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Geotechnical properties of stabilized peat

Propriétés géotechniques de la tourbe stabilisée

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ABSTRACT
Unstabilized peat is very compressible; the relative compression may be up to 60%, defined at a stress increase of 80 kPa. It has a high permeability, normally within the interval 10^{-5} - 10^{-7} m/s, and low shear strength and bulk density ($\rho \approx 1000$ kg/m^3). On the other hand the laboratory stabilized peat (the stabilizer used for stabilization was 80% Merit 5000 and 20% cement and its quantity was 200 kg/m^3) has a high elasticity modulus (E_{50} = 149 - 230 MPa for fibrous peat and E_{50} = 131 - 141 MPa for pseudo-fibrous peat), stiffness (M_L = 9.3 MPa for fibrous peat and M_L = 10 MPa for pseudo-fibrous peat) and shear strength (c_u = 386 - 402 kPa for fibrous peat and c_u = 305 - 393 kPa for pseudo-fibrous peat), and low permeability ($k_0 = 10^{-10}$ m/s for fibrous peat and $k_0 = 10^{-9}$ m/s for pseudo fibrous peat). To achieve this, the stabilized peat must cure for at least 7 days and be loaded with an 18 kPa load while curing.

RÉSUMÉ
La tourbe non-stabilisée est très compressible; la compression relative peut atteindre 60%, définie à une contrainte de 80 kPa. Elle a une perméabilitée élevée, normalement entre 10^{-5} - 10^{-7} m/s, et une faible résistance au cisaillement ainsi qu´une faible masse volumique (1000 kg/m^3). D'un autre côté, la tourbe stabilisée (le stabilisateur utilisé pour la stabilisation était 80% Merit 5000 et 20% ciment, et sa quantité était de 200 kg/m^3) a un module élastique élevé (E_{50} = 149 - 230 MPa pour une tourbe fibreuse et E_{50} = 131 - 141 MPa pour une tourbe pseudo-fibreuse), une résistance à la compression élevée (M_L = 9.3 MPa pour une tourbe fibreuse et M_L = 10 MPa pour une tourbe pseudo-fibreuse), une résistance au cisaillement élevée (c_u = 386 - 402 kPa pour une tourbe fibreuse et c_u = 305 - 393 kPa pour une tourbe pseudo-fibreuse), et une faible perméabilité ($k_0 = 10^{-10}$ m/s pour une tourbe fibreuse et $k_0 = 10^{-9}$ m/s pour une tourbe pseudo-fibreuse). Ces propriétés sont atteintes dans une tourbe stabilisée, après une période d'au moins 7 jours après le traitement et avec un chargement de 18 kPa appliqué au cours de cette période.

1 INTRODUCTION

The low compressibility moduli and low bearing capacity of peat make it unsuitable as a base for road and railway embankments. When encountering peat, the usual procedure has therefore been to excavate it and replace it with crushed rock. Since the beginning of the 1990's an alternative method has been developed, which eliminates some of the disadvantages associated with the soil replacement method. The method is called mass stabilization (the term 'block stabilization' is also used). In mass stabilization, the peat is left in place and its geotechnical properties are improved by mixing in a chemical stabilizer, preferably cement or cement combined with different by-products from industrial processes. The goal is to create a block (monolith) of strengthened peat, which spreads the load from the embankment to deeper soil layers. The block normally has a thickness that varies with the height of the embankment, i.e. between 1 and 5 m. This block must have certain shear and tensile strengths, elasticity moduli and homogeneity to fulfill its purpose. The surroundings to which the created block will be exposed are fairly acidic and for this reason a stabilization performed with the aforementioned stabilizers will probably not remain constant for a period equal to the technical lifetime of the road or railway.

Stabilization of peats using mass stabilization has increased significantly in Finland and Sweden during the last 10 years. The main applications have been to increase stability and reduce settlements in road and railway embankments constructed on peat. Mass stabilization has also been used for:

- foundations for oil and gas pipelines
- foundations for water pipelines and sewers
- foundations for buildings
- stabilization of hazardous (chemical) wastes
- stabilization of excavations for building foundations
- soil improvement for ground adjacent to buildings.

2 PEAT IN GENERAL

Peat is an organic soil, consisting principally of the remains of bog and fen plants that have accumulated during postglacial time. Peatlands develop through the overgrowing of open water bodies or through flooding of land. Peatlands are divided into bogs, fens and mixed mires. A single peatland can also comprise several different types of peat. The water content is high, 200 - 2500%, and decreases with increasing of degree of humification.

Peat has an inhomogeneous and anisotropic structure (different properties in different directions), which means that it is difficult to evaluate its properties (Landva, 1980). Peat is very compressible; the relative compression may be up to 60%, defined at a stress increase of 80 kPa (Jelisic, 2004). It has a high permeability, normally within the interval 10^{-5} - 10^{-7} m/s, and low shear strength and bulk density ($\rho \approx 1000$ kg/m^3) (Carlsten, 1988). When peat is loaded its permeability quickly decreases (Carlsten, 1988). With 50% compression, it is not unusual for only 1‰ of the original permeability to remain (Carlsten, 1988). A fibrous peat often has strength parameters similar to non-cohesive soils, while an amorphous peat is more similar to quick clay (Carlsten, 1988).

3 GEOTECHNICAL PROPERTIES OF STABILIZED PEAT

In order to study geotechnical properties (shear strength, tensile strength, compressibility modulus, elasticity modulus and permeability) of laboratory stabilized peat, laboratory tests (triaxial tests, undrained direct shear tests, unconfined compression tests, Brazilian tests, compression tests, CRS-tests and permeability tests) were performed on laboratory mixed samples. The laboratory stabilization of peat is carried out as follows:

1. The peat was investigated accurately and its water content, pH value, bulk density and organic content determined.
2. The peat was homogenized for approximately 5 minutes in a dough beating machine.
3. The homogenized peat was placed in a pre-weighed bowl.
4. The bowl with the homogenized peat was weighed.
5. A predetermined stabilizer with a determined quantity of stabilizer was added to the homogenized peat and the whole mass was mixed for approximately 5 minutes in the dough beating machine. For example, if the quantity of the stabilizer was 200 kg/m^3 and 1 kg peat was used in the test, then 200 g stabilizer was needed.
6. The mixture (peat and stabilizer) was compacted by hand in cases with a diameter of 68 mm (at least two cases for each mixture and storage time, i.e. at least two samples each mixture and storage time). The height of the sample in the case was approximately 195 mm.
7. The cases (samples) were stored at room temperature, approximately 20°C, and loaded with an 18 kPa load (a load corresponding to a 1 m embankment). The tops and bottoms of the cases were equipped with filters and the cases allowed access to the water both from above and below.
8. The deformation that occurred during loading (curing/compressing) was measured.
9. After 30 days, the shear strength for the mixture was determined by the unconfined compression test, which had a deformation rate of 2 mm/min.

The stabilizer used for stabilization was 80% Merit 5000 and 20% cement and its quantity was 200 kg/m^3.

Merit 5000 is granulated blast-furnace slag, which has been ground to obtain a specific area of 5000 cm^2/g.

The laboratory tests were a part of Jelisic's doctor's thesis (Jelisic, 2004).

To be able to determine the effect of stabilization, it is necessary to know the geotechnical properties of the unstabilized peat. Therefore, these were studied and determined in this project. Two types of laboratory tests were performed on unstabilized peat samples: undrained direct shear tests and compression tests.

In the undrained direct shear test, the unstabilized peat had been consolidated with a 40 kPa load before shearing started. A shear rate of 0.001 mm/min was used in tests.

In the compression test, a number of rings replace the oedometer ring. The additional rings are placed with a reciprocal space between them so that they can move during compression of the sample without causing frictional forces between the ring and the sample. The compression test is used almost solely for non-cohesive soils. Because an unstabilized undisturbed fibrous and pseudo-fibrous peat has strength and consolidation parameters similar to a non-cohesive soil (Landva, 1980 and Carlsten, 1989), it was decided to use the compression test in these tests, instead of the CRS test.

Because of limited space of this article the geotechnical properties of the unstabilized peat are not shown and the reader is referred to Jelisic's doctor's thesis (Jelisic, 2004).

3.1 *Shear strength*

According to Landva (1980), the unstabilized fibrous (humification degree H1-3) and pseudo-fibrous (humification degree H4-6) peat have low drained shear strengths ($c' = 2$ - 3 kPa and $\Phi' = 27$ - 33°).

An evaluation of the drained parameters (Φ' and c') was made, but since it should be based on at least two samples of the same mixture with different stress levels and the evaluation of the drained parameters presented in this project was based on only one sample per type of peat, the evaluated drained parameters should be used with caution. The friction angle Φ' has been assumed to be 30° in order to enable an evaluation of the drained parameters of both types of peat. Comparisons between stabilized fibrous (humification degree H1) and pseudo-fibrous peat (humification degree H5) show that higher cohesion values c' were obtained in stabilized fibrous peat (179 kPa) than in stabilized pseudo-fibrous peat (99 kPa), see Table 1.

Table 1: Result of the triaxial tests on stabilized samples.

Type of peat	E_{50} inner gauge 1 (MPa)	E_{50} inner gauge 2 (MPa)	E_{50} outer gauge (MPa)[3]	ϕ'[4] (°)	c' (kPa)
Pf[1]	230	149	71	30	179
Pp-f[2]	131	141	57	30	99

[1] Fibrous peat (humification degree H1).
[2] Pseudo-fibrous peat (humification degree H5).
[3] E_{50} is the secant modulus of the stabilized peat evaluated at half the major principal stress at failure.
[4] The friction angle Φ' has been assumed to be 30° in order to enable an evaluation of the drained parameters of both types of peat.

The undrained shear strength values of the stabilized fibrous peat (humification degree H1) obtained by direct shear tests vary between 386 and 402 kPa (see Fig. 1 and 2) and those of the stabilized pseudo-fibrous peat (humification degree H5) vary between 305 and 393 kPa (see Fig. 3 and 4). Two tests were carried out on each type of peat. The shear deformations vary between 9 and 16 rad/100 for the stabilized fibrous peat and between 9 and 12 rad/100 for the stabilized pseudo-fibrous peat. Furthermore, the undrained shear strengths of the stabilized fibrous peat (consolidated with an 18 kPa load) are almost 20 times higher than the shear strengths of the unstabilized fibrous peat (consolidated with a 40 kPa load). The shear strengths of the stabilized pseudo-fibrous peat (consolidated with an 18 kPa load) are approximately 17 times higher than the shear strengths of the unstabilized pseudo-fibrous peat (consolidated with a 40 kPa load).

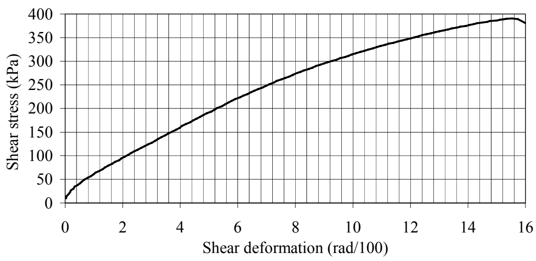

Figure 1. Undrained shear strength of stabilized fibrous peat.

Figure 2. Undrained shear strength of stabilized fibrous peat.

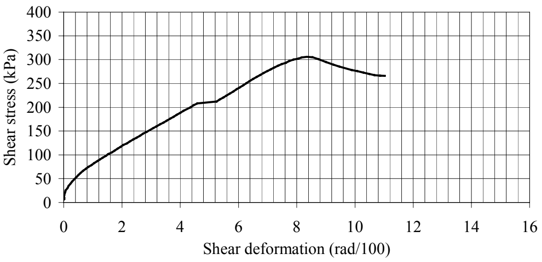

Figure 3. Undrained shear strength of stabilized pseudo-fibrous peat.

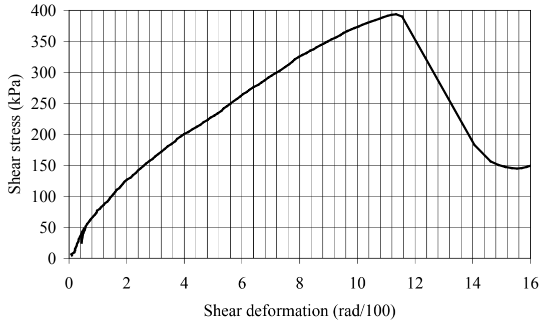

Figure 4. Undrained shear strength of stabilized pseudo-fibrous peat.

The undrained shear strength values obtained by unconfined compression tests on the samples with a diameter of 68 mm are in the order of 230 kPa for the stabilized fibrous peat (humification degree H1) and 200 kPa for the stabilized pseudo-fibrous peat (humification degree H5), while those from the samples with a diameter of 100 mm are in the order of 425 kPa for the stabilized fibrous peat (humification degree H1) and 285 kPa for the stabilized pseudo-fibrous peat (humification degree H5).

The shear strengths obtained by direct shear tests on stabilized fibrous peat (humification degree H1) and stabilized pseudo-fibrous peat (humification degree H5) are higher by 41% and 43%, respectively, than the shear strengths obtained by unconfined compression tests (a diameter of 68 mm).

3.2 *Tensile strength*

According to Landva (1980), the unstabilized fibrous (humification degree H1-3) and pseudo-fibrous (humification degree H4-6) peat have low tensile strengths.

The tensile strength values of the stabilized fibrous peat (humification degree H1) obtained from Brazilian tests are in the order of 240 kPa and those of the stabilized pseudo-fibrous peat (humification degree H5) vary between 120 and 150 kPa. Two tests were carried out on each type of peat. These values indicate that both types of stabilized peats have high tensile strengths, in particular stabilized fibrous peat, and that both types of stabilized peats can be exposed to large horizontal tensile stresses without cracking in the mass stabilized block.

The Brazilian tests were performed according to ISRM's standard (ISRM, 1981) with the following changes: the samples have a diameter of approximately 100 mm and length of 100 mm and the axial strain rate was of 1.8 mm/min.

The ratio of shear strength to tensile strength was found to be 2, i.e. the tensile strength is half the shear strength.

A comparison between the tensile strengths of stabilized fibrous peat (humification degree H1) with the tensile strengths of stabilized pseudo-fibrous peat (humification degree H5) shows that the tensile strengths of stabilized fibrous peat are approximately 40 - 50% higher than the tensile strengths of pseudo-fibrous peat. An explanation for this difference is that the fibre in the peat improves the tensile strength of the stabilized peat. For example, stabilized fibrous peat, which has more fibre than pseudo-fibrous peat, has greater tensile strength than pseudo-fibrous peat. Furthermore, it should be mentioned that Porbaha et al. (2000) concluded that an increase in initial water content significantly reduces the compressive strength of the mixture (cement/soil) for any particular quantity of cement. Fibrous peat has larger water content than pseudo-fibrous peat and therefore it might be expected that fibrous peat would have smaller tensile strengths than pseudo-fibrous peat. However, the opposite applies owing to the fibre content in the peat.

The tensile strength of the stabilized peat was calculated with the equation:

$$\sigma_T = \frac{2 \cdot P}{\pi \cdot D \cdot L} \qquad (1)$$

where P = failure load, D = diameter of sample and L = length of sample.

3.3 *Elasticity modulus*

According to the Dutch Ministry of Transport, Public Works and Water Management (1999), the unstabilized fibrous (humification degree H1-3) and pseudo-fibrous (humification degree H4-6) peat have low elasticity moduli E_{50} = 0.2 - 1 MPa.

The secant modulus E_{50} values obtained by triaxial test vary between 149 and 230 MPa for the stabilized fibrous peat (humification degree H1) and between 131 and 141 MPa for the stabilized pseudo-fibrous peat (humification degree H5), see Table 1. Two consolidated drained triaxial tests (one test for each type of peat) were performed.

The ratio of 1 kPa shear strength to 450 kPa elasticity modulus (secant modulus) was obtained from the shear strength values, which were obtained by unconfined compression tests, and the elasticity modulus (secant modulus) values, which were obtained by triaxial tests.

Both the inner strain gauges and one outer strain gauge were used to measure the axial deformation, which was used as a base for the calculation of the secant modulus E_{50}. The inner gauges are not influenced by fault sources (if a sample is rigid and brittle) and therefore only their results are analyzed in this section.

The secant moduli E_{50} of the stabilized fibrous peat (humification degree H1) are higher than the secant moduli E_{50} of the stabilized pseudo-fibrous peat (humification degree H5), which agrees with the results of other investigations in this project. Both types of peats have very high secant moduli E_{50}, i.e. both types are very stiff. Furthermore, the secant moduli E_{50} of stabilized fibrous peat (consolidated with an 18 kPa load) are approximately 380 times higher than that of unstabilized (unloaded) fibrous peat and that of pseudo-fibrous peat (consolidated for an 18 kPa load) are approximately 270 times higher than that of unstabilized (and unloaded) pseudo-fibrous peat.

3.4 *Compressibility modulus*

Figure 5 shows that between approximately 55 and 40% of deformation (compression) of the laboratory stabilized fibrous (humification degree H1) and pseudo-fibrous peats (humification degree H5), respectively, developed during the curing period of two hours. Approximately 99% of deformation (compression) developed in both types of peats during the first 24 hours, which means that the compression developing in laboratory stabilized cured peat (Jelisic, 2004) is slightly slower than that developing in unstabilized peat (Landva, 1980), although it can still be considered very rapid.

The compressibility modulus (M_L) value of stabilized fibrous peat (humification degree H1) obtained by CRS-test is in the order of 9.3 MPa and the compressibility modulus (M_L) value of stabilized pseudo-fibrous peat (humification degree H5) obtained by the same type of test is in the order of 10 MPa, see Table 2.

Table 2: Result of the CRS tests on stabilized samples.

Depth (m)	Type of peat	σ_c (kPa)	σ_L (kPa)	M_0 (MPa)	M_L (MPa)	M'	k_0 (m/s)
0 - 1	Pf [1]	330	780	18.6	9.3	1.8	6.34×10^{-10}
2 - 3	Pp-f [2]	300	800	20	10	3	2.63×10^{-9}

[1] Fibrous peat (humification degree H1).
[2] Pseudo-fibrous peat (humification degree H5).

The tests show that the compressibility moduli (M_L) of stabilized fibrous peat (consolidated with an 18 kPa load) are approximately 220 times higher than the values for unstabilized (and unloaded) fibrous peat and that for pseudo-fibrous peat (consolidated with an 18 kPa load) are approximately 150 times higher than the values for unstabilized (and unloaded) pseudo-fibrous peat.

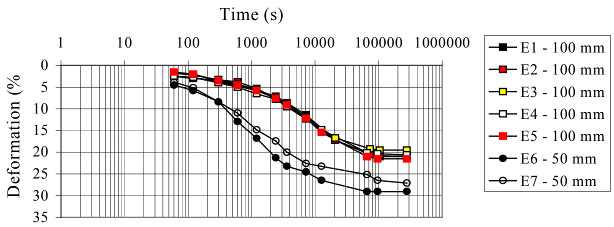

Figure 5. Deformation versus time under an 18 kPa load (curing/ compressing) for fibrous peat.

3.5 *Permeability*

The permeability was obtained by four permeability tests (two tests for each type of peat). The permeability tests were performed by using the pressure cell and according to Nordtest report 254 (Sjöholm et al., 1994). The permeability of the laboratory stabilized fibrous peat (humification degree H1) varies between 6.9×10^{-10} m/s and 3.4×10^{-10} m/s, and the permeability of the laboratory stabilized pseudo-fibrous peat (humification degree H5) varies between 1.5×10^{-9} m/s and 1.2×10^{-9} m/s. These values indicate that mass stabilization, in combination with an 18 kPa load, reduced the permeability of the fibrous peat from 10^{-5} and 10^{-6} (Carlsten, 1988) to 10^{-10} m/s (Jelisic, 2004) and that of the pseudo-fibrous peat from 10^{-6} (Carlsten, 1988) to 10^{-9} m/s (Jelisic, 2004).

4 DISCUSSION

The following differences appear to exist between unstabilized and laboratory stabilized peat:

- the unstabilized fibrous (humification degree H1-3) and pseudo-fibrous peat (humification degree H4-6) have low elasticity moduli (E_{50} = 0.2 - 1 MPa for both types of peats), while the stabilized peat has high elasticity moduli (E_{50} = 149 - 230 MPa for fibrous peat H1 and E_{50} = 131 - 141 MPa for pseudo-fibrous peat H5). The elasticity modulus E_{50} is 450 times the unconfined compressive strength.
- the unstabilized fibrous (humification degree H1-3) and pseudo-fibrous peat (humification degree H4-6) have a high permeability (high coefficient of permeability: $k_0 = 10^{-5}$ m/s for fibrous peat H1 and $k_0 = 10^{-6}$ m/s for pseudo-fibrous peat H5), while the stabilized peat has a low permeability (low coefficient of permeability: $k_0 = 10^{-10}$ m/s for fibrous peat H1 and $k_0 = 10^{-9}$ m/s for pseudo fibrous peat H5).
- the unstabilized fibrous (humification degree H1-3) and pseudo-fibrous peat (humification degree H4-6) have low undrained shear strengths (about c_u = 20 kPa for both types of peats, obtained by direct shear test), while stabilized peat has high undrained shear strengths (c_u = 386 - 402 kPa for fibrous peat H1, obtained by direct shear test, and c_u = 305 - 393 kPa for pseudo-fibrous peat H5, obtained by direct shear test).
- the unstabilized fibrous (humification degree H1-3) and pseudo-fibrous peat (humification degree H4-6) have low drained shear strengths (c' = 2 - 3 kPa and Φ' = 27 - 33° for both types of peats), while stabilized peat has high drained shear strengths (c' = 179 kPa with Φ' = 30° for fibrous peat H1 and c' = 99 kPa with Φ' = 30° for pseudo-fibrous peat H5). Observe that the friction angle (Φ') has been assumed to be 30° in order to en able an evaluation of the drained parameters of both types of peats.
- the unstabilized fibrous (humification degree H1-3) and pseudo-fibrous peat (humification degree H4-6) have low tensile strengths, while stabilized peat has high tensile strengths, 240 kPa for fibrous peat H1, obtained by Brazilian test, and 120 and 150 kPa for pseudo-fibrous peat H5, obtained by Brazilian test.

5 CONCLUSIONS

The peat fibre improves the geotechnical properties of the stabilized peat.

The stabilized fibrous peat (humification degree H1), which has more fibre than pseudo-fibrous peat (humification degree H5), has greater elasticity moduli, shear strengths and tensile strengths than pseudo-fibrous peat.

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