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Studia Geotechnica et Mechanica, 2023; 45(2): 133–143

Original Study **Open Access**

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Effect of fibre content on the geotechnical properties of peat

https://doi.org/10.2478/sgem-2023-0003
received May 9, 2022; accepted December 6, 2022.

Abstract: The purpose of the study was to determine the geotechnical properties of peat and relate them to the fibre content. Peat soil tested in this study was collected from the peatland in the north-eastern Poland, 250 km north-east of Warsaw. Peat samples were taken from eight different depths below the ground surface over an area of approximately 2500 m^2. The research programme consisted of laboratory tests of the physical properties of peat and compressibility tests conducted in oedometers. Tests were performed in accordance with the current international and European standards using specialised research equipment. Based on the degree of decomposition, peat was divided into fibric (with more than 66% of fibres), hemic (fibre content from 33% to 66%) and sapric (less than 33% of plant fibres). The bulk and particle densities, natural water content, organic content, initial void ratio and the degree of decomposition were investigated as the physical properties of peat. Based on the oedometer tests, the constrained modulus, compression and secondary compression indexes were determined. It was concluded that the fibric peat is characterised by the lowest bulk and particle densities, the highest water and organic contents, void ratio and compressibility in comparison to hemic and sapric peat. The characteristics of peat have been related to the results presented in the literature.

Keywords: organic soils; peat; fibre content; geotechnical properties.

1 Introduction

Organic soils are classified based on the content of organic matter (Shotyk, 1992). One of the types of organic soils with the highest organic content is peat, which is the objective of research for civil engineers, geologists, geotechnical engineers, botanists, soil scientists and farmers. Peat is an organic material (less than 25% by weight of mineral matter) composed of partially or totally decomposed plant remains, which have accumulated under water-saturated conditions (Huat et al., 2009; Rezanezhad et al., 2016; Skreczko et al., 2021; Zaccone et al., 2007). It has a spongy consistency, a distinctive organic odour and is brown to black in colour (Craig, 1992; Huat et al., 2011b, 2014). The elemental composition of peat depends on the botanical composition and the degree of decomposition (Shotyk, 1988). In terms of geotechnical engineering, peat is recognised as a material with high porosity, low shear strength and high compressibility (Rahgozar and Saberian, 2016; Wong et al., 2008). All of these engineering characteristics are related to the high natural water content (more than 200%) and very high organic matter content (even more than 75%) of peat (ASTM, 2007; Huat, 2004; Kazemian et al., 2011; Rahgozar and Saberian, 2016).

Peat deposits are formed when organic matter accumulates more rapidly than it decomposes, which is mainly connected with the ecosystem and climate conditions (Rahgozar and Saberian, 2016). Peatlands are found throughout the world and constitute 5%–8% of the land surface of the earth (Huat et al., 2011b; Mesri and Ajlouni, 2007). They occur in the temperate and cold regions in countries such as Canada, Finland, Sweden and Norway; however, 8%–11% of global peat deposits are in tropical or subtropical regions. Peatlands are also found in the USA, China, Germany and Poland (Malawska et al., 2006; Mesri and Ajlouni, 2007; Schulz et al., 2019; Szajdak et al., 2020).

The properties of peat depend on its botanical composition, fibre content and the degree of decomposition of the plant remains (Rezanezhad et al., 2016). Several

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methods of determining the degree of decomposition (humification) of peat have been reported in the literature (Farnham and Finney, 1965; Zaccone et al., 2018). However, one of the most well-known and commonly used field tests used to classify peat soils based on their decomposition is the 10-step von Post scale, where H1 refers to the least and H10 to the most decomposed peat (Huat et al., 2011a, b; Long, 2005; O'Kelly and Pichan, 2013; Rezanezhad et al., 2016). In practice, the degree of decomposition of peat using von Post scale is determined based on the visual inspection of its structure and on the squeezing test result.

The United States Department of Agriculture (USDA) compresses the von Post scale into three levels and divides peat based on the fibre content into fibric (fibrous), hemic (semi-fibrous) and sapric (amorphous) (USDA, 1999). Fibrous peat is the least humified (H1–H4 on the von Post scale) and consists of undecomposed distinct fragments of plant structure. It has more than 66% of fibres (ASTM, 2007) and is brown to brownish-yellow in colour (Larsson, 1996). Hemic peat has a medium degree of decomposition (H5–H6) and a recognisable structure. The fibre content of semi-fibrous peat is in the range from 33% to 66%. It is usually brown (Larsson, 1996). Sapric peat is highly humified (H7–H10). It is composed of less than 33% of very indistinct or invisible plant fibres (ASTM, 2007; Huat et al., 2011b; Larsson, 1996). It has a dark brown to black colour.

It has been recognised that the degree of decomposition and the fibre content determine the physical and mechanical properties of peat (O'Kelly and Pichan, 2013). The direct effects of fibre content on the geotechnical properties have not been investigated sufficiently (Hobbs, 1986). However, the main correlations are known and are presented in the literature. According to Huat et al. (2011b), the decomposition process causes decrease in organic matter and changes in peat structure. During decomposition, the structure of peat changes from highly porous and cellular to amorphous. The voids in peat are mostly saturated (O'Kelly and Pichan, 2013). Hence, fibric peat is characterised by a higher initial void ratio and natural water content in comparison to sapric and hemic peat. O'Kelly and Pichan (2013) have pointed out that particle and bulk densities of peat are strongly connected with the degree of decomposition and/or high mineral content. Higher values of bulk and particle densities generally indicate higher degree of decomposition and mineral content (Huat et al., 2011b). Due to the very high initial void ratio, the compressibility of fibric peat is much higher than the compressibility of sapric and hemic peat. Moreover, the decomposition process may reduce the long-term compression of peat soil (Berry, 1983).

The aim of the study was to determine the geotechnical properties of peat and relate them to the fibre content. The study included an experimental investigation on the physical properties of peat, such as unit weight, water and organic contents, degree of humification and fibre content. Consolidation and compressibility characteristics were also determined. The characteristics of peat have been related to the results presented in the literature.

2 Materials and methods

2.1 Peat sampling

The peat soil tested in this study was collected from the peatland in the north-eastern Poland, 250 km north-east of Warsaw. The area under consideration is located in the lake region within the river basin. Figure 1 shows the occurrence of peatlands in Poland and the location of the study area. The subsoil profile of considered peatland consists of peat with a thickness of about 1–7 m. Below the peat layer, glacial sediments, mainly in the form of silt and sand, are deposited. The water level is at a depth from 0.1 to 1.5 m below the ground surface.

The peat was sampled with thin wall cylinders with a diameter of 70 mm. The cylinders were pressed into the subsoil in a vertical direction. Samples were collected from eight different depths, 1.0, 1.4, 1.9, 2.3, 3.1, 3.6, 4.7 and 5.0 m, below the ground surface, over an area of approximately 2500 m^2. A total of 40 samples were tested. The results presented in the study are the average test results for each group of peat samples collected from a certain depth.

2.2 Physical properties

The bulk and particle densities, natural water content, organic content, initial void ratio and the degree of decomposition were investigated as the physical properties of peat. Tests were performed on the samples with natural water content and natural structure. The bulk and particle densities and the natural water content were determined in accordance with the international standards (ISO 17892-1:2014, ISO 17892-2:2014, ISO 17892-3:2015). The determination of the water content was carried out according to the procedure used commonly in soil testing. The organic content of peat was determined using the method of loss on ignition (LOI) in accordance with the European standard (EN 15935:2012). The method is widely

Table 1: Degree of decomposition of peat soil based on the von Post scale (Landva and Pheeney, 1980).

Peat classification		Decomposition	Plant structure	Material extruded on squeezing (passing between fingers)
Fibric peat	H1	None	Easily identified	Clear, colourless water
	H2	Insignificant	Easily identified	Yellowish water
	H3	Very slight	Still identifiable	Brown, muddy water
	H4	Slight	Not easily identified	Dark brown, muddy water
Hemic peat	H5	Moderate	Recognisable, but vague	Muddy water and some peat
	H6	Moderately strong	Indistinct	About one-third of peat squeezed out, dark brown water
Sapric peat	H7	Strong	Faintly recognisable	About one-half of peat squeezed out, very dark brown water
	H8	Very strong	Very indistinct	About two-thirds of peat squeezed out, also some pasty water
	H9	Nearly complete	Almost unrecognisable	Nearly all the peat squeezed out as a paste
	H10	Complete	No discernible	All the peat passes between the fingers, no free water visible

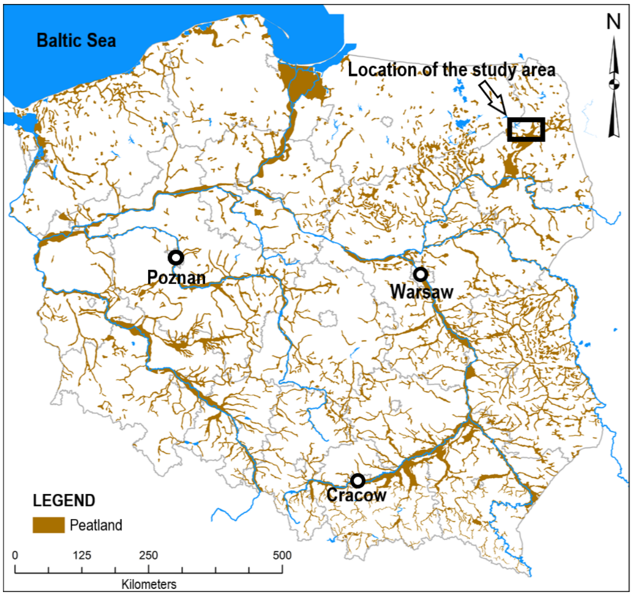


Figure 1: Peatlands in Poland and the location of the study area (based on Majtyka, 2013).

used by researchers and consists of strongly heating the oven-dried soil sample at a specified temperature (Heiri et al., 2001; Hoogsteen et al., 2015). The temperature of 550°C causes combustion of organic matter to ash (Heiri et al., 2001). When the natural water content of peat w_n is known, the organic content I_{om} can be predicted using the equation given below (Huat et al., 2009):

$$I_{om} = 0.0592 w_n + 54.34 \tag{1}$$

where w_n is the natural water content in percentage.

The degree of decomposition of peat was determined using the von Post scale. Table 1 shows the categories of peat based on the squeezing and visual tests results (Landva and Pheeney, 1980).

2.3 Consolidation and compressibility characteristics

The consolidation and compressibility characteristics of peat were determined in an oedometer by incremental loading. Tests were carried out on cylindrical samples with an initial height of 20 mm and a diameter 63.5 mm using a set of oedometers with automatic registration of displacement sensor readings presented in Figure 2. The peat samples were tested in non-deformable rings with top and bottom porous stones. Tests were performed in accordance with the international standard (ISO 17892-5:2017) at different effective vertical stresses σ_v': 15, 32, 64, 96, 128 and 256 kPa. The maximum stress applied to the sample depended on the peat compressibility and the technical capabilities of the laboratory equipment.

With the vertical stress increment, the height of the sample and the void ratio of soil decrease. When the initial void ratio e_0 is known, the void ratio e at any stage of the oedometer test can be calculated from the equation (Head, 1994)

$$e = e_0 - (\Delta H / H_0) \cdot (1 + e_0) = e_0 - \varepsilon_v \cdot (1 + e_0) \tag{2}$$

where ΔH is the change in the sample height as a result of the application of stress, H_0 is the initial height of the sample and ε_v is the vertical strain.

Figure 2: Set of oedometers used for the tests.

Based on the oedometer tests, the constrained modulus, compression and secondary compression indexes of peat were determined. The constrained modulus was determined by measuring the sample height changes under an applied stress. The constrained modulus E_{oed} can, therefore, be calculated from the formula

$$E_{oed} = \Delta\sigma_v'/\varepsilon_v = (\Delta\sigma_v' H)/\Delta H \quad (3)$$

where $\Delta\sigma_v$’ is the effective vertical stress increment and H is the height of the sample before the stress increment.

The compression index C_c is one of the most important parameters in the analysis of primary consolidation of soil. It is used to predict the foundation settlements. The parameter describes the change in the void ratio Δe as a function of the change in vertical effective stress plotted in the logarithmic scale $\Delta\log \sigma_v$’, $C_c = \Delta e/\Delta\log \sigma_v$’.

The number of correlations between the compression index and other physical parameters of soil (water content, void ratio, liquid or plastic limit) is known. The following dependencies can be used to predict the compression index in peat and other organic soils: $C_c = 0.01w_n$ (Mesri and Ajlouni, 2007), $C_c = 0.0115w_n$ (Moran et al., 1958), and $C_c = 0.35\cdot(e_0 - 0.5)$ (Hough, 1957).

The secondary compression index C_α is often more significant in peat than in other soils because of the relatively short duration of the primary consolidation and the long-term secondary consolidation of peat deposits (Mesri et al., 1997). It can be defined as the tangential slope of the e □ $\log t$ curve at any particular time t after the end of primary consolidation. It is directly related to the compression index (Mesri and Castro, 1987; Mesri and Godlewski, 1977) and stress (Jiang et al., 2020). The secondary compression index can be determined from the equation

$$C_\alpha = (\Delta e/\Delta\log t) = (\Delta\varepsilon/\Delta\log t)(1 + e_0) \quad (4)$$

3 Results and discussion

3.1 Physical properties

Table 2 shows the physical properties of the tested peat. Based on the degree of decomposition, peat from the peatland in north-eastern Poland was divided into fibric, hemic and sapric. Peat from a depth of 3.1 m, designated as P1, was classified as fibric, peat from the depths 1.9, 2.3, 3.6, 4.7 and 5.0 m below the ground surface (peat P2–P6) was classified as as hemic and peat designated as P7 and P8 from the depths 1.0 and 1.4 m was classified as sapric.

It can be observed in Table 2 that the lowest bulk density (ρ = 1.010 g/cm^3) was estimated for fibric peat, whereas it was the highest (ρ = 1.112 and 1.127 g/cm^3) for sapric peat. The bulk density of hemic peat varied from 1.029 to 1.039 g/cm^3. The estimated values were within the range reported in the literature (ρ = 0.80–1.43 g/cm^3) (Huat et al., 2011b; Rahgozar and Saberian, 2016; Wong et al., 2008). However, even lower values of bulk density have been reported by Zaccone et al. (2017, 2018). The particle density of the tested peat was determined to be 1.443–1.530 g/cm^3, whereas the particle density presented in the literature varies from 1.23 to 1.64 g/cm^3 (Boylan et al., 2008; Rahgozar and Saberian, 2016; Wong et al., 2008). As expected, the fibric peat had the highest natural water content (w_n = 828.3%), whereas sapric had the lowest water content (w_n = 236.5% and 320.2%). The water content of hemic peat was in the range of 335.7%–465.4%. The water content of peat presented in the literature has a wide range of 200%–1950% (Mesri and Ajlouni, 2007; Rahgozar and Saberian, 2016; Wong et al., 2008, 2009). The organic content of the tested peat varied from 83.42% to 94.86% and was within the range presented in the literature (I_{om} = 65.00%–99.06%) (Lechowicz et al., 2018; Mesri and Ajlouni, 2007; Rahgozar and Saberian, 2016; Wong et al., 2008). The highest value of organic content was determined for fibric peat, which had the highest natural water content. Figure 3 shows the I_{om}–w_n dependence.

It can be seen in Figure 3 that the organic content increased with the increase in the natural water content. However, the tested peat was characterised by a lower variability of organic content depending on the natural water content than the results obtained from Equation (1) (Huat et al., 2009). An empirical correlation between the organic and water contents of the tested peat was established (Fig. 3). The coefficient of determination R^2 of the linear regression fit was relatively low (R^2 = 0.442). The prediction of the organic content based on the water

Table 2: Physical properties of the tested peat.

Peat designation	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**
Depth of sampling (m)	3.1	1.9	2.3	3.6	4.7	5.0	1.0	1.4
Bulk density ρ (g/cm^3)	1.010	1.045	1.039	1.029	1.034	1.031	1.127	1.112
Particle density ρ_s (g/cm^3)	1.443	1.473	1.530	1.461	1.524	1.489	1.474	1.492
Natural water content w_n (%)	828.3	465.4	335.7	449.0	315.8	451.4	236.5	320.2
Organic content I_{om} (%)	94.86	90.73	83.42	92.39	84.16	88.57	90.61	88.23
Initial void ratio e_0 (–)	12.26	6.969	5.415	6.794	5.156	6.963	3.399	4.638
Degree of decomposition	H3	H5	H6	H5	H6	H5	H8	H7
Peat classification	Fibric	Hemic					Sapric	

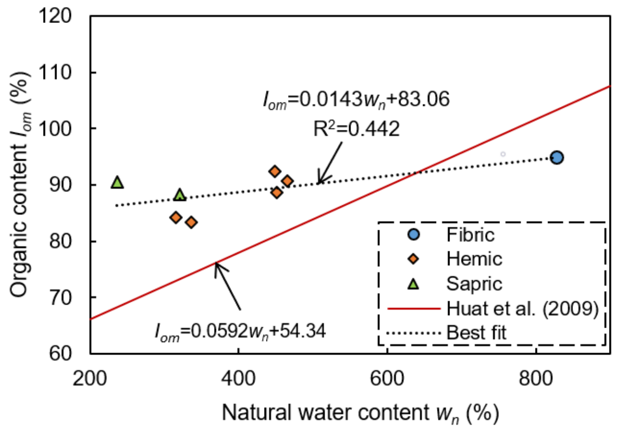


Figure 3: The relation between organic content I_{om} and natural water content w_n.

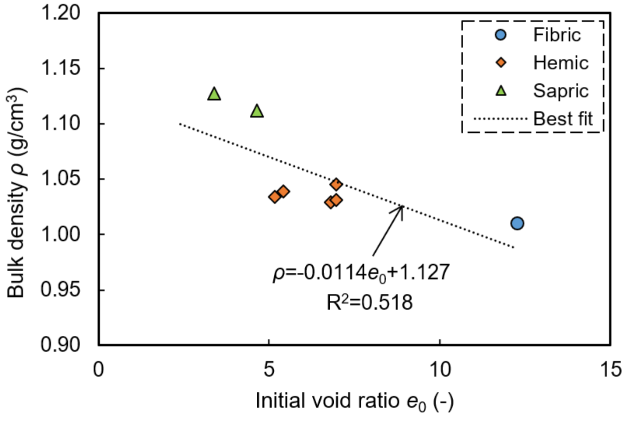


Figure 4: The relation between bulk density ρ and initial void ratio e_0.

content using empirical correlations should be made cautiously.

It can be observed in Table 2 that the highest initial void ratio (e_0 = 12.26) was determined for fibric peat, whereas it was the lowest (e_0 = 3.399 and 4.638) for sapric peat. For hemic peat, the e_0 values ranged from 5.156 to 6.969. The initial void ratio of hemic and sapric peat was lower than that reported by researchers (e_0 = 7.28–14.2) (Mesri and Ajlouni, 2007; Rahgozar and Saberian, 2016; Wong et al., 2008). This may be connected with the high degree of decomposition of the peat soil investigated in this study.

Based on the results presented in Table 2, it can be concluded that the initial void ratio had an influence on the bulk density and the natural water content of peat. The ρ □ e_0 and w_n □ e_0 dependences are shown in Figures 4 and 5.

It can be observed in Figure 4 that with the increase in void ratio (volume of voids), the bulk density of peat decreased. An empirical correlation between the bulk density and the initial void ratio was established (Fig. 4). The R^2 coefficient obtained for the regression fit line was 0.518. As expected, the natural water content of saturated peat increased with the increase in initial void ratio. The correlation between the w_n and e_0 parameters was determined and is shown in Figure 5. The coefficient of determination of the regression line estimated for w_n □ e_0 dependence was very high (R^2 = 0.993); thus, the prediction of the natural water content based on the initial void ratio of the tested peat would be possible with a high accuracy.

3.2 Consolidation and compressibility characteristics

Figure 6 shows the relation between vertical strain and effective vertical stress for fibric, hemic and sapric peat for the primary loading and unloading phases. Due to the high compressibility of the tested soil and the technical capabilities of the laboratory equipment, the maximum

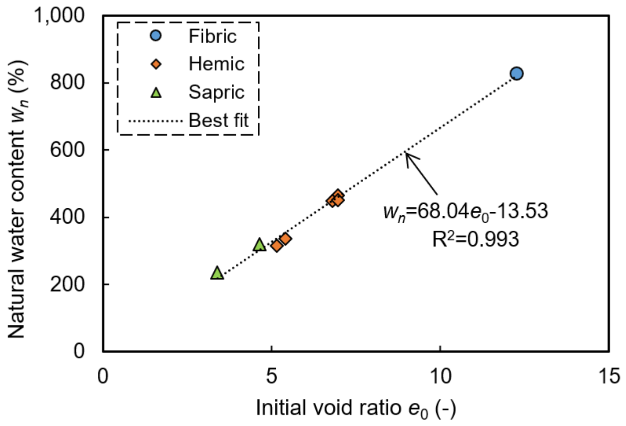


Figure 5: The relation between natural water content w_n and the initial void ratio e_0.

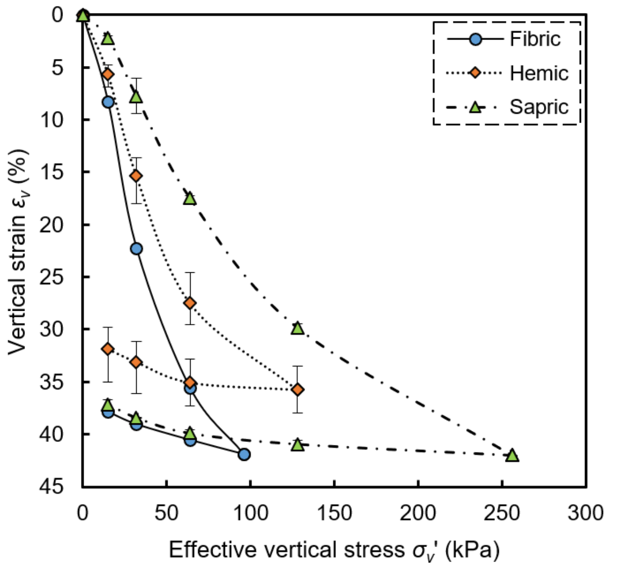


Figure 6: The relation between vertical strain ε_v and effective vertical stress σ_v'.

Table 3: Averaged values of the constrained modulus of the tested peat.

Vertical stress (kPa)	**Constrained modulus E_{oed} (kPa)**		
	Fibric peat	**Hemic peat**	**Sapric peat**
15	181.7	266.9	683.8
32	111.6	179.9	321.5
64	186.8	224.7	348.5
96	327.4	Not investigated	Not investigated
128	Not investigated	534.0	428.0
256	Not investigated	Not investigated	738.9

vertical stress applied to fibric, hemic and sapric peat was 96, 128 and 256 kPa, respectively.

The biggest change in height of the sample caused by stress increment was determined for fibric peat, whereas it was the lowest for sapric peat (Fig. 6). It can be observed in Figure 6 that the vertical strain during the primary loading phase obtained for fibric peat, depending on the stress level, was approximately two to four times greater than it was determined for sapric peat. For hemic peat, the difference was not so significant.

Based on the results of the oedometer tests, the constrained modulus at different vertical stresses was obtained (Table 3).

The highest values of the constrained modulus were determined for sapric peat, whereas they were the lowest in fibric peat. It can be observed in Table 3 that the constrained modulus of sapric peat was even several times higher than the constrained modulus of fibric and sapric peat. The difference decreased with the increase in vertical stress.

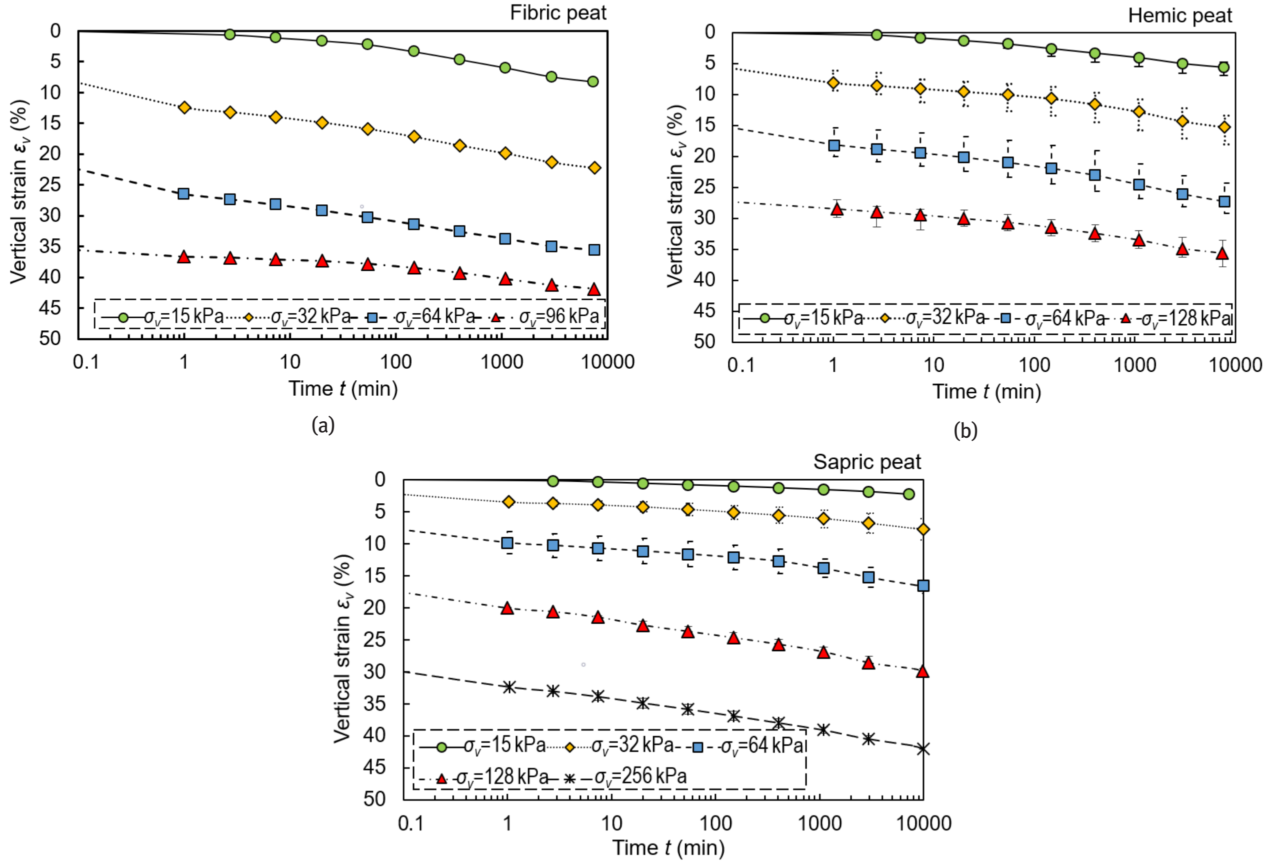
For a complete consolidation analysis, the vertical strain should be related to time. The ε_v □ log t dependencies used for determining the secondary compression index are shown in Figure 7.

Figure 7 also shows the highest vertical strain and, therefore, the biggest compressibility of fibric peat in comparison to hemic and sapric peat.

The relations between void ratio and effective vertical stress are shown in Figure 8. The e values were calculated from Equation (2). Based on the results presented in Figure 8a, the compression index of fibric, sapric and hemic peat was determined.

The biggest change in the void ratio with the stress increment was determined for fibric peat, whereas it was the lowest for sapric peat (Fig. 8). The percentage decrease in the e values in relation to e_0 for the primary loading phase at vertical stress up to 64 kPa was estimated to be 38% for fibric peat, 32% for hemic peat and 22% for sapric peat. The σ_v' □ e dependence for fibric peat shown in Figure 8b is very close to that reported in the literature, $\sigma_v' = (40/e)^{2.7}$ (Mesri and Ajlouni, 2007). Due to the low void ratio of hemic and sapric peat, the relation σ_v' □ e estimated for them is slightly different, but still comparable to the values presented by researchers. The empirical correlations between vertical stress and void ratio along with R^2 coefficients were established and are presented in Figure 8b.

The values of compression index are shown in Figure 9. They were related to the natural water content and initial void ratio.

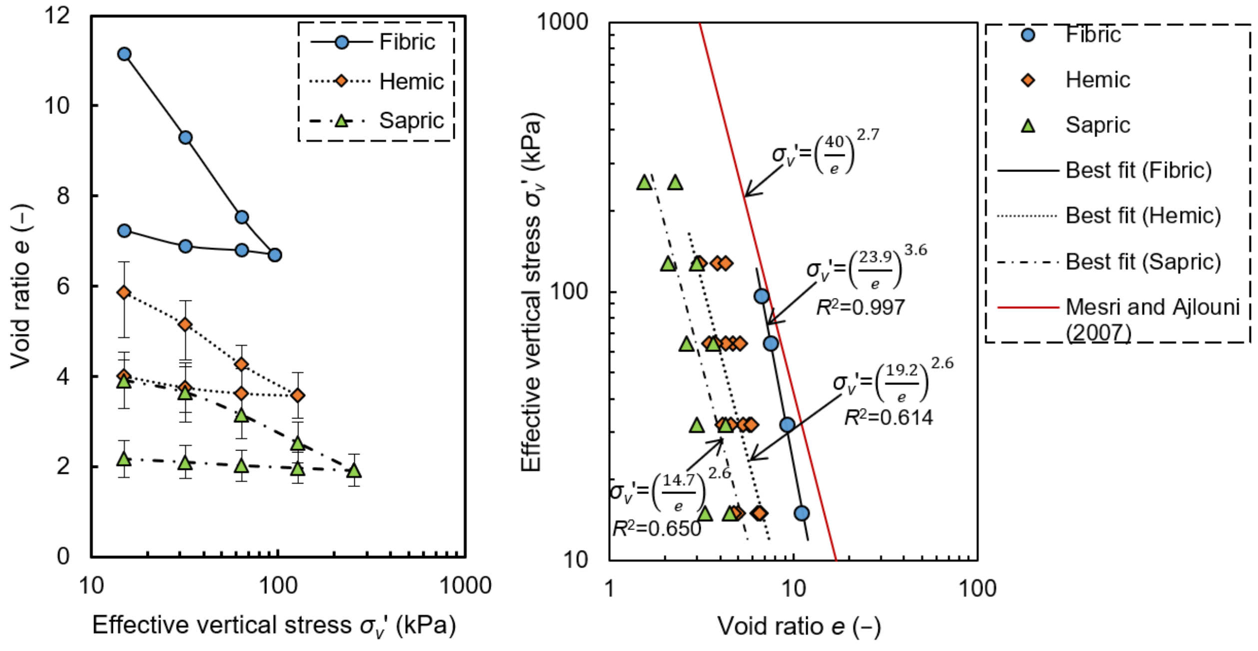


(a)

(b)

(c)

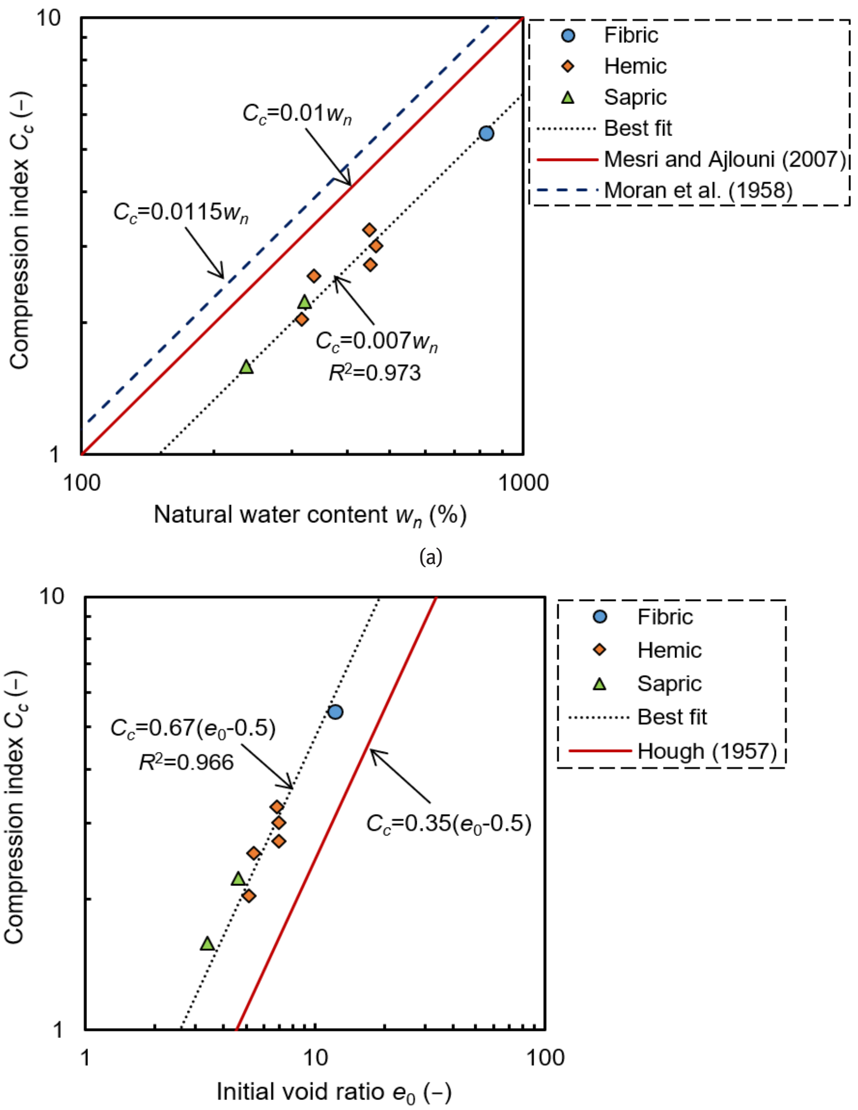
Figure 7: Vertical strain ε_v versus time t depending on the stress level σ_v for (a) fibric peat, (b) hemic peat, (c) sapric peat.



(a)

(b)

Figure 8: The relation between (a) void ratio e and effective vertical stress σ_v' and (b) effective vertical stress σ_v' and void ratio e.



(a)

(b)

Figure 9: The relation between compression index C_c and (a) natural water content w_n and (b) initial void ratio e_0.

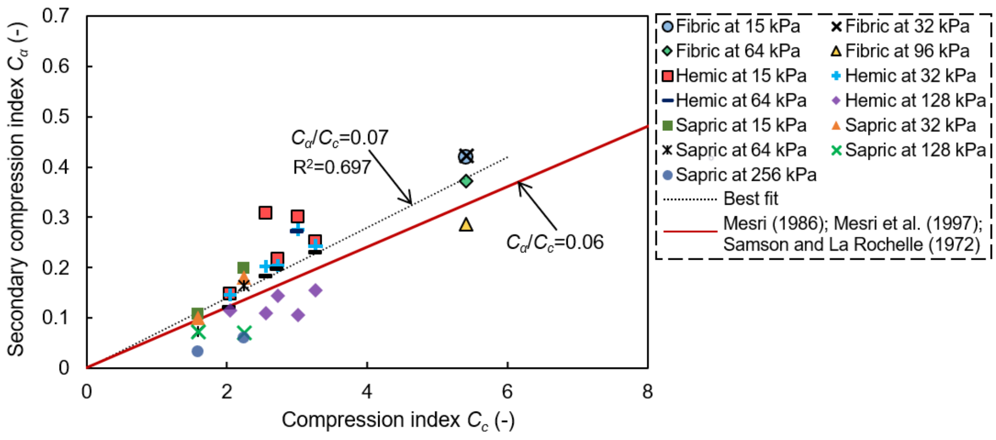


Figure 10: Secondary compression index C_α versus compression index C_c.

It can be observed in Figure 9 that C_c □ w_n and C_c □ e_0 correlations were established with a high reliability ($R^2 = 0.973$ and 0.966, respectively). The C_c value increased with the increase in w_n and e_0 values. The compression indexes of the tested peat could be predicted based on the natural water content or the initial void ratio from the equations: $C_c = 0.007w_n$ and $C_c = 0.67{\cdot}(e_0 - 0.5)$. The obtained compression index is comparable to the values presented by researchers ($C_c = 0.2$–10) (Hough, 1957; Mesri and Ajlouni, 2007; Moran et al., 1958).

The secondary compression index of fibric, hemic and sapric peat and the C_α/C_c correlation are shown in Figure 10. The C_α values were determined for each level of vertical stress.

With a medium reliability ($R^2 = 0.697$), a relation between the secondary compression index and the compression index was established, $C_\alpha/C_c = 0.07$. The determined C_α/C_c ratio for the peat is the same as that reported in the literature ($C_\alpha/C_c = 0.06 \pm 0.01$) (Mesri, 1986; Mesri et al., 1997; Samson and La Rochelle, 1972).

4 Conclusions

Based on the degree of decomposition, peat from the peatland in north-eastern Poland was divided into fibric, hemic and sapric peat. The following conclusions may be derived from the performed experimental study:

1. Fibric peat, with the highest fibre content, has the lowest bulk and particle densities and the highest natural water content, organic content and initial void ratio in comparison to hemic and sapric peat.
2. The following equations may be used for the prediction of the physical parameters of tested peat: $I_{om} = 0.0143w_n + 83.06$, $\rho = -0.0114e_0 + 1.127$, $w_n = 68.04e_0 - 13.53$.
3. The highest compressibility was found in fibric peat. The vertical strain during the primary loading phase obtained for fibric peat, depending on the stress level, was approximately two to four times greater than it was determined in sapric peat.
4. The constrained modulus of sapric peat was even several times higher than the constrained modulus of fibric and sapric peat. The difference decreased with the increase in vertical stress.
5. The empirical equations for predicting the compression index of tested soil based on the natural water content and the initial void ratio are $C_c = 0.007w_n$ and $C_c = 0.67{\cdot}(e_0 - 0.5)$.
6. The C_α/C_c ratio for the investigated peat was 0.07.
7. The determined peat characteristics are close to those presented in the literature.

Experimental investigation about the properties of peat soil with additives is in the author's plans for future research.

Acknowledgements: This research was funded by the Ministry of Science and Higher Education, grant number WZ/WB-IIL/2/2022. The investigations were carried out at Bialystok University of Technology in Poland.

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