Tensile and Compressive Contributions of Fibres in Peat

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ABSTRACT

Structural anisotropy in peat is induced by the presence of fibres. This paper presents laboratory test results of the fibre effect in peat on pre-failure compression behaviour and failure modes originating from both tensile and compressive stresses supported by fibres. Furthermore, a hyperviscoplastic constitutive model for peat is extended to account for structural anisotropy. Undrained triaxial compression tests were carried out with vertical and horizontal undisturbed peat specimens. Additional oedometer tests on vertical and horizontal undisturbed peat specimens were used to compare the fibre effect on the failure mechanism of fibrous peat in undrained triaxial compression. The experimental results quantified the tensile and compressive effects of fibres in peat and also indicated that the strain softening in horizontal specimens resulted in the development of cracks rather than a mere buckling of fibres under compressive loads. The structural cross-anisotropy was modelled by extending a hyperviscoplastic model proposed for peat with a fibre layer characterized by a vector field.

INTRODUCTION

Peat inherits its structural anisotropy from its formation process via partially decomposed prostrate vegetation accumulated in water-logged conditions. Hence, peat is routinely described as being composed of isotropic fillings and fibres (Sellmeijer, 1993). This conceptual decomposition is analogous to the extensive investigation on sand reinforced by fibre additions, e.g. by Michalowski and Cermák (2002, 2003). Hendry et al. (2014) confirmed that the fibre effects on strength and stiffness of these fibre mixtures and on those of peat are generally consistent. However, the fibre network morphology differs in the fibre-sand mixture and in peat, i.e. fibres in peat are interwoven and form an integrated fibre-reinforced matrix with the isotropic filling. Besides, peat fibre microstructure (Landva and Pheeney, 1980) may be partially responsible for observed strain-rate dependence. Therefore,

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this study carried out experimental investigations of the fibre effect on peat stiffness and strength in triaxial compression tests at three strain rates as well as in oedometer tests on both vertically (horizontal fibre alignment) and horizontally (vertical fibre alignment) harvested peat specimens. The strain-rate effect as well as the failure mechanism of fibrous peat in undrained triaxial and drained one-dimensional compressions were analysed. Correspondingly, a cross-anisotropic constitutive model by extending a hyperviscoplastic model with a fibre layer was proposed to simulate the pre-failure peat geomechanical behaviour.

TESTED PEAT MATERIAL

For both undrained triaxial and oedometer tests, peat specimens were trimmed from undisturbed peat blocks collected beneath ground water level in Clara bog (Ireland) which were sealed and transported to the laboratory testing environment at 19 °C ± 4 °C. The physical properties of the peat material (Table 1) have been investigated previously and reported in O'Kelly and Zhang (2013).

Table 1: Physical properties of the tested peat material (O'Kelly and Zhang, 2013).

Undisturbed Clara bog peat	Value
Average water content	720 %
Specific gravity of solids	1.42
Loss in dry mass on ignition	98.6 %
Fibre content by dry mass retained on 63 μm sieve	74.2 %
Fibre content by dry mass retained on 150 μm sieve	63.5 %

LABORATORY EXPERIMENTS

Unconsolidated undrained triaxial loading-unloading tests at axial strain rates of 16 %/hr, 1.6 %/hr and 0.16 %/hr were carried out on undisturbed peat specimens with both horizontal and vertical fibre alignments. The purposes of the undrained triaxial loading-unloading tests were: 1. comparison of initial compression stiffness of vertical and horizontal specimens at different strain rates; 2. comparison of strain recoveries of vertical and horizontal specimens; 3. observation of the different failure mechanism of vertical and horizontal specimens in undrained triaxial compression. The oedometer tests were carried out to further understand the compression of vertical and horizontal specimens in constrained compression under drained conditions as well as the permeability anisotropy. The triaxial test specimens were initially 38 mm in diameter and 76 mm in height, whereas the oedometer test specimens were 76.2 mm in diameter and 19.2 mm in height.

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Undrained Triaxial tests

Unconsolidated undrained triaxial tests were used to avoid the non-uniformity of pore size distribution induced by consolidation. Specimen saturation was confirmed at the end of tests by Skempton pore pressure parameter measurements ($B > 0.95$). The cell pressure effect was investigated by undrained triaxial loading-unloading tests of an undisturbed peat specimen to an axial strain of 5 %, which indicated that the cell pressure had a negligible effect on the constitutive behaviour of the undisturbed vertical peat in undrained loading-unloading tests. Therefore, a zero cell pressure was applied for the following undrained triaxial tests.

Figures 1 and 2 show a series of undrained triaxial loading-unloading tests at axial strain rate of 16 %/hr on vertical and horizontal specimens, respectively. Figures 3 and 4 present undrained triaxial loading-unloading tests at an axial strain rate of 0.16 %/hr on vertical and horizontal specimens. The rate effect on the initial undrained compression of the vertical and horizontal specimens is compared in Figures 5 and 6. The test carried out on the horizontal specimen at 1.6 %/hr was eccentrically loaded and thus is not presented in Figure 6. The pore water pressure recorded during the undrained compression was less than 5 kPa up to 20 % axial strain for all strain rates.

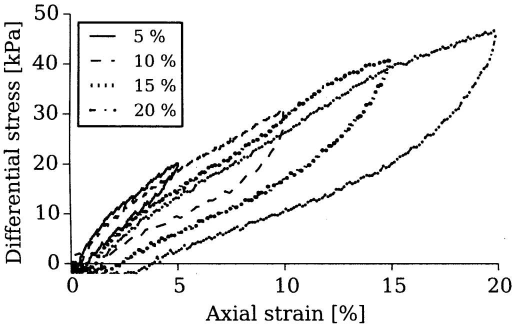

Figure 1: Undrained triaxial loading-unloading tests on vertical specimen at 16 %/hr.

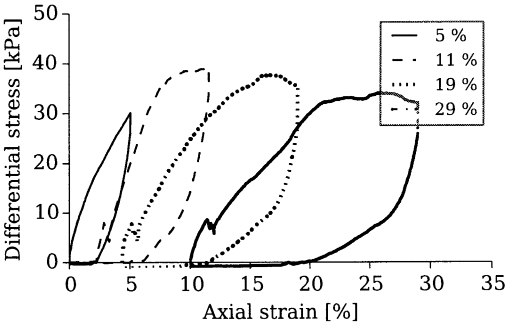

Figure 2: Undrained triaxial loading-unloading tests on horizontal specimen at 16 %/hr.

Oedometer tests

Oedometer rings were pushed into the undisturbed peat block in vertical and horizontal directions to obtain the undisturbed peat specimens with horizontal and vertical fibre alignments. Four oedometer consolidation tests were carried out, with two for each type of specimen. Seven loading increments, viz. 25 kPa, 50 kPa, 100 kPa, 200 kPa, 400 kPa, 800 kPa and 1600 kPa, were applied with a one day duration for each load stage. Figures 9 and 10 present the plots of void ratio

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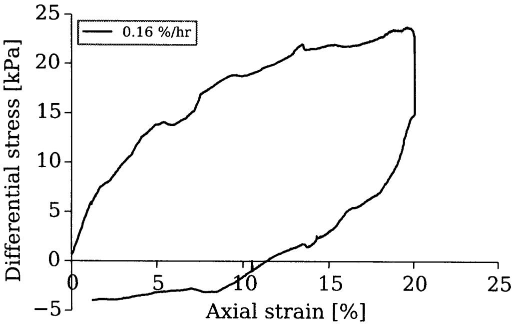

Figure 3: Undrained triaxial loading-unloading tests on vertical specimen at 0.16 %/hr.

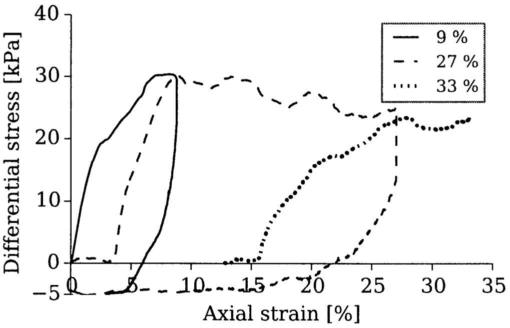

Figure 4: Undrained triaxial loading-unloading tests on horizontal specimen at 0.16 %/hr.

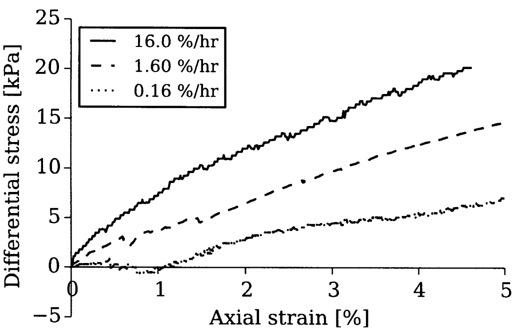

Figure 5: Undrained triaxial compression tests on vertical specimen at 16 %/hr, 1.6 %/hr and 0.16 %/hr.

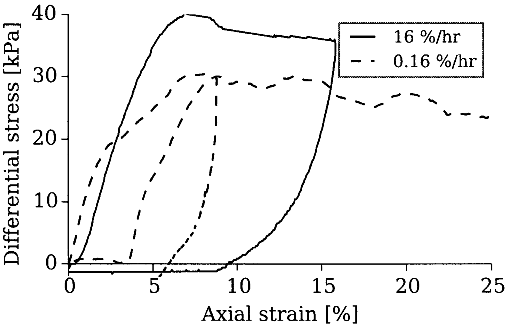

Figure 6: Undrained triaxial loading-unloading tests on horizontal specimen at 16 %/hr and 0.16 %/hr.

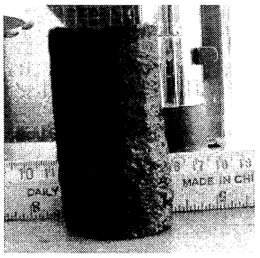

Figure 7: Vertical peat specimen at the end of undrained triaxial testing.

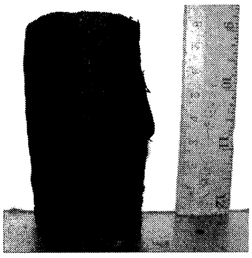

Figure 8: Horizontal peat specimen at the end of undrained triaxial testing.

against vertical effective stress on semi-log scale and constrained modulus against vertical effective stress on double log-scale, where constrained modulus $D = 1/m_v$, with $m_v = \frac{\Delta e}{(1+e_0)\Delta\sigma'_v}$ is the coefficient of volume compressibility. At the end of the oedometer tests, the specimens were visually checked revealing that the vertically ori-

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ented fibres in horizontal specimens were buckled and fibre orientation was partially changed to horizontal. The coefficient of permeability for vertical drainage conditions was calculated based on BSI (1990). The relationship between the coefficient of permeability and void ratio in a semi-log scale is plotted in Figure 11.

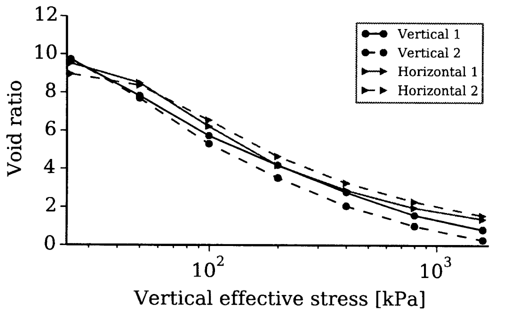

Figure 9: Vertical peat specimen at the end of undrained triaxial testing.

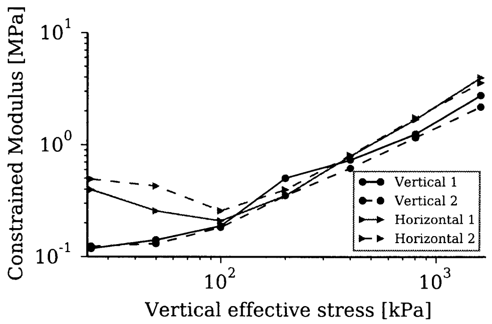

Figure 10: Horizontal peat specimen at the end of undrained triaxial testing.

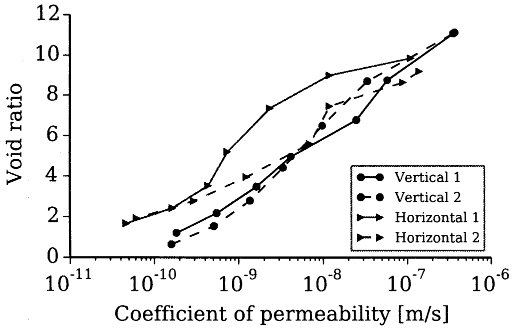

Figure 11: Relationship between the coefficient of permeability and void ratio.

INTERPRETATION AND DISCUSSION OF EXPERIMENTAL RESULTS

The initial stiffness obtained in undrained compression tests and the constrained modulus in oedometer tests for horizontal specimens are higher than those for the vertical specimens, which indicates that the vertical fibres contributed compressive resistance upon compression. Comparing the stress-strain behaviour of vertical and horizontal specimens in the undrained loading-unloading tests, vertical specimens showed greater strain recoveries, smaller rate-dependent initial compression stiffness and a strain hardening with no sign of failure plane development. The rate impact on the relatively larger initial stiffness of undrained compression on horizontal specimens was insignificant. This finding deviates from the fibre-sand mixture research carried out by Michalowski and Cermák (2002), arguing that vertically oriented fibres were detrimental to the stiffness.

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The reason lies in the fibre structure in peat as an integrated interwoven matrix. Additionally, for tests on horizontal specimens, strain softening occurred around 8 % engineering axial strain for tests carried out at all the strain rates. The specimen profiles after the compression tests showed that the vertical specimen preserved its integrity, with nearly constant cross-sectional area, whereas through-cracks occurred in the horizontal specimen. The constrained modulus plotted against vertical effective stress of the oedometer tests on the undisturbed vertical and horizontal specimens elucidated that for the horizontal specimens, the fibre matrix provided enhanced resistance for up to 100 kPa effective stress in compression, beyond which similar compression behaviour of vertical and horizontal specimens was observed for the same effective stress level. The permeability anisotropy of the tested peat material was not significant with an increasing ratio of vertical permeability coefficients obtained from vertical to horizontal specimens from 2.37 to 3.19 under step consolidation from 25 kPa to 1600 kPa. The coefficient of permeability decrease can be approximated by a power law, from Figure 11, as $k_\mathrm{v} = k_0 \mathrm{e}^{a\Delta e}$, where k_v is the vertical coefficient of permeability, k_0 is the initial coefficient of permeability and e is void ratio, a is the gradient of the $e - \log k_\mathrm{v}$ curve.

It is reasonable to conclude that the strain-hardening behaviour in the vertical peat specimen compression resulted from fibre enhancement. For horizontal specimens, the principal major stress was parallel to the fibre orientation, peat fibres were firstly subjected to compression, resulting in a higher stiffness, then buckled, inducing strain-softening with vertical cracks in the specimen. This is congruent with the considerations based on friction to determine the reinforcing and detrimental effects of fibres in peat, outlined by Hendry et al. (2014). The mechanism of compression failure on horizontal specimens was due to structural disintegration rather than by mere fibre buckling. It shed some light on the cross-anisotropic constitutive model to be proposed in simulating peat: (1) the anisotropic contribution is rate-independent and exhibits a lower initial compressibility along the fibre direction than across it; (2) the failure criterion for fibrous peat should be defined based on the failure characteristics of the fibre matrix.

CONSTITUTIVE MODEL

The proposed constitutive model considering the structural cross-anisotropy of peat was developed based on an existing isotropic hyperviscoplastic model. The compressibility of the organic particles was neglected since the water content was around 720 %. Thus the principle of effective stress applies. The tested peat was assumed to be fully saturated with incompressible and immiscible solid and fluid constituents. The total second Piola-Kirchhoff stress (2PK) equals the sum of the effective stress and excess pore water pressure parts:

$$\mathbf{S} = \mathbf{S}_\mathrm{S}^\mathrm{E} - p J_\mathrm{S} \mathbf{C}_\mathrm{S}^{-1} \qquad \text{with} \qquad J_\mathrm{S} = \det \mathbf{F} \quad \text{and} \quad \mathbf{C}_\mathrm{S} = \mathbf{F}^\mathrm{T} \mathbf{F} \tag{1}$$

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where $\mathbf{F}$ is the solid deformation gradient.

With an additional fibre layer, the cross-anisotropic hyperviscoplastic model consists of elastic, two viscoelastic, elastoplastic and fibrous (anisotropic) contributions. By using the overlay concept (Pande et al., 1977), the effective 2PK stress in the solid matrix can be additively decomposed as

$$\mathbf{S}_{\mathrm{S}}^{\mathrm{E}} = \underbrace{\mathbf{S}_{\mathrm{eq0}} + \sum_{i}^{2} \mathbf{S}_{\mathrm{ov}}^{i} + \mathbf{S}_{\mathrm{p}}}_{\mathbf{S}_{\mathrm{iso}}} + \mathbf{S}_{\mathrm{ani}} \tag{2}$$

In each inelastic element of the isotropic components, the multiplicative decomposition of the deformation gradient reads

$$\mathbf{F} = \mathbf{F}_{\mathrm{ev}}^{i} \mathbf{F}_{\mathrm{v}}^{i} = \mathbf{F}_{\mathrm{ep}} \mathbf{F}_{\mathrm{p}} \tag{3}$$

which is analogous to the additive decomposition used under small strain conditions. The constitutive relationships for the isotropic components were obtained from the entropy inequality of the porous medium (Ehlers, 2002):

$$\mathbf{S}_{\mathrm{S}}^{\mathrm{E}} : \dot{\mathbf{E}}_{\mathrm{s}} - \rho_{\mathrm{S0}} \left(\bar{\psi}_{\mathrm{S}}\right)_{\mathrm{S}}' - \hat{\mathbf{p}}_{\mathrm{F}}^{\mathrm{E}} \cdot \mathbf{w}_{\mathrm{F}} \geq 0 \tag{4}$$

by assuming Darcy's law for the description of possibly anisotropic fluid flow through the porous solid, the third item can be satisfied. $\bar{\psi}_{\mathrm{S}} = \bar{\psi}_0 + \sum_i^2 \bar{\psi}_{\mathrm{ov}}^{i} + \bar{\psi}_{\mathrm{p}}$ as specific Helmholtz free energy. Isotropic permeability is assumed based on the experimental results.

For the formulation of the fibre layer, the i^{th} fibre direction is defined in the undeformed configuration with a unit vector field $\mathbf{a}_0^i(\mathbf{X}, t)$. Fibres are assumed to be evenly distributed in the horizontal plane such that the fibre distribution is described by a unit circle in the reference configuration without considering any out-of-plane fibres.

During deformation, the fibre vectors $\mathbf{a}_0^i$ are stretched and/or rotated to their representation in the current configuration $\tilde{\mathbf{a}}^i = \mathbf{F}\mathbf{a}_0^i$. Defining the structure tensor $\mathbf{M}^i$ in the undeformed configuration as

$$\mathbf{M}^i = \mathbf{a}_0^i \otimes \mathbf{a}_0^i \tag{5}$$

and introducing a pseudo-invariant I_4^i for the anisotropic component of the constitutive relationship as $I_4^i = \mathrm{tr}\left(\mathbf{M}^i \mathbf{C}\right)$, the 2PK stress for all fibre contributions are added up via

$$\mathbf{S}_{\mathrm{ani}} = 2 \sum_{i}^{n_{\mathrm{fib}}} \frac{\partial \psi_{\mathrm{ani}}^{i}}{\partial I_4^i} \mathbf{a}_0^i \otimes \mathbf{a}_0^i \tag{6}$$

where anisotropic Helmholtz free energy density functions ψ_{ani}^{i} have been added to the previous definitions. Both tensile and compressive behaviour of the fibres

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are included and follow different constitutive formulations. Equation (6) is motivated by the integration over the unit circle. While the material is transversely isotropic in the undeformed state, material symmetry evolves due to deformation-induced anisotropy in the horizontal plane as well as the direction-dependent distinction whether a given fibre family is loaded in a tensile or compressive manner.

CONCLUSION

Peat fibres can be subjected to both compression and tension affecting both its rate-dependent behaviour and compressive failure modes. The integration approach by adding continuously distributed fibre families is straightforward to implement and versatile in simulating complex anisotropy patterns. This research shed light onto the mechanical effects of fibres inherent to peat as well as an advanced constitutive modelling approach for structural anisotropy in geomaterials.

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