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Large scale triaxial compression tests on three peat samples from Eemdijk, the Netherlands

Essais de compression triaxiale à grande échelle sur trois échantillons de tourbe d'Eemdijk, aux Pays-Bas

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ABSTRACT: The fibrous nature of peat introduces complexity in describing its mechanical behavior. Large fibres have sizes in the same order of magnitude as the dimensions of conventional specimen for laboratory testing. Therefore, size effects are expected when analyzing conventionally sized laboratory tests on peats. This paper shows the results of three large triaxial tests conducted on peat and gives a comparison with previously obtained results. In undrained shearing the pore pressure builds up until the lateral effective stress is reduced to zero. When shearing continues a (semi) drained stress path is followed. The samples fails along clear sliding planes, which are usually not found in conventional sized tests. This behavior can be explained by sliding or rupture of the fibres, which is dominated by displacement rather than strain. Failure is found at an elongation of the diameter in the order of 3 to 5 cm, equivalent to previously obtained results. The mobilized fibre reinforcement is in the order of 10 to 15 kPa.

RÉSUMÉ: La nature fibreuse de la tourbe rend complexe la description de son comportement mécanique. Les larges fibres ont des tailles du même ordre de grandeur que les dimensions des échantillons conventionnels des essais en laboratoire. Par conséquent, des effets de taille sont à prévoir lors d'analyse d'essais de taille conventionnelle en laboratoire. Ce papier montre les résultats de trois essais de larges compressions triaxiales réalisés sur de la tourbe et permet une comparaison avec des résultats obtenus précédemment. En cas de cisaillement non drainé, la pression interstitielle s'accumule jusqu'à ce que la contrainte effective latérale soit réduite à zéro. Lorsque le cisaillement se poursuit, un chemin de contrainte (semi) drainé est suivi. Les échantillons se rompent sur des plans de glissement clairs, que l'on ne trouve généralement pas dans les essais de taille conventionnelle. Ce comportement peut s'expliquer par le glissement ou la rupture des fibres, qui est dominé par le déplacement plutôt que par la contrainte. La rupture est constatée à une élongation du diamètre de l'ordre de 3 à 5 cm, équivalent aux résultats précédemment obtenus. Le renforcement en fibres mobilisé est de l'ordre de 10 à 15 kPa.

Keywords: organic soil, experimental testing, shear strength, heterogeneity

1 INTRODUCTION

Peat has a fibrous nature. The fibres consist of leaves, stems, rootlets, woody remains, plant remains etc. Through frictional forces and pullout resistance, fibres provide an internal reinforcement when load is applied perpendicular to their prevailing direction. Yamaguchi et al. (1985) found that the friction angle, determined from compression tests on a normally consolidated peat from Japan, varied from 52^0 to 35^0 when the major principal stress coincides with the vertical or horizontal direction respectively. The shearing resistance depends on the orientation of the failure plane relative to the general alignments of the fibers. Fibres that are aligned perpendicular to the major principal stress reinforce the soil, as a function of the friction between the fibres or between the fibres and the matrix and of the tensile strength of the fibres. (Landva, 2007)

The reinforcement provided by the fibers is discontinuous and the behaviour is strongly anisotropic. Stiffness and strength have an heterogenous behaviour at different scales, from microscopic level to the order of magnitude of meters. Conventional tests are dominated by heterogeneity at small level. The fluctuations in strength parameters due to small scale heterogeneity, in the order of centimeters, is not averaged in conventional laboratory tests.

For stability analysis of embankments on a peat foundation the governing heterogeneity occurs beyond the meter scale, while lab testing is dominated by heterogeneity at centimeter scale. Tests on conventional sized samples will overestimate the variation in strength parameters required for embankment stability which relates to meter level. Therefore, the use of conventional sized samples might lead to conservative design parameters.

Following a general rule of thumb, in order to apply continuum mechanics for soils the largest dimension of the soil particles should not more than $1/10^{th}$ of the smallest sample dimension. In conventional size samples, the fibres are large compared to sample dimensions.

To understand the influence of scale effects large element testing can be done as discussed by Zwanenburg & Van (2015). The heterogeneity at small level averages for large samples, leading to a smaller variation in operational shear strength compared to conventional sized tests. This paper presents the results of three slightly overconsolidated large triaxial tests on samples taken near Eemdijk, the Netherlands and discusses the influence of the heterogeneity at fibre level on the strength behaviour of peat samples. The samples reported in this paper are conducted in addition to previously conducted experiments (Zwanenburg & Van, 2015) to check if the findings are reproducible for different types of peat.

2 MATERIAL CHARACTERISTICS

The samples were taken from a site at Eemdijk, the Netherlands, approximately 25 km Northeast of Utrecht. At the test site the sub soil consist of a 1 m thick light non-organic clay layer, a 2.5 m thick peat deposit followed by a Pleistocene sand layer. Three samples, DLDS-01, DLDS-03 and DLDS-06, are collected at the same depth, 2.5m below ground level.

The water contents of DLDS-01 and DLDS-03 vary between 420 and 540%. The botanical background of the peat samples is mainly reed. The peat samples classified with von Post humification scale (a.o. Landva, 2007). Minor differences in humification between the samples are found: H4 (*slightly decomposed*) for DLDS-01, H3 (*very slightly decomposed*) for DLDS-03 and H2 to H3 (*almost entirely undecomposed* and *very slightly decomposed* respectively) for DLDS-06.

There is no large variation in the composition of the peat in the sample.

Table 1 describes some characteristics of the tested material. It should be noticed that no classification tests have been carried out for sample DLDS-03. As a matter of fact, since the height of the sample extracted from the Sampler was 0.79 m, all sample material was needed for the execution of the test.

Several boreholes and CPT tests in the location reveal a small variety of the subsoil. The average estimated vertical effective stress for the peat layer is equal to 16 kPa, and the K_0, averaged from five K_0-CRS tests, is equal to 0.2. The peat is slightly overconsolidated: the OCR varies between 1.2 to 2.5.

Table 1. Classification parameters: water content, w [%]; weight solid particles, γ_s [kN/m^3]; Loss of Ignition, LOI [%].

w [%]	**γ_s [kN/m^3]**	**LOI [%]**
540	15.35	79.8

3 TEST SET-UP

3.1 Soil sampling

The Deltares Large Diameter Sampler, DLDS, Figure 1, collect the peat samples in the field at the required depth. The DLDS is described by Zwanenburg (2017). The peat samples are taken with a metal cylindrical sampler with a cutting edge. The sampler has an internal diameter of 40 cm and a height of 1 m. Since the required specimen height is 0.80 m, the 1 m sample height allows trimming and therefore flattening of the top and bottom part of the specimen

Figure 1. Foto impression of the soil sampling

After being transported vertically to the laboratory in a conditioned transport the samples are stored in a temperature-conditioned room at 10 °C and 85% humidity. The samples are taken in September 2017 and tested between October 2017 and January 2018.

3.2 Large triaxial cell test set-up

The experimental set-up (Figure 2 and 3) for the tests is a large diameter triaxial cell, which tests a soil sample with a diameter up to 40 cm and a height of up to 80 cm. The sample is tested with a rigid bottom and top plate surrounded by a rubber membrane.

A 1 mm thick membrane protects the sample against water penetration from the cell and it allows the application of effective pressure in the sample. The water in the cell applies horizontal lateral pressure to the sample. The drain is connected to a buret. A back pressure of 300 kPa is applied by increasing both the buret pressure as the cell pressure. An initial difference of an 80 cm between buret and cell is applied (Figure 3). In this way an initial effective stress of 8 kPa is applied to the specimen.

A vertical pressure is applied to the sample by means of a hydraulic plunger.

Figure 2. Large triaxial test

3.3 Test procedure for large triaxial tests

The test procedure resembles a conventional compression test as closely as possible. After placing the sample into the triaxial cell, the cell is filled allowing the sample to consolidate. Back-pressure is then applied, with the purpose to reduce the amount of air in the sample.

The B-factor is determined in order to measure the saturation of the sample. The drainage tap between the buret and the sample is closed and the cell pressure is increased by 10 kPa. Next, the pressure is kept constant for at least half an hour before the cell pressure is reduced to the original level. The B factor is equal to 0.997, 0.999 and 0.989 for the three samples respectively.

The sample is subjected first to isotropic and then to anisotropic consolidation. Isotropic consolidation is reached through the application of effective pressure equal to 8 kPa and the opening of the drainage tap between buret and sample. Then, a vertical load is applied to achieve a ratio between horizontal and vertical stress of $K_0 = 0.2$, corresponding to the K_0 values found in conventional laboratory testing.

In this way, field stress conditions are simulated. This phase ends when the final value of the force is reached and the plunger displacement and the weight of the outflow water reach a constant final value, vertical strain rate and volume strain rate both less than 0.3% per day.

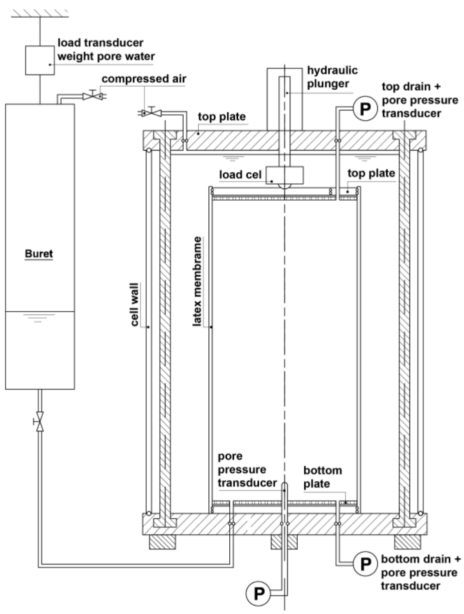

Figure 3. Schematisation of large triaxial test

After closing the drainage tap, the undrained shear phase is performed by imposing a shear rate of 4% per hour, that is consistent with conventional triaxial tests. The test is stopped when either the maximum stroke of the plunger is reached or when the sample, due to bulging, touches the cell. The applied displacement during shear is at leas25% axial strain.

The sample remains in the rubber membrane until the laboratory operator performs a examination of the sliding surfaces and other details.

4 TEST RESULTS

4.1 Results

Figure 4a shows the horizontal effective stress, σ'_h versus the vertical effective stress, σ'_v: due to pore pressure build up the horizontal effective stress reduces to almost zero during the shearing phase. It is hypothesized that from that point on some pore water can be stored between the membrane and sample due to the lack of lateral support. The sample will behave (partly) drained. As a consequence the stress path in the p'- q diagram, Figure 4b, will follow the line 1:3. This line corresponds to condition $\sigma'_h = 0$ and is therefore referred to as the tension cut off, TCO, line. It should be noted that this behaviour is also found in conventional sized tests.

The q - ε_a diagrams of the performed large triaxial tests, in Figure 6, show good mutual similarities, proving the fact that the tests are well reproducible. Collapse occurs at a vertical strain of 15% and an absolute vertical displacement of approximately 12 cm. After the occurrence of failure, the deviator stress does not immediately reduce to 0 kPa. A residual strength remains which is reduced once again when the axial strain reaches approximately 20 - 21%. The samples fail along clear sliding planes, see Figure 7 and the residual strength follows from the friction along the sliding planes and stretching of the membrane.

The photographs at the end of the test, Figure 5, show a clearly sheared sample. One or more sliding surfaces are clearly visible and the membrane is bent over at the location of the shearing surfaces.

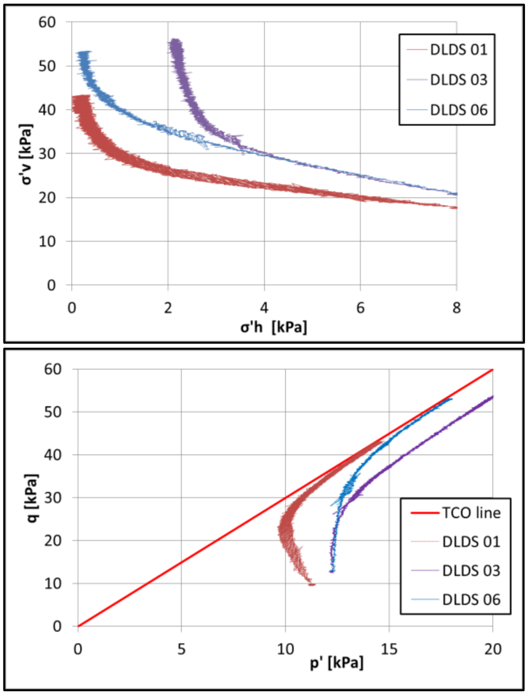

Figure 4. Test results a) horizontal effective stress σ'_h vs vertical effective stress σ'_v ; b) deviatoric stress q vs Isotropic effective stress p'

Figure 5 Overview of the sample after the large TXT. After removal of the membrane, the pieces of the sample disintegrated by failure.

Zwanenburg & Van (2015) show that failure of the samples is typical for testing large sized samples and is not found for conventional sized samples. For conventional sized samples, usually, a continuous increase in deviator stress is found until maximum plunger displacement is reached.

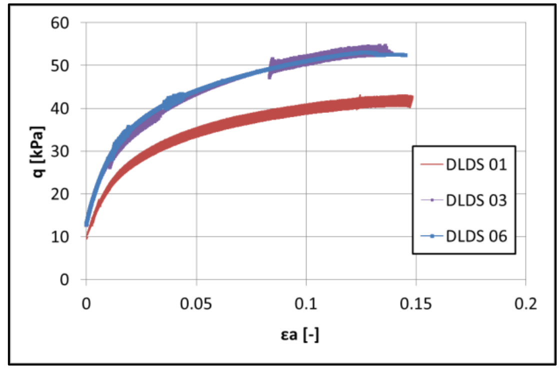

Figure 6 Deviatoric stress q vs axial strain ε_a

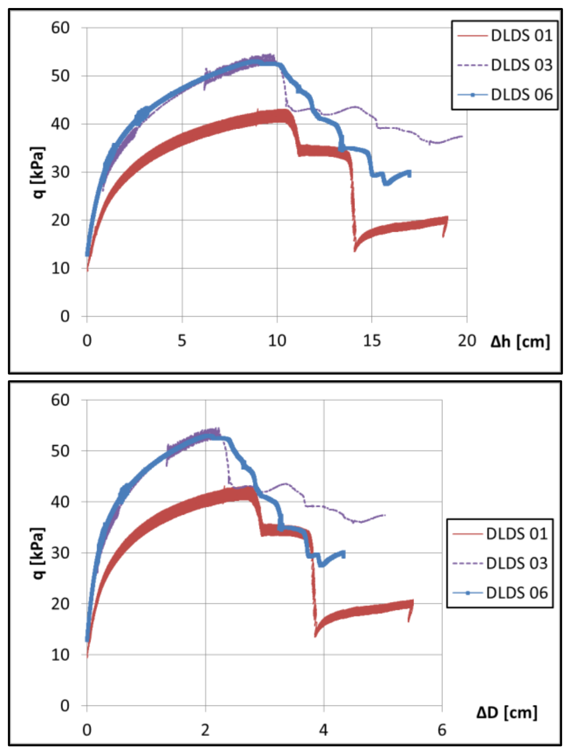

Figure 7 Deviatoric stress q vs vertical deformation Δh (above) and Deviatoric stress q vs horizontal deformation ΔD (below)

It is hypothesized that failure of the peat samples is not related to strain, rather than actual displacement. The strength of the peat fibers are mobilized when deformation develops. As a result of the imposed deformation, the fibres stretch and finally break or slip upon collapse. The strength behaviour of the peat is thus related to the actual deformation and not to the strain, which is instead a relative measurement. Figure 7 shows the deviatoric stress development as a function of the vertical displacement and radial displacement.

4.2 Fiber contribution

Cola & Cortelazzo (2005) describe a practical procedure to establish the contribution of the fibres to the strength of peat. The procedure compares the observed strength from tests on fibrous material to the strength observed in tests on the same material in which the fibre action is absent. Assuming a dominant horizontal fibre direction, this behaviour can be found from direct simple shear, DSS, testing, in which shearing is conducted parallel to the main fibre orientation. For the Eemdijk location an extended series of DSS has been conducted. The combination of large triaxial test results and the conventional sized DSS test results enables the assessment of the mobilized fibre resistance.

Cola & Cortelazzo (2005) found a clear stress dependency of the mobilized fibre reinforcement. The present tests do not provide enough information to study the stress dependency of the fibre reinforcement. However, the large triaxial tests are conducted at field stress level, which is the same for each of the tested samples, which allows for mutual comparison.

Following Cola & Cortelazzo (2005), the maximum horizontal stress provided by the fibers σ_R (kPa) is given by:

$$\sigma_R = |\sigma'_{3,f} - \sigma'_{3,m}| \quad (1)$$

where $\sigma'_{3,f}$ (kPa) is the minor principal stress at failure found in the large triaxial testing and $\sigma'_{3,m}$ (kPa) is the minor principal stress at failure found for DSS testing. Equation 1 is visualized by Figure 8. The figure shows the failure line for loading conditions for which the reinforcement of the fibres is activated and the failure line for loading conditions for which the fibre reinforcement is not activated.

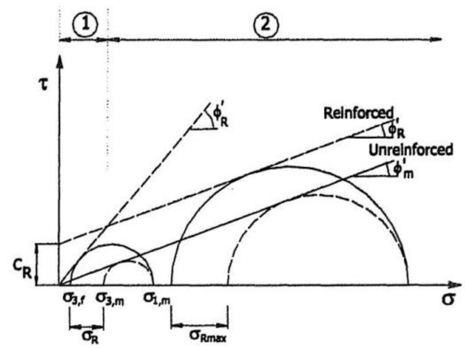

Figure 8. Derivation of the horizontal stress provided by the fibers (Cola & Cortelazzo, 2005)

In conventional DSS tests, the shear stress remains constant at large strain and the strength is therefore independent from the strain (Figure 9).

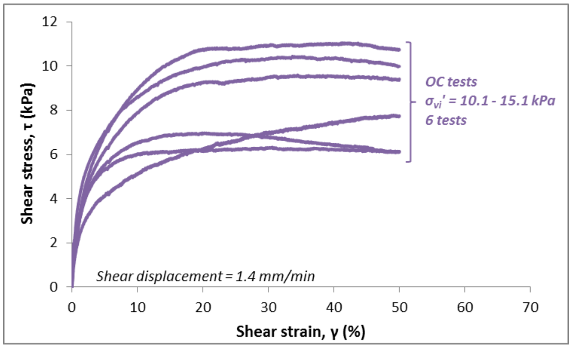

Figure 9. Shear stress versus shear strain for conventional DSS

Figure 10 shows the stress conditions at failure for the large triaxial tests by the Mohr's circles. The conventional DSS test results are shown by their vertical stress, σ'_v and shear strain, τ at 40% strain. A best fit regression line through the data points is shown, $\tau = 0.734\ \sigma'_v$, indicating $\varphi'_{DSS} = 36.3°$.

To establish the fibre contribution Mohr circles are drawn, through the σ'$_1$ found in the large triaxial tests and touching the DSS failure line. The results are shown by Figure 10.

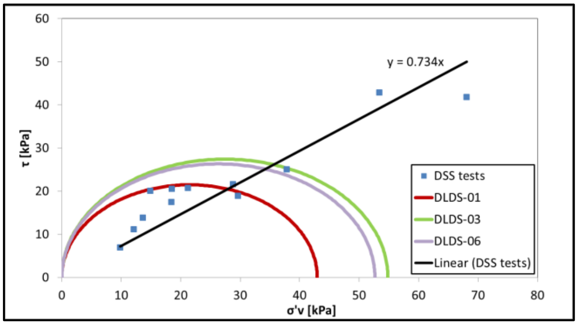

Figure 10. Mohr plane showing the results of the large TXT at failure and results of the DSS tests at 40% strain. The latter are plotted and fitted with a trendline.

Finally the fiber contribution can be derived using equation (1). Table 2 shows the results. The value for σ_R show a small range in mobilized fibre force between the three samples. It should be noted that DLDS-01 has a lower $\sigma'_{1,f}$ at failure, however, σ_R is in the same range as found for the other tests, indicating a good reproducibility for the estimation of the mobilized fibre resistance. For the tested stress conditions the estimated horizontal stress in the fibres at failure is in the range of 10 to 15 kPa.

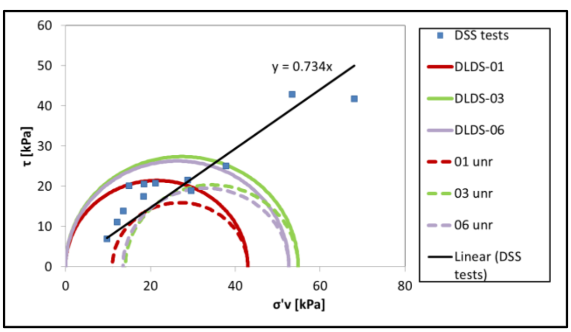

Figure 11. Mohr's circles for reinforced and unreinforced material.

Table 2. Fibre contribution

test nr	σ'$_{1,f}$ [kPa]	σ'$_R$ [kPa]
DLDS-01	42.96	11.02
DLDS-03	54.84	14.07
DLDS-06	52.65	13.50
average		12.9

4.3 Comparison to previous test results

Figure 12 shows the results of large triaxial tests described by Zwanenburg & Van (2005). The peat used for the tests has a low density and it is defined as H2-H3 in the von Post classification with mainly Phragmites (with sedge and sphagnum inclusions).

Equivalent to the tests from the Eemdijk location, the excess pore pressure builds up during the shearing phase until radial effective stress reduces to 0 kPa. On continuous shearing the stress path follows the line $p' = 3\ q$. Equivalent to the behaviour shown by Figure 4b.

Figure 11b shows the change in diameter, ΔD of the specimen during the shearing phase of the tests described by Zwanenburg & Van (2015). During the consolidation phase the specimen reduces in volume leading to reduction in diameter. At the start of the shearing phase the actual diameter is smaller than the initial diameter. As a consequence negative values for ΔD are shown in Figure 11b at the start of the shearing phase. During the shearing phase the sample bulges. It is assumed that after reaching the initial diameter, the fibres start acting as a reinforcement. Bulging of the specimen during shearing continues until a 3 to 4 cm elongation of the diameter, after which failure is found. This is in the same order of magnitude as found in Figure 6b for the Eemdijk tests, where failure is found after a 2.5 to 3 cm diameter elongation.

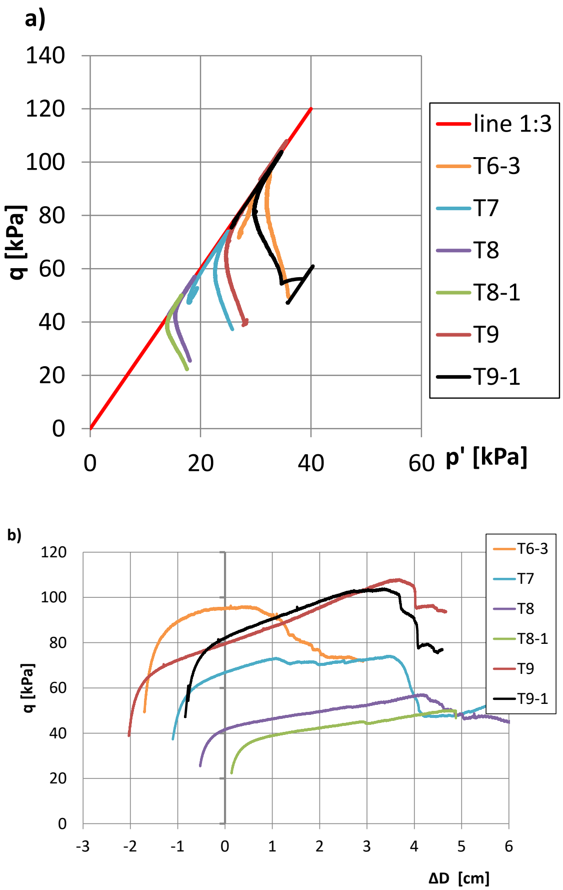

Figure 12. Previous test results a) deviatoric stress q vs isotropic effective stress p' b) Deviatoric stress q vs horizontal deformation ΔD from: Zwanenburg & Van(2015)

5 CONCLUSION

In total three large triaxial tests on peat samples from Eemdijk, The Netherlands, have been conducted. The results are compared to previously obtained results.

The samples fail in the same failure mode as in previously conducted tests. During the shearing phase pore pressure builds up until the lateral effective stress is reduced to 0 kPa. Clear sliding planes are found in large triaxial testing, which is not found in tests on conventional sized samples.

It is stated that the mobilized fibre reinforcement is induces by applied displacement rather than applied strain. For both, the Eemdijk samples and previously tested samples, the diameter elongation at failure is about 2.5 to 4 cm.

Comparing different testing conditions provides an approximation of the mobilized fibre resistance in the order of 10 to 15 kPa. This shows that the presence of the fibre matrix has a clear influence on the strength development of peat.

6 ACKNOWLEDGEMENTS

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