate on the Gradient of Primary Compression Curves

The primary compression index (C_c) is determined from the gradient of normalized void ratio (e/e_0) vs. logarithmic effective stress (σ'). The e/e_0 vs. log σ' curves of tropical fibrous peat loaded at various strain rates, shown in Figure 9, indicate that the strain rate does not shift the curve to the right. In contrast, increased strain rates in cohesive soils typically shift the curve to the right in a parallel manner, causing the pre-consolidation stress to increase with increasing strain rates [40–43].

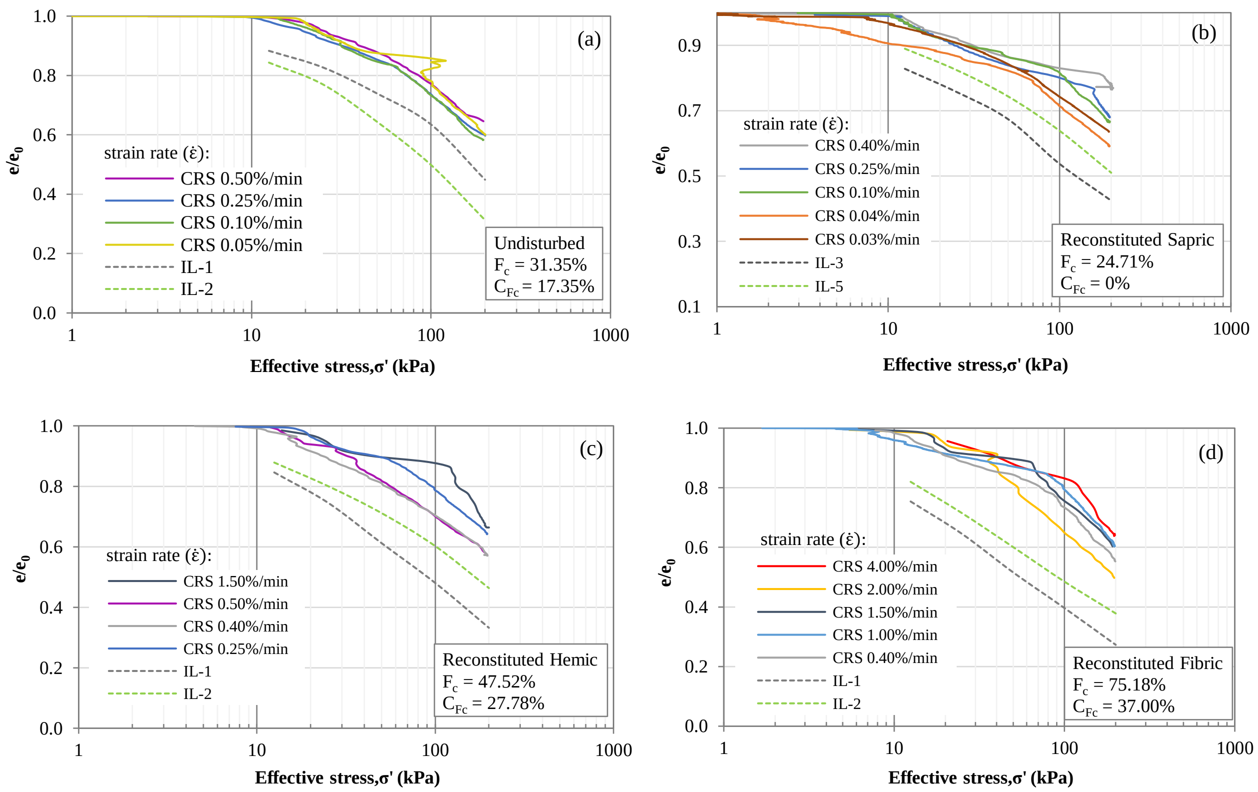


Figure 9. Comparison of the e/e0 versus σ' curve shapes obtained using CRS and conventional increment-load tests

Table 2 presents the strain rate that causes the e/e_0 vs. log σ' curve (shown in Figure 9) to yields a shape comparable to that of the conventional load-increment test (shown as a dashed line). The data indicate that an increase in F_c and C_{Fc} requires higher strain rates to obtain a comparable e/e_0 vs. log σ' curve to the conventional test. However, since C_{Fc} influences the generation of u_b more than F_c (as discussed previously), it is suggested that the appropriate strain rate for conducting the CRS test on tropical fibrous peat be selected based on its C_{Fc}, as presented in Table 3.

Table 2. Strain rate in the CRS test that yields a comparable primary compression curve shape to the

No.	Specimen Type	F_c (%)	C_{Fc} (%)	Strain rate range (% min^{-1})
1	Undisturbed peat	31.35	17.35	0.05 – 0.50
2	Reconstituted peat			
	• Sapric ($F_c < 33\%$)	24.71	0.00	0.03 – 0.04
	• Hemic ($33\% \leq F_c \leq 67\%$)	47.52	27.78	0.25 – 0.50
	• Fibric ($F_c > 67\%$)	75.18	37.00	0.40 – 4.00

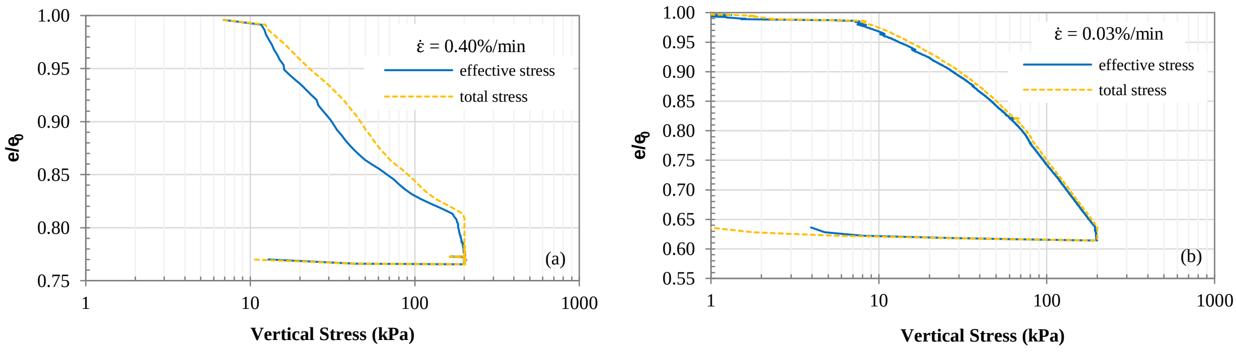
Table 3. Suggested strain rate for conducting the CRS test on tropical fibrous peat

No.	Coarse fiber content, C_{Fc}	Strain rate range (% min^{-1})
1	$C_{Fc} = 0$ %	0.03 – 0.04
2	$0\% < C_{Fc} \leq 17\%$	0.05 – 0.50
3	$17\% < C_{Fc} < 28\%$	0.25 – 0.50
4	$28\% \leq C_{Fc} \leq 37\%$	0.40 – 4.00

When conducting the CRS test on tropical fibrous peat, several factors should be considered if the e/e_0 vs log σ' curve exhibits noticeable deviations compared to the conventional load-increment test. These factors are as follows:

Undrained Conditions

The undrained conditions occur due to a significant increase in u_b over a short period under excessively high constant strain rate loading. These conditions can be evaluated by comparing the e/e_0 versus σ' curve and the e/e_0 versus σ curve, as shown in Figure 10. Under excessively high constant strain rates, the e/e_0 versus log σ' curve shows a concave shape, creating a horizontal gap between this curve and e/e_0 versus log σ curve, as illustrated in Figure 10-a. Undrained conditions also result in an inflection point observed in the later stages of loading, indicating that the targeted vertical total stress has been reached, but the vertical effective stress value is still lower than the targeted vertical total stress. Subsequently, increases in vertical effective stress occur as a result of a decrease in u_b under constant load (σ = 200 kPa). In contrast, Figure 10-b demonstrates that at lower strain rates, the e/e_0 versus log σ' and e/e_0 versus log σ curves for the reconstituted sapric specimen become nearly identical. This condition results in an e/e_0 versus log σ' curve that is comparable to that obtained from the conventional load-increment test.



(a) (b)

Figure 10. Effect of generated u_b on vertical effective and vertical total stress for reconstituted sapric specimens at strain rates of: a. 0.4%/min, b. 0.03%/min

Apparent Fiber Reinforcement

Apparent fiber reinforcement refers to the temporary ability of the coarse fibers (woody materials) in tropical fibrous peat to support the applied load [15, 16, 44]. This effect is observed in undisturbed specimens loaded at a strain rate of 0.05%/min (as indicated by the circled region in Figure 11). To confirm the effect of apparent fiber reinforcement, a visual inspection should be performed after the CRS test, as shown in Figure 11.

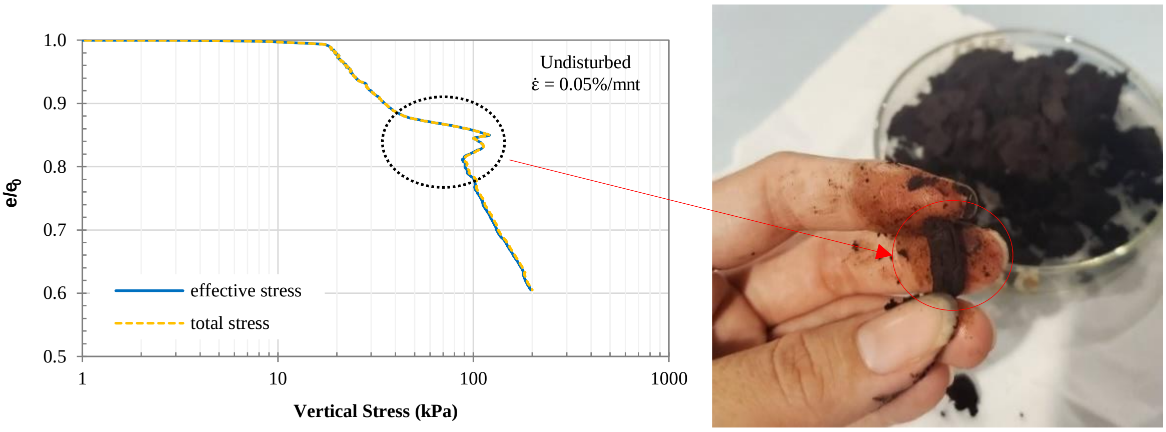


Figure 11. The effect of apparent fiber reinforcement on e/e_0 versus σ' curve

Influence of the Absence of Immediate and Secondary Compression

The influence of the absence of immediate compression (Δe_i) and secondary compression (Δe_α) is evaluated by comparing the e vs log t curve from the CRS test with that from the conventional load-increment test, as shown in Figure 12. The e vs log t curve in the CRS test, as illustrated in Figure 12-a, shows that during loading at a constant strain rate, the specimen is continuously subjected to a small strain rate, preventing the occurrence of immediate and secondary compression. The constant strain rate loading is then terminated when the targeted vertical total stress is achieved, as indicated by the onset of the inflection point. As a result, the e/e_0 versus log σ' curve obtained from the CRS test accurately represents the primary compression behavior.

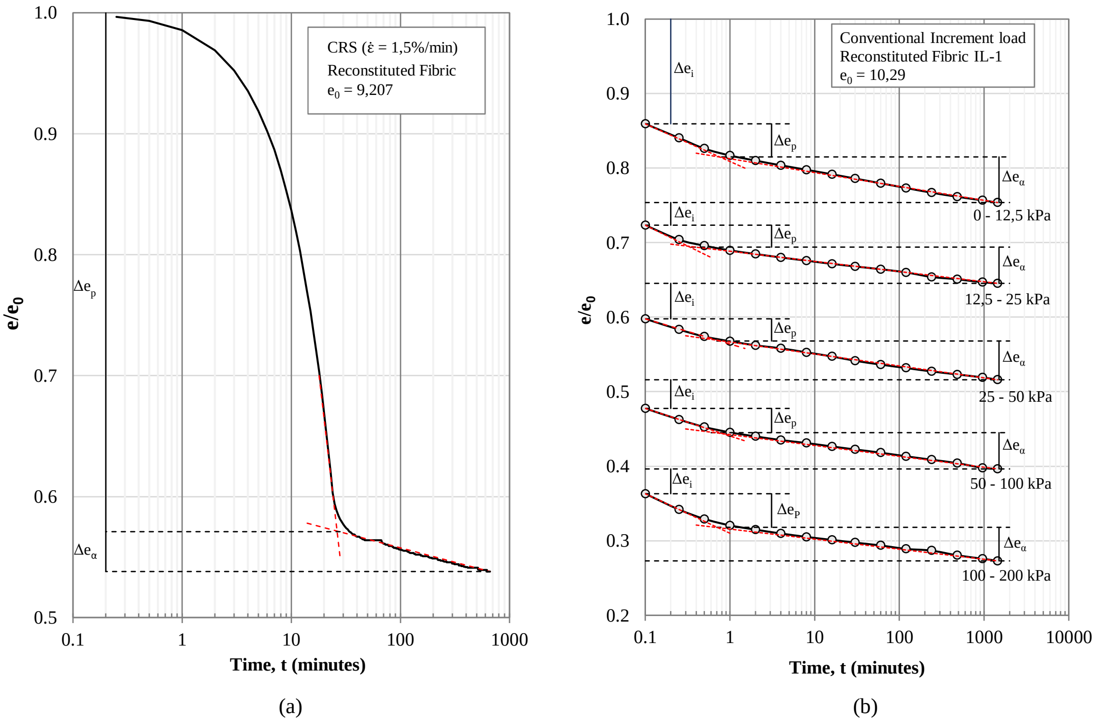


Figure 12. Compression phase occurs in: a). improved-CRS consolidation test; b). conventional load-increment test

In contrast, Figure 12-b shows that the conventional load-increment test exhibits both immediate and secondary compression at each load increment stage. Consequently, the short duration of primary compression (Δe_p) in the conventional test does not accurately represent the primary compression behavior of tropical fibrous peat. These conditions also correlate with the e/e_0 versus log σ' curves obtained from the CRS test for reconstituted fibric peat, which are composed of two distinct straight lines and are steeper than those observed in the conventional load-increment test (Figure 9-d). Therefore, under these conditions, the CRS test provides a more reliable estimate of C_c than the conventional load-increment test.

3.4. Effect of Strain Rate on Coefficient of Consolidation (C_v)

The coefficient of consolidation (C_v) is used to predict the progress of consolidation over time. Most procedures for determining C_v based on CRS test results are derived from the research conducted by Wissa et al. [45]. In this study, C_v is calculated using nonlinear solutions from ASTM D4186 [33], shown in Equation 2. This equation was developed by modifying the nonlinear solutions of Wissa et al. [45]. The relationships between the coefficient of consolidation (C_v) and vertical total stress (σ) for reconstituted specimens, as determined using the strain rates specified in Table 3, are illustrated in Figure 13. The data indicate that applying these strain rates to load the specimens results in the separation of C_v values into two conditions: the transient state and the steady state. The transient state, indicated by a high C_v value, occurs during the early stages of loading. During this state, the C_v value tends to increase as a higher strain rate is applied to load the specimens. Afterward, as vertical total stress increases, the C_v values gradually decrease until they reach a relatively constant value, indicating that the steady-state conditions have been achieved.

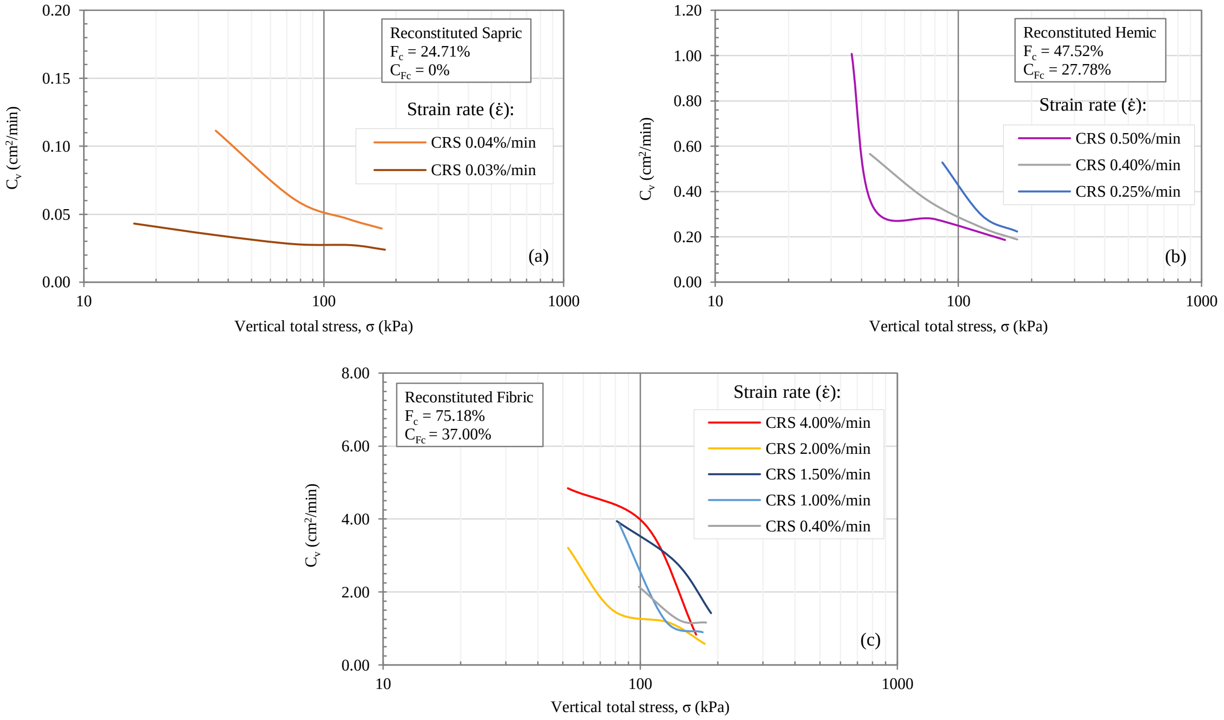


Figure 13. Behavior of the coefficient of consolidation (C_v) during vertical total stress (σ) increments

Once steady-state conditions are reached, the strain rates have no significant influence on the C_v values, resulting in similar C_v values. As a result, the influence of fiber content (F_c) and coarse fiber content (C_{Fc}) on the C_v value can be evaluated under this condition. As shown in Figure 13, the steady state is achieved at a vertical total stress (σ) of 200 kPa, resulting in average C_v values of 0.05 cm^2/min (2.63 m^2/year), 0.28 cm^2/min (14.72 m^2/year), and 1.02 cm^2/min (53.61 m^2/year) for reconstituted sapric, hemic, and fibric specimens, respectively. This pattern indicates that:

- An increase in fiber content (F_c) and coarse fiber content (C_{Fc}) increases the C_v value, causing the end of primary (t_p) to occur sooner;
- The C_v value of tropical fibrous peat is about 26 – 45 times higher than that of clay, where the C_v value of clay typically ranges from 0.1 to 1.2 m^2/year [46].

3.5. Effect of Strain Rate on the Gradient of Secondary Compression Curves

Figure 14 illustrates the normalized void ratio (e/e_0) versus logarithmic time (t) curve obtained from the improved-CRS consolidation test for both undisturbed and reconstituted specimens. The secondary compression index (C_α) is determined from the gradient of the secondary compression curves. As explained previously, compression under a constant load is recorded for approximately one day to obtain the secondary compression curve. The data demonstrates that the gradient of the secondary compression curves can be identified during this test period. The parallel gradients observed in both undisturbed and reconstituted specimens suggest that variations in strain rate do not influence the C_α value, as shown in Table 4.

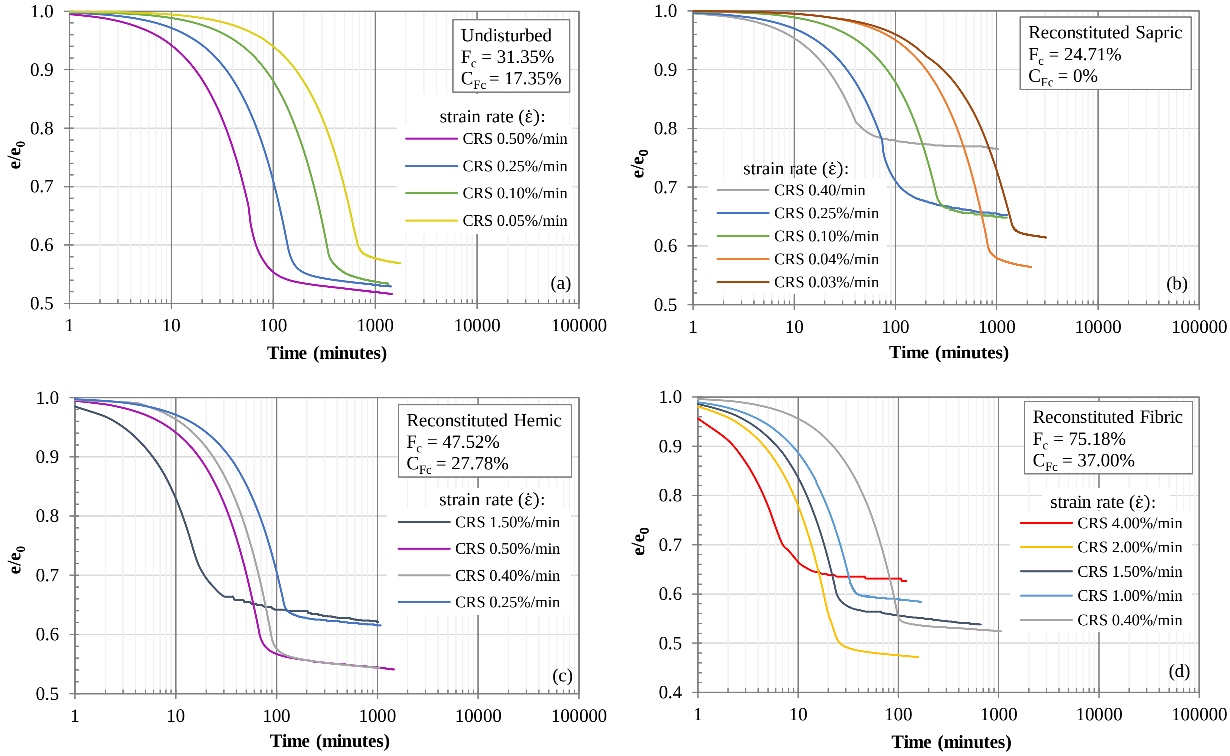


Figure 14. The e/e_0 vs log t curves in undisturbed and reconstituted specimens under various strain rates

Table 4. The determination of the end of primary (t_p) value based on improved-CRS consolidation test

Strain rate (1/min)	Undisturbed			Reconstituted sapric			Reconstituted hemic			Reconstituted fibric		
	t_p (min)	u_b/σ (%)	C_α	t_p (min)	u_b/σ (%)	C_α	t_p (min)	u_b/σ (%)	C_α	t_p (min)	u_b/σ (%)	C_α
4.00%										9	14.16	0.12
2.00%	-	-		-	-		-	-		23	7.87	0.19
1.50%	-	-		-	-		-	-		26	2.00	0.21
1.00%	-	-		-	-		-	-		35	4.51	0.16
0.50%	72	10.24	0.13	-	-		76	7.96	0.10	-	-	
0.40%	-	-		-	-		100	5.48	0.11	100	1.49	0.13
0.25%	170	3.89	0.15	90	21.99	0.11	120	6.01	0.10	-	-	
0.10%	400	4.90	0.11	270	8.58	0.09	-	-		-	-	
0.05%	700	2.45	0.18	-	-		-	-		-	-	
0.04%	-	-		820	6.06	0.11	-	-		-	-	
0.03%	-	-		1570	2	0.10	-	-		-	-	

The end of primary (t_p) parameter, presented in Table 4, is identified at the inflection point in the e/e_0 vs log t curves, which is essential for determining the C_α value. This parameter is determined using the method proposed by Casagrande & Fadum (1940) [47]. The data generally indicate that loading specimens at higher strain rates causes t_p to occur earlier, indicating a shorter duration of primary compression. Additionally, the u_b/σ value at t_p is reported in Table 4 to evaluate the applicability of the t_p determination method proposed by Mesri & Choi [48] and Mesri et al. [49], which assumes that t_p occurs when the u_b/σ value is approximately 2%. The data indicate that the u_b/σ values at t_p increase with strain rate for both undisturbed and reconstituted specimens, ranging from 1.49% to 21.99%. This variability suggests that the determination of t_p based on the u_b/σ value may not be appropriate for the tropical fibrous peat studied.

Figure 15 shows the gradients of secondary compression (C_α) in the e/e_0 vs log t/t_p curve obtained from the improved-CRS consolidation test, compared with those obtained from conventional single-load tests (shown as a dashed line). These data demonstrate that the gradients of secondary compression obtained from the CRS test are comparable to those from conventional single-load tests. This suggests that the C_α value can be directly obtained from the improved-CRS consolidation test apparatus used in this study.

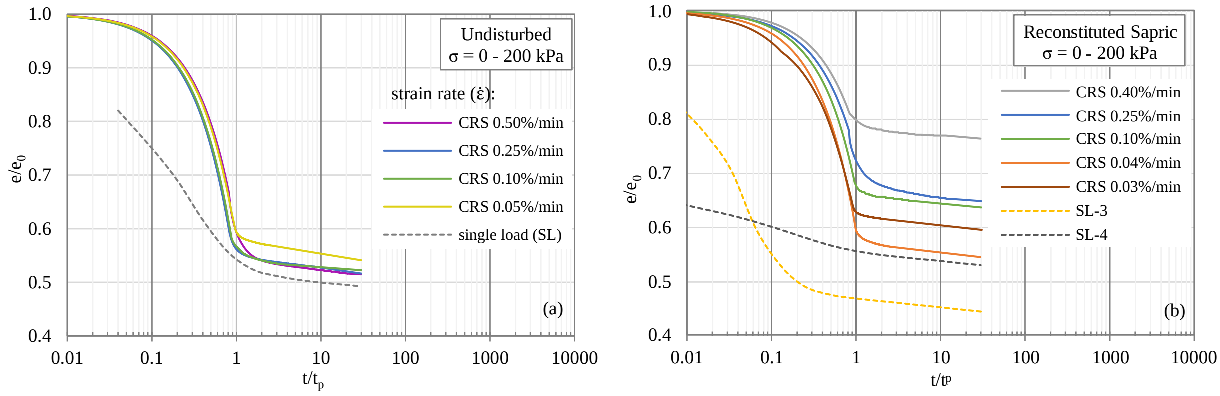


Figure 15. Comparison of e/e_0 versus logarithmic t/t_p relationship curves obtained using improved-CRS consolidation test and conventional Oedometer test apparatus

4. Conclusions

According to the experimental investigation of tropical fibrous peat conducted in this study, the following conclusions can be drawn:

- An increase of 50.44% in fiber content (F_c) in the tropical fibrous peat studied leads to a reduction in excess pore-water pressure at the specimen's base (u_b) by up to 89.47%. Meanwhile, a 17.35% increase in coarse fiber content (C_{Fc}) in sapric peat leads to a reduction in u_b to 77.78%. This indicates that:
  - C_{Fc} has more significant influence on the specimen's ability to generate u_b than F_c.
  - Specimens with higher C_{Fc} values should be loaded using higher strain rates to achieve appropriate u_b value.
- The application of the maximum u_b/σ ratio limit of 3%-15%, as suggested in ASTM D 4186 for cohesive soils, is not suitable for tropical fibrous peat. For tropical fibrous peat, the strain rates should be selected based on the coarse fiber content (C_{Fc}).
- The compression parameters (C_c, C_α, and C_v) of tropical fibrous peat can be obtained directly from the improved-CRS consolidation test results by using the suggested strain rates based on the coarse fiber content (C_{Fc}), as follows:
  - 0.03%/min to 0.04%/min for $C_{Fc} = 0\%$,
  - 0.05%/min to 0.5%/min for $0\% < C_{Fc} \leq 17\%$,
  - 0.25%/min to 0.5%/min for $17\% < C_{Fc} < 28\%$, and
  - 0.4%/min to 4.0%/min for $28\% \leq C_{Fc} \leq 37\%$.

5. Declarations

5.1. Author Contributions

Conceptualization, A.P., N.E.M., and I.B.M.; methodology, A.P.; validation, A.P.; investigation, A.P.; data curation, A.P.; writing—original draft preparation, A.P.; writing—review and editing, N.E.M.; supervision, N.E.M. and I.B.M. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

5.3. Funding

This research is supported and funded by the Indonesia Endowment Fund for Education Agency (LPDP) from the Ministry of Finance of the Republic of Indonesia (0001321/TRP/D/PDD-2020).

5.4. Conflicts of Interest

The authors declare no conflict of interest.

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