Hydraulic conductivity and compressibility characteristics of fibrous peat

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Abstract. This research was studying the mechanical characteristics of fibrous based on hydraulic conductivity/permeability and compressibility tests. The samples for the test were obtained by the block sampling method. The location of sampling was on Banyuasin Regency, South Sumatra. The permeability test using constant head method was used for hydraulic conductivity parameter of peat soil. And consolidation test using Oedometer test was also used to find out compressibility characteristics of peat soil. The hydraulic conductivity test results are horizontal hydraulic conductivity ($k_h$)=6.13x10^{-4} cm/s and vertical hydraulic conductivity ($k_v$) = 3.76.10^{-4} cm/s. The ratio of $k_h$/$k_v$ (20°C) about 2.04. The coefficient of $k_h$ is greater than $k_v$, this is due to the effect of fiber arrangement such as the roots of peat soil. Beside of that, the consolidated test results based on compression index parameters ($c_c$) are 1,428 and 1,215. The consolidation coefficient parameters ($c_v$, m\(^2\)/year) were 13,671 (50 kPa), 11,511 (100 kPa), 8,268 (200 kPa), and 3,312 (400 kPa) from the Banyu Urip Dusun III sample. The results of parameter $c_v$ can be affected by applied the pressure where the greater the pressure the smaller the value of $c_v$.

Keywords: hydraulic conductivity, compressibility, fibrous peat

1. Introduction

The hydraulic conductivity of the soil is a function of three components: (1) ground water pressure, (2) water content, and (3) soil moisture retention. The hydraulic conductivity of the soil is needed for understanding transport processes, water balance, and irrigation [1]. The hydraulic conductivity/permeability of peat is controlled by the original structure, engineering characteristics, high of decomposition, and density [2]. The results of hydraulic conductivity (k) of peat soil can be as sand: 10^{-5}-10^{-4} m/s.

The value of initial coefficient of vertical hydraulic conductivity from 10^{-5}-10^{-8} m/s [3]. The permeability of peat soil can be affected by mineral content, the presence of gas, degree of decomposition, chemistry, and void ratio. Previous researcher [4] reported the physical properties and
hydraulic properties of peat soil. The results of this research describe that peat soil impacted by the presence of soil pores so the permeability of peat soil is medium.

Two permeability testing methods are: (1) the falling head test method, and (2) the constant head test method. The falling head test method is used for soil types that are less permeable. If the soil belongs to a permeable type so the permeability test can be used constant head method. The peat soil is permeable. So the permeability testing for this soil suggested use constant head method. According to [5] the coefficient of vertical permeability \(k_v\) is \(5.86 \times 10^{-4}\) m/s and the coefficient of horizontal permeability \(k_h\) is \(8.19 \times 10^{-4}\) m/s. [6] reported fibrous peat have horizontal permeability \(k_h\) more than vertical permeability \(k_v\) from Ogan Ilir sample.

The hydraulic conductivity of the soil describes the nature of water flow through the soil. Parameters of hydraulic conductivity of the soil are commonly used to analyze seepage in construction eg: (a) sheet pile walls, (b) earth dams, (c) ponds, and (d) landfills.

Commonly, the permeability of the deposit decreases with increasing depth (decreasing void ratio), and the state of bio degradation [7]. From previous researcher stated that coefficient of horizontal permeability \(k_h\) usually more than in coefficient of vertical permeability \(k_v\) for fibrous peat [2].

The constant head method had been used in this research. A steady state head condition on permeability test using constant head method allows water to flow through the soil. The volume of flow water can be calculated based on period of time. Parameter of hydraulic conductivity (k) using constant head method has been calculated using the following equation:

\[
k = \frac{Q \cdot L}{A \cdot t \cdot h}
\]

Where \(Q\) = the volume of water discharged, \(A\) = the cross-sectional area, \(L\) = distance, \(h\) = the head difference, \(t\) = the total time of discharged.

Vertical coefficient hydraulic conductivity \(k_v\) can be evaluated from the results of consolidation test. The formula \(k_v\) is:

\[
k_v = c_v \cdot m_v \cdot \gamma_w
\]

Where, \(m_v\) is coefficient of volume compressibility and \(c_v\) is coefficient of rate of consolidation.

Furthermore, compressibility of clay soil characteristics is not same with fibrous peat soil. In fibrous peat soil, Compressibility generally consists of two processes: (1) primary consolidation, and (2) secondary consolidation. Several factors controlling the compressibility characteristics peat soil include water content, void ratio, the fiber content, and permeability. Peat soil parameters such as weight units have the same value as water.

The value of effective stress \((\sigma'_p)\) usually small. So at the time of consolidation testing, these parameters are sometimes difficult to analyze. In addition, to analyze parameters such as time of beginning of secondary compression \(t_p\) was also very difficult. This is because the consolidation process is usually occurs quickly. The parameters obtained from the consolidation test are: compression index \((c_c)\), coefficient of volume compressibility \((m_v)\), recompression index \((c_r)\), and coefficient of axial compressibility \((a_v)\).

The consolidation parameters can be determined from consolidation test (Oedometer test). The consolidation parameters such as: compression index \((c_c)\), the beginning of secondary compression \(t_p\), the time of secondary compression \(t_s\), the rate of secondary compression \(c_r\), and coefficient of rate of consolidation \(c_c\). The coefficient of rate of consolidation \(c_c\) for a particular pressure increment in Oedometer test can be determined by curve fitting methods. There are two methods commonly used to determine the value of \(c_c\) i.e. the logarithmic time (Cassagrande’s) method and the square root time (Taylor’s) method. These empirical procedures were developed to fit approximately the observed laboratory test data to the Terzaghi theory of consolidation. Figure 1 explained the analysis of the compression versus time curves from Oedometer test.
Published data on $c_c$ ranges from 2-15. [8] reported the decrease in $c_v$ with load during consolidation due to large reduction in permeability. Beside of that, [6] determined the results from Oedometer test such as: $c_c = 3.253$, $c_v = 2.074$ m$^2$/year (under consolidation pressure 25 kPa), and $c_v = 0.850$ m$^2$/year (under consolidation pressure 400 kPa).

![Figure 1. Analysis of the compression-time curves from oedometer test](image1)

There are two types of samples are undisturbed samples and disturbed samples. Undisturbed samples can be obtained at shallow depth by block sampling method (ASTM D 7015-04). In this research, undisturbed block samples had been used to determine the hydraulic conductivity/permeability and compressibility characteristics of fibrous peat.

2. Methodology
Mechanical characteristics evaluated in this research were hydraulic conductivity/permeability and compressibility of fibrous peat soil. The samples of the fibrous peat were taken from Banyuasin regency, South Sumatera, Indonesia. The location of hydraulic conductivity samples are hydraulic conductivity KTM Telang Mulya Sari, Dusun I Banyu Urip, Dusun III Banyu Urip, and Desa Gasing Tanjung Api-Api. And the locations of compressibility samples are Dusun I Banyu Urip and Dusun III Banyu Urip. Figure 2 shows the location of peat soil sampling.

![Figure 2. Location of sampling](image2)

In this research, the block sampling method had been selected. The size of tube for the test Consolidation test are diameter $(D) = 15$ cm diameter and height $(h) = 30$ cm). Beside of that, the size of tube for the test hydraulic conductivity/permeability test are diameter $(D) = 15$ cm diameter and height $(h) = 15$ cm). Hydraulic conductivity measurements were carried out on a sample using constant head method. Parameter of horizontal permeability $(k_h)$ and vertical permeability $(k_v)$ obtained from this method. The following is the procedure of examination of hydraulic conductivity of peat soil in accordance with ASTM D 2434-68 standard.

Hydraulic conductivity testing conducted in laboratory of soil mechanic of Civil Engineering Department of the Polytechnic Sriwijaya Palembang. The sample of permeability test height $(H) = 93.5$
cm high by permeameter test tube (L) 15 cm. The temperature will increase the viscosity decrease and increase permeability. Standard temperature in determining the permeability coefficient is 20˚C. The parameters results from hydraulic conductivity test such as vertical coefficient of hydraulic conductivity \( k_v \) and horizontal coefficient of hydraulic conductivity \( k_h \). From the results of consolidation testing, permeability parameters will be obtained \( k_v \).

Moreover, the parameters of compressibility of peat soil characteristics can be estimated by consolidation testing (Oedometer test). Consolidation tests at laboratory of soil mechanic Department of Civil Engineering Department of Universitas Sriwijaya. Procedures on consolidation testing according to ASTM D 2435-96 standard. Sample size on Oedometer test were sample height (h) = 2 cm and sample diameter (d) = 5 cm. The load increment ratio (LIR) in this test was one. As well as the pressure (P, kPa) given in the test were 50, 100, 200, and 400. At each load given for one sample will be maintained for two weeks (based on standard). But in this tests, changed to for 1 week. The time intervals had been used during the reading of test data were as follows (minutes): 0.25, 0.50, 1, 2, 8, 15, 30, 60, 120, 240, 480, 1440, 2880, 4320, 5760, 7200, 8640, and 10080. The number of samples for one location is 6 samples.

There are two relationship curves can be analyzed from consolidation test results. The first curves of the relationship between time and compression. The second curve is the relationship between the void ratio and the logarithmic pressure \( (e \text{-log } p') \). Based on the logarithmic curve of time-compression curve methods, the compression parameter of the coefficient of rate of consolidation \( (c_v) \) is obtained. The methods had been used to obtain the parameter were (1) the square root time method (Taylor’s), and (2) the logarithmic time method (Cassagrande’s). The compressibility parameters derived from other consolidation tests such as: (a) the beginning of secondary compression \( (t_p) \), (b) the time of secondary compression \( (t_s) \), (c) the rate of secondary compression \( (c_s) \), and (d) compression index \( (c_i) \).

3. Results and discussion

Soil properties testing and peat soil classification have been done in this research. The results of this test were taken from previous researcher. Table 1 presented the average results of index properties, and classification tests from Banyuasin regency. The average water content \( (\omega) \) obtained from laboratory tests is 258.100 %. The value of average specific gravity \( (G_s) \) obtained 1.80. The average organic content of peat is found at 78.70 % and the average fiber content 73.60 %. According to Von Post scale, peat soils are classified as fibrous peat. Based on Von Post, the degree of decomposition was \( H_4 \) scale. While, the classification of peat based on ASTM D 4427-84 is highly acidic. If compared with the results of previous research, all the results of the index properties and classification on peat soils result is still in range of publication data.

| No. | Parameter          | Range published data | Average results |
|-----|--------------------|-----------------------|-----------------|
| 1.  | Water Content \( (\omega) \) | 200-700 %            | 258.100 %       |
| 2.  | Acidity \( (pH) \)     | 3.0-4.5               | 3.26            |
| 3.  | Specific Gravity \( (G_s) \) | 1.38-1.90            | 1.80            |
| 4.  | Dry unit weight \( (\gamma_d) \) | -                    | 4.10 kN/m$^3$   |
| 5.  | Void Ratio \( (\varepsilon_0) \) | 3-15                 | 3.22            |
| 6.  | Organic Content \( (OC) \) | > 80 %                | 78.70 %         |
| 7.  | Fiber Content \( (FC) \)  | > 20 %                | 73.60 %         |
| 8.  | ASTM D 4427-84       | less than 4.5         | Highly acidic    |
| 9.  | Von Post             | \( H_1 - H_4 \)       | \( H_4 \)       |

The summary of permeability of peat soil showed in Table 2. And the value of coefficient hydraulic conductivity results from Dusun III Banyu Urip can be seen in Table 3. From the Table 2, the average of hydraulic conductivity coefficients from four locations were 3.76.10-4 cm/sec \( (k_v 20^\circ) \).
and 6.13.10^-4 cm/sec ($k_h$). Dusun I Banyu Urip has the highest value pore size that is equal to 1470 nm according to Scanning Electron Microphotograph (SEM) analysis and also has the highest of void ratio value that is 3.445.

Because if pore size is large and void ratio is high then the value of permeability coefficient is high too. Therefore, peat soil classification was categorized having medium hydraulic conductivity. With this behaviour, it can be conclude that peat soil has good drainage. Figure 3 and 4 shows the graph horizontal hydraulic conductivity ($k_v$ and $k_h$) with hydraulic gradient ($i$).

### Table 2. The summary of hydraulic conductivity of peat soil

| Parameter (average) | KTM Telang Mulya Sari | Dusun I Banyu Urip | Dusun III Banyu Urip | Desa Gasing Tanjung Api-Api |
|---------------------|------------------------|--------------------|----------------------|-----------------------------|
| $k_v$ (cm/s).10^-4  | 6.07                   | 3.40               | 3.10                 | 4.52                        |
| $k_v$ (cm/s) 20°C.10^-4 | 5.28                   | 2.92               | 2.86                 | 3.96                        |
| $k_h$ (cm/s).10^-4  | 8.40                   | 6.68               | 6.80                 | 7.04                        |
| $k_h$ (cm/s) 20°C.10^-4 | 7.07                   | 5.69               | 5.86                 | 5.91                        |

**Figure 3.** Vertical hydraulic conductivity ($k_v$) versus hydraulic gradient ($i$) from Dusun III Banyu Urip sample

**Figure 4.** Horizontal hydraulic conductivity ($k_h$) versus hydraulic gradient ($i$) from Dusun III Banyu Urip sample
Based on the research of [7], the values of the coefficient of hydraulic conductivity for biodegraded (H₄) peat material was $10^{-9}$-$10^{-10}$ m/s. This result is lower than the value in the field. The calculated hydraulic conductivity coefficient was founded comparative to the effective stress on a logarithmic plot. [5] reported the range of value permeability coefficient were $k_v = 5.30 \times 10^{-4}$-$6.24 \times 10^{-4}$ cm/sec and and $k_h = 7.14 \times 10^{-4}$-$9.93 \times 10^{-4}$ cm/sec. The coefficient of permeability based on [14] were $k_v = 2.99 \times 10^{-4}$ cm/sec (depth 6.2-6.4 m) and $k_h = 6.88 \times 10^{-4}$ cm/sec (depth 8.8-9.0 m). The result of permeability coefficient from the present study is greater than previous researcher.

The standar procedures outlined in ASTM D 2435-96. This test was carried out to establish the preliminary estimation of the possible response of the peat to loading. Typical logarithmic of time compression curve derived from the consolidation test is shown in Figure 5. It can be observed from the figure that the primary consolidation is still dominant in the compression of the peat, but the consolidation occur in relatively shorter time.

Consolidation parameters obtained by using Cassagrande’s method based on the time-compression curves were: (a) the end of primary consolidation ($t_s$), (b) the coefficient of secondary compression ($c_v$), (c) the end of secondary compression ($t_v$), and (d) the coefficient of rate of consolidation ($c_s$). The average value of the coefficient of rate of consolidation ($c_s$) for each pressure show in Table 4.

### Table 3. Hydraulic conductivity results from Dusun III Banyu Urip

| Parameter          | H (cm) | L (cm) | i | T (°C) | ηT (g/cm.s) | Q (cm³) | T (s) | $k_v$ (cm/s) | $k_h$ (cm/s) | $k_{20}$ (cm/s) |
|--------------------|--------|--------|---|--------|-------------|---------|-------|--------------|--------------|----------------|
| Vertical Hydraulic |        |        |   |        |             |         |       |              |              |                |
| conductivity ($k_v$) | 93.5   | 15     | 6.233 | 26    | 0.00874     | 250     | 3578.82 | 2.54          | 2.21          |                |
| Horizontal Hydraulic | 93.5   | 15     | 6.233 | 26    | 0.00874     | 250     | 4116.00 | 2.21          | 1.92          |                |

### Table 4. The average value of $c_v$ for each pressure

| Pressure ($p'$, kPa) | Dusun I Banyu Urip | Dusun III Banyu Urip | Dusun I Banyu Urip | Dusun III Banyu Urip |
|----------------------|--------------------|----------------------|--------------------|----------------------|
| 50                   | 12.260             | 13.671               | 18.048             | 18.098               |
| 100                  | 9.725              | 11.511               | 10.271             | 8.615                |
| 200                  | 8.425              | 8.268                | 8.911              | 7.226                |
| 400                  | 5.322              | 3.312                | 3.318              | 3.086                |
Table 5. Results of consolidation test based on Cassagrande’s Method

| Parameter                              | Pressure (\(p', \text{kPa}\)) | Cassagrande’s Method |
|----------------------------------------|---------------------------------|-----------------------|
|                                        | Dusun I Banyu Urip | Dusun III Banyu Urip |
| End of primary consolidation (\(t_{100} = t_p\), minutes) | 50 | 50 | 55 |
|                                        | 100 | 36 | 44 |
|                                        | 200 | 29 | 31 |
|                                        | 400 | 24 | 20 |
| Coefficient of secondary compression (c) | 50 | 0.064 | 0.114 |
|                                        | 100 | 0.135 | 0.212 |
|                                        | 200 | 0.248 | 0.376 |
|                                        | 400 | 0.119 | 0.187 |
| End of secondary compression (\(t_s\), minutes) | 50 | 2613 | 4025 |
|                                        | 100 | 2058 | 2825 |
|                                        | 200 | 1800 | 2183 |
|                                        | 400 | 1438 | 1800 |
| Compression Index (c_{ci})             | 1.428 | 1.215 |

Table 5 described the compressibility parameters obtained from consolidation curves. Figure 6 shows the results of analysis based on Cassagrande’s method. Figure 7 is an analysis of Taylor’s method. Figures 6 and 7 were taken from the location of Dusun III Banyu Urip sample. The coefficient of rate of consolidation (\(c_v\), \(m^2/\text{year}\)) based on Cassagrande’s method from Dusun III Banyu Urip were 3.671 (50 kPa), 11.511 (100 kPa), 8.268 (200 kPa), and 3.312 (400 kPa).

Figure 6 (Cassagrande’s method) explains that the [9] had been studying the compressibility parameter. These study about reversed again organic peat soil in Khulna region (Bangladesh). The variation of the coefficient of rate of consolidation (\(c_v\)) with the increase of applied pressure for varying organic contents was evaluated. The value of coefficient of rate of consolidation (\(c_v\)) increases: 0.0135 to 0.1200 \(cm^2/s\) for the organic content of 35 % (consolidation pressure from 25 to 800 kPa). [12] show the results \(c_v\) decreases because of increasing consolidation pressure.
The value of $t_p$ is decreasing nonlinearly with the consolidation pressure. Beside of that, the average value of this $t_s$ versus pressure based on Table 5, also show the value of this $t_s$ is decreasing with the consolidation pressure. The average compression index ($c_c$) in the Dusun I Banyu Urip is 1.428. And the average $c_c$ in the location of Dusun III Banyu Urip is 1.215. The value obtained from the Oedometer test conducted on fibrous peat soil from Banyusin is slightly lower than published in the range 6-9 [8]. [10] reported the value of the compression index ($c_c$) was 2.68 for peaty soil from Parit Nipah Darat, Johor. This test uses the undisturbed sample and 1-D Oedometer consolidation tests.

High compression index ($c_c$) values explain that the settlement was also high. The compression index ($c_c$) parameter from consolidation test (Oedometer) has been performed by researchers [11]. The results of this test follow: (a) fibric ($c_c = 1,453-3,211$), (b) hemic ($c_c = 1,290-2,780$), and (c) sapric ($c_c = 1,150-2,440$). Based on the study literature, the range of values for $c_c$ is 5-10. Thus if this parameter compared with the study [11], then the $c_c$ result was smaller. The parameters of the coefficient of secondary compression ($c_{sc}$) were in the range of 0.08-0.09 for fibric, hemic and sapric peat soil. This range of values explains that at the time of the consolidation process, peat soil has high secondary compressibility.

Fiber orientation is identified as a principal factor in the structure of fibrous peat. The existence of the fiber induces the peat soil imperfections such as: rootlets, pockets, cracks, and fissures of organic material which may result in higher initial hydraulic conductivity/permeability of the peat soil. The
function of consolidation pressure may encourage a rearrangement of fiber orientation of peat soil drastically reduces the void, causing a significant reduction in the vertical permeability.

Figure 8 shows the results of Scanning Electron Microphotograph (SEM). This result based on consolidation pressure before and after test. The fibrous peat soil sample was taken from Dusun III Banyu Urip. From Figure 8 it can be seen that there are differences in SEM results before and after the test. Before the test, the arrangement of fiber from peat soil was larger. When compared after the test, the pores on the fibrous peat soil become more closely. [3] concluded that compressibility of peat soil can be influenced by the soil consist (macropores and micropores) in the photomicrographs of the peat soil. Also, SEM images based on [13] show uninterrupted peat soils with fibrous structure characteristics and coarse organic particles.

![Figure 8. Results of analysis of SEM under consolidation pressure (a) Before test and (b) After test](image)

Compressibility characteristic be related with hydraulic conductivity characteristics. Based on the result of consolidation test, the coefficient of hydraulic conductivity in vertical direction ($k_v$) was obtained. Table 6 shows the results of the $k_v$ parameters below the 50 kPa-400 kPa pressure range. The relationship between pressure giving and the vertical coefficient of hydraulic conductivity was described in Figure 9. The applied of pressure on the consolidation test affected the results of the $k_v$ values.

| Parameter                          | Pressure (p', kPa) | Dusun I Banyu Urip | Dusun III Banyu Urip |
|-----------------------------------|-------------------|--------------------|----------------------|
| Coefficient of volume compressibility ($m_v$, 1/kPa) | 50                | 0,0026233          | 0,0034000            |
|                                   | 100               | 0,0015133          | 0,0022967            |
|                                   | 200               | 0,0004733          | 0,0002633            |
|                                   | 400               | 0,0004467          | 0,000170             |
| Coefficient of Vertical Hydraulic Conductivity ($k_v$, cm/s) | 50 | 1.07.10^{-9} | 1.37.10^{-9} |
|                                   | 100               | 4.86.10^{-10}      | 7.03.10^{-10}        |
|                                   | 200               | 1.04.10^{-10}      | 4.63.10^{-11}        |
|                                   | 400               | 4.44.10^{-10}      | 1.69.10^{-11}        |
Figure 9. Variation coefficient of vertical hydraulic conductivity with consolidation pressure (Dusun III Banyu Urip)

It can be seen from the Table 6 the average value coefficient of vertical hydraulic conductivity ($k_v$) under consolidation pressure 50 kPa are $1.07 \times 10^{-9}$ cm/s (Dusun I Banyu Urip) and $1.37 \times 10^{-9}$ cm/s (Dusun III Banyu Urip). The value of hydraulic conductivity in vertical direction ($k_v$) of Figure 9 appears to decrease. This is a result of pressure ($p'$, kPa) of 50, 100, 200, and 400. So it can be concluded that the greater the pressure value ($p'$), the $k_v$ value obtained will be smaller.

4. Conclusion
The hydraulic conductivity/permeability and compressibility of fibrous peat soil affected by the behaviour of fibrous peat soil as: (a) depth, (b) water content, (c) void ratio, and (d) classification. The peat soil in Banyuasin Regency was categorized as fibrous peat soil. This research gave the information that the peat soil is one of the typical peat soil, which is can be found in South Sumatera.

Based on hydraulic conductivity test (Constant Head method), the average coefficient vertical hydraulic conductivity coefficient ($k_v$ $20^\circ$C) was $3.76 \times 10^{-4}$ cm/s. And the average coefficient of the horizontal hydraulic conductivity coefficient ($k_h$ $20^\circ$C) was $6.13 \times 10^{-4}$ cm/s. Results show that the ratio of $k_h/k_v$ ($20^\circ$C) was 2.04 (Dusun III Banyu Urip). The value of horizontal coefficient hydraulic conductivity ($k_h$) is more than the value of vertical coefficient hydraulic conductivity ($k_v$). This is because in the horizontal direction, peat soil has a larger pore size.

The hydraulic conductivity/permeability parameters also obtained from consolidation test. The average value coefficient of vertical hydraulic conductivity ($k_v$) from Dusun I Banyu Urip was $1.07 \times 10^{-9}$ cm/s (for consolidation pressure 50 kPa).

The analysis of compressibility characteristics of fibrous peat soil had been done using Oedometer test. The results from consolidation test were the average compression index ($c_v$) in the Dusun I Banyu Urip 1.428 and the average compression index ($c_v$) on the location of Dusun III Banyu Urip is 1.215. The coefficient of rate of consolidation ($c_v$) based on Cassagrande’s method from 13.671 from 3.312 under consolidation pressure in range of 50 to 200 kPa (Dusun III Banyu Urip).

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