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Article

Consequences of drying on the hydro-mechanical response of fibrous peats upon compression

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Abstract

Peats are encountered in waterlogged deltaic areas, where degradation is delayed by favourable environmental conditions. The recent increase in frequency and severity of droughts is expected to accelerate peat degradation, in turn increasing subsidence and flood risk, urging better understanding of the response of peats to drying events. To this aim, compression tests on natural and reconstituted peat samples were performed, supported by X-ray micro-computed tomography. The peat fabric was found to be the key factor in the response to drying, with fibres playing the most significant role. Drying in peats starts affecting the macro-fabric, with an irreversible reduction in volume and disruption of the fibrous network occurring under saturated conditions until a threshold void ratio is reached, below which desaturation occurs of the intra-fibres and intra-peds pores. The first drying stage dramatically decreases the compressibility, while the hydraulic conductivity is hardly affected due to the enlargement of macropores. Secondary compressibility is affected by the peat fabric besides the organic content. The total organic content does not change substantially during drying; hence, it is not the best proxy to describe the consequences of drying on the response of fibrous peats. The fibre content can be better used to serve the aim.

Key words: fibrous peat, hydro-mechanical compression behaviour, fabric, drying–wetting cycles

Résumé

On trouve des tourbes dans les zones deltaïques gorgées d’eau, où la dégradation est retardée par des conditions environnementales favorables. L’augmentation récente de la fréquence et de la gravité des sécheresses devrait accélérer la dégradation des tourbières, augmentant ainsi les risques de subsidence et d’inondation, ce qui nécessite une meilleure compréhension de la réaction des tourbières aux épisodes de sécheresse. À cette fin, des essais de compression sur des échantillons de tourbe naturelle et reconstituée ont été réalisés, avec l’aide de la micro-tomographie à rayons X. Le tissu de la tourbe s’avère être le facteur clé de la réponse au séchage, les fibres jouant le rôle le plus important. Le séchage des tourbes commence à affecter le macro-tissu, avec une réduction irréversible du volume et une perturbation du réseau fibreux dans des conditions de saturation jusqu’à ce qu’un seuil de taux de vide soit atteint, en dessous duquel se produit une désaturation des pores intra-fibres et intra-peds. La première étape de séchage diminue considérablement la compressibilité, tandis que la conductivité hydraulique est à peine affectée en raison de l’élargissement des macropores. La compressibilité secondaire est affectée par le tissu de la tourbe en plus de la teneur en matières organiques. La teneur en matières organiques totales ne change pas de manière substantielle au cours du séchage, ce n’est donc pas le meilleur indicateur pour décrire les conséquences du séchage sur la réponse des tourbes fibreuses. La teneur en fibres peut être mieux utilisée pour l’objectif suivant. [Traduit par la Rédaction]

Mots-clés : tourbe fibreuse, comportement en compression hydromécanique, tissu, cycles séchage-humidification

Introduction

Peats are frequently encountered in the shallow subsoil of deltaic areas. In the Netherlands, they cover about 10% of the country, but they are widely distributed all over the world both in the Northern Hemisphere and in the tropical regions. Peats are recognized as “problematic soils”, owing to their high compressibility and long-term time-dependent response to loading. Although primary consolidation has a relatively short duration, long-lasting secondary compression is large, and its rate can increase over time when the so-called “tertiary compression” occurs (Mesri et al. 1997; Gunaratne et al. 1998; Colleselli et al. 2000).

Peat is formed in wet conditions, and waterlogged peat deposits are poor in oxygen, which together with low

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temperatures inhibits the growth of aerobic fungi and bacteria and delays the biodegradation of plant remains (Wardwell et al. 1983; Van der Heijden et al. 1994). However, the frequency and the severity of droughts are expected to increase dramatically in the near future (IPCC 2007; KNMI 2014), which will increase the susceptibility of peats to degradation. In deltaic regions, this will result in an increasing risk of subsidence, flooding, and loss of integrity of water defences, as the water availability from rivers, canals, and ditches is not expected to be high enough to compensate for increasing evaporation rates (Nichol and Farmer 1998; Hoving et al. 2008). In the Netherlands, severe climatic conditions have been recognized to be responsible for dyke failures over the last century (e.g., van Baars 2005) and increased rates of subsidence in urban and rural areas (Kok and Hommes-Slag 2020; Stouthamer et al. 2020). Management and adaptation strategies are being developed (Hoogheemraadschap van Rijnland 2009) to reduce the costs of soil subsidence in peat areas, which may run into billions of euros. Understanding of the consequences of drying on the fabric and engineering behaviour of peats is crucial to understand the potential consequences of drying on structures on peat and to design proper mitigation measures.

In the literature, the complex compression behaviour of peats has been related to different state variables, including water content, initial void ratio, and organic and fibre content (Gofar and Sutejo 2007; Mesri and Ajlouni 2007). Fibres are considered to be of special interest for peats, as they allow fabric arrangements different from those of mineral soils, and they are claimed to be responsible for peculiar aspects of their hydro-mechanical response (Edil 2003). The role of fibres on the mechanical response of peats has been discussed often in relation to shear strength, after the observation that increasing the fibre content results in an enhanced reinforcing effect, which increases the shear strength (Long 2005; Kumar et al. 2006; Mesri and Ajlouni 2007; Hendry et al. 2012). The relevance of fibres on the fabric of peats, specifically their entanglement, has been confirmed using scanning electron microscopy, SEM (Elsayed 2003). However, more fabric features are of relevance on the hydro-mechanical response of peats, and specifically on their compression behaviour, including highly irregular and interconnected large pores, as well as smaller open pores, dead-end pores, and isolated closed or partially closed pores (Quinton et al. 2009; Rezanezhad et al. 2010). The multi-porosity structure, confirmed by many researchers (Hayward and Clymo 1982; Yamaguchi et al. 1985; Kazemian et al. 2011), is believed to be responsible for delayed compression under load. Shrinking and swelling of peats have been described as multistage processes in many studies performed over the last years (Pyatt and John 1989; Price 2003; Hendriks 2004; Kennedy and Price 2005; Oleszczuk and Brandyk 2008), highlighting that when very dry conditions occur, peats can undergo permanent physical and chemical changes causing moisture and volume losses, which can be recovered only to a very limited extent upon rewetting (Hobbs 1986; Pyatt and John 1989; Wösten et al. 1997).

Investigating the multiscale deformation mechanisms that follow from drying has a two-fold perspective. Volume changes as a direct consequence of drying are relevant to the immediate response of structures and infrastructure. Besides, understanding how the physical and geotechnical properties of natural peat change as a consequence of drying and wetting is of paramount importance to assist in the maintenance and to assure proper service conditions over time. The latter is the focus of this study, which presents the results of a series of one-dimensional compression tests on saturated samples of peat that had been previously subjected to drying events of variable duration. The study aims to investigate the changes in the fabric of peats during drying and their relevance on the engineering behaviour, and to quantify the changes in the compression and hydraulic behaviour of peats suffering from drying.

Materials and methods

Tested materials

Samples of natural fibrous peat were retrieved using a 106 mm diameter piston sampler at the Leendert de Boerspolder, a 6 ha island in the Kagerplassen, south of the Haarlemmermeer in the Netherlands (hereinafter, the samples are denoted by the borehole number and the tube number). Samples from B1008-4 were tested starting from the natural state, while samples from B1009-3 and B1009-4 were tested in reconstituted state. Reconstituted samples were prepared by mixing the material with demineralized water to a slurry with a water content of about 855%. The material was placed into a mould and consolidated under a vertical stress of 10 kPa. The initial water content, specific gravity, organic content, and fibre content were determined for each sample. The water content was determined by oven drying at 60 °C to avoid loss of organic mass (Head 2014). The specific gravity was measured with a gas expansion ultra-pycnometer. Loss on ignition was determined by placing a small amount of oven-dried sample in a muffle furnace at 500 °C for 5 h. The fibre content was determined as the percentage of the dry mass of fibres retained by the ASTM No. 100 sieves over the dry mass of the sample. The material was a sphagnum peat with an average fibre content of 30% with a predominant amount of fine fibres and few big reed fibres (ASTM 2008).

Fabric, organic content, and fibres were analysed on different but comparable samples in an attempt to identify their specific role in the response of the samples. Natural (B1008-4) and reconstituted samples (from B1009-3 and B1009-5) were tested to isolate the effect of drying on the natural fabric of the soil. The effect of organic content on the compression behaviour was investigated on the two samples B1009-3 and B1009-5 having different organic content (88% and 72%, respectively). To isolate the effect of fibres on the response upon drying, the fibres were removed, and parallel tests were conducted on the peat samples with no fibres. The properties of the tested samples are summarized in Table 1.

Testing programme

The variation in the soil physical–chemical properties, compression behaviour, and hydraulic conductivity due to drying was studied by comparing the response of peat

Table 1. Index properties, compression index, and swelling index for peat samples before and after drying.

Sample	Drying days	Water content after drying (%)	Void ratio after re-saturation	Fibre content (%)	Organic content (%)	G_s	λ	κ	Apparent yield stress (kPa)
B1008-4	0	711.4	10.96	35.96	90.57	1.421	2.201	0.276	15
B1008-4	2	666.5	10.32	34.65	90.22	1.425	1.888	0.223	16
B1008-4	7	419.2	7.40	20.77	78.06	1.519	1.363	0.149	25
B1008-4	14	264.1	4.92	17.59	59.79	1.680	1.170	0.118	41
B1008-4	21	147.9	3.74	26.61	88.03	1.445	0.854	0.088	80
B1008-4	30	76.4	1.12	10.64	89.00	1.455	0.166	0.025	150
B1009-3	0	744.4	10.56	26.75	88.30	1.420	1.809	0.312	—
B1009-3	7	340.4	8.85	17.15	88.15	1.437	1.509	0.278	—
B1009-3	14	123.4	4.75	15.56	87.83	1.450	0.497	0.139	—
B1009-3	21	10.3	4.41	14.50	88.84	1.401	0.313	0.100	—
B1009-3	31	5.3	3.59	13.93	89.27	1.472	0.091	0.077	—
B1009-5	0	708.0	11.55	30.65	72.22	1.527	2.037	0.266	—
B1009-5	7	431.2	9.63	23.12	76.08	1.475	1.653	0.204	—
B1009-5	14	123.4	7.95	18.89	73.89	1.490	0.930	0.136	—
B1009-5	21	10.3	3.11	17.72	73.60	1.470	0.341	0.064	—
B1009-5	31	7.2	3.06	16.93	70.23	1.500	0.107	0.053	—

samples subjected to air drying lasting different periods. The samples were dried in a climate-controlled room at 20 °C and a relative humidity of 50%. The drying period durations were 2, 7, 14, 21, and 30 days. At the end of the drying period, the samples were left equalizing for 48 h at constant water content. All the samples were re-saturated before starting the compression tests. Full saturation was achieved by saturating them under vacuum pressure of 80 kPa over 24 h. After the drying and re-wetting cycle and before starting the compression tests, the water content, particle density, fibre content, and organic content of the samples were determined.

Incremental loading compression tests were performed on samples 19.1 mm high having a diameter of 63.5 mm, with each step lasting 24 h in both the loading and unloading stages. All the tests were performed under strictly controlled environmental conditions, at constant temperature $T = 10$ °C and relative humidity RH = 90%, to avoid further sample degradation during the compression tests. To assist in the interpretation of the test results, a comparison between the fabric of undisturbed and reconstituted samples was attempted on two samples, which were investigated in a micro-computed tomography (CT) scanner. To maximize the resolution (which increases with decreasing sample size), the specimens were cut into small cubes having a side length of 35 mm, still representative of the peat fabric. Micro-CT scans were conducted on the samples after 24 and 72 h of drying to visualize the change in fabric due to the drying process. Owing to their small size, these samples dried faster than the samples tested in oedometer, and their water content, 340% and 150%, respectively, was used to identify their state in the discussion of the results. Similar water contents were reached by the samples tested in the oedometer after 10 days and 3 weeks of drying, respectively.

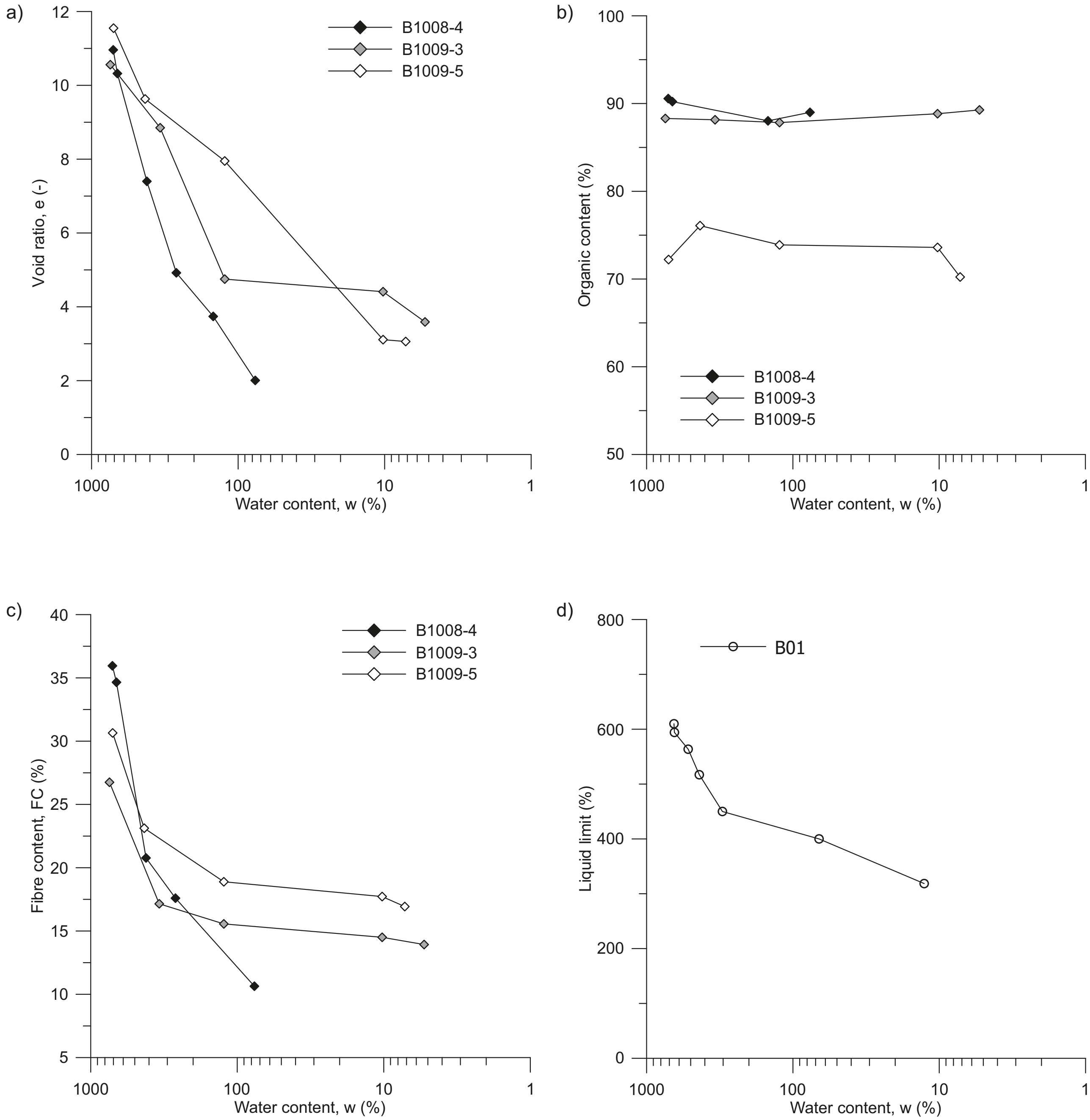
Experimental observations during drying of natural peat samples

Soil classification properties

In Table 1 and Fig. 1, relevant state variables of the different samples after drying are compared. The very high shrinkage potential of the organic material upon drying caused a dramatic change in the void ratio, which reduced from about 11 to nearly 2 after 1 month of drying. However, the detected amount of organic content did not change substantially with the drying period. The scatter in the organic content of the samples from tube B1008-4 is due to the natural heterogeneity of undisturbed peat and not to the drying period duration, as confirmed by the data on the more homogenous reconstituted samples in the same table. On the contrary, drying affects the fibre content, which decreases with the drying period. It is worth noting that the fibre content is a physical measure of the length of the fibres, not of their mass, which shows that drying breaks down the fibres into smaller pieces.

Irreversible drying processes in organic matter are accompanied by a reduction in the water retention capacity. This is well known from data on many grass-covered clayey peat and peaty clay soils, which may become even water repellent after a prolonged drying period (Dekker and Ritsema 1996). The reduced water storage capacity is testified by the significant decrease in the liquid limit of peat with drying (Fig. 1*d*). The falling cone penetrometer method was used to determine the liquid limit after removing the fibres longer than 425 μm. The liquid limit decreased linearly above an initial water content $w = 300\%$, as well as below $w = 300\%$, but at different rates, which suggests that different water storage mechanisms may be involved in the two ranges.

Fig. 1. Effect of drying on (*a*) void ratio; (*b*) organic content; (*c*) fibre content; (*d*) liquid limit.

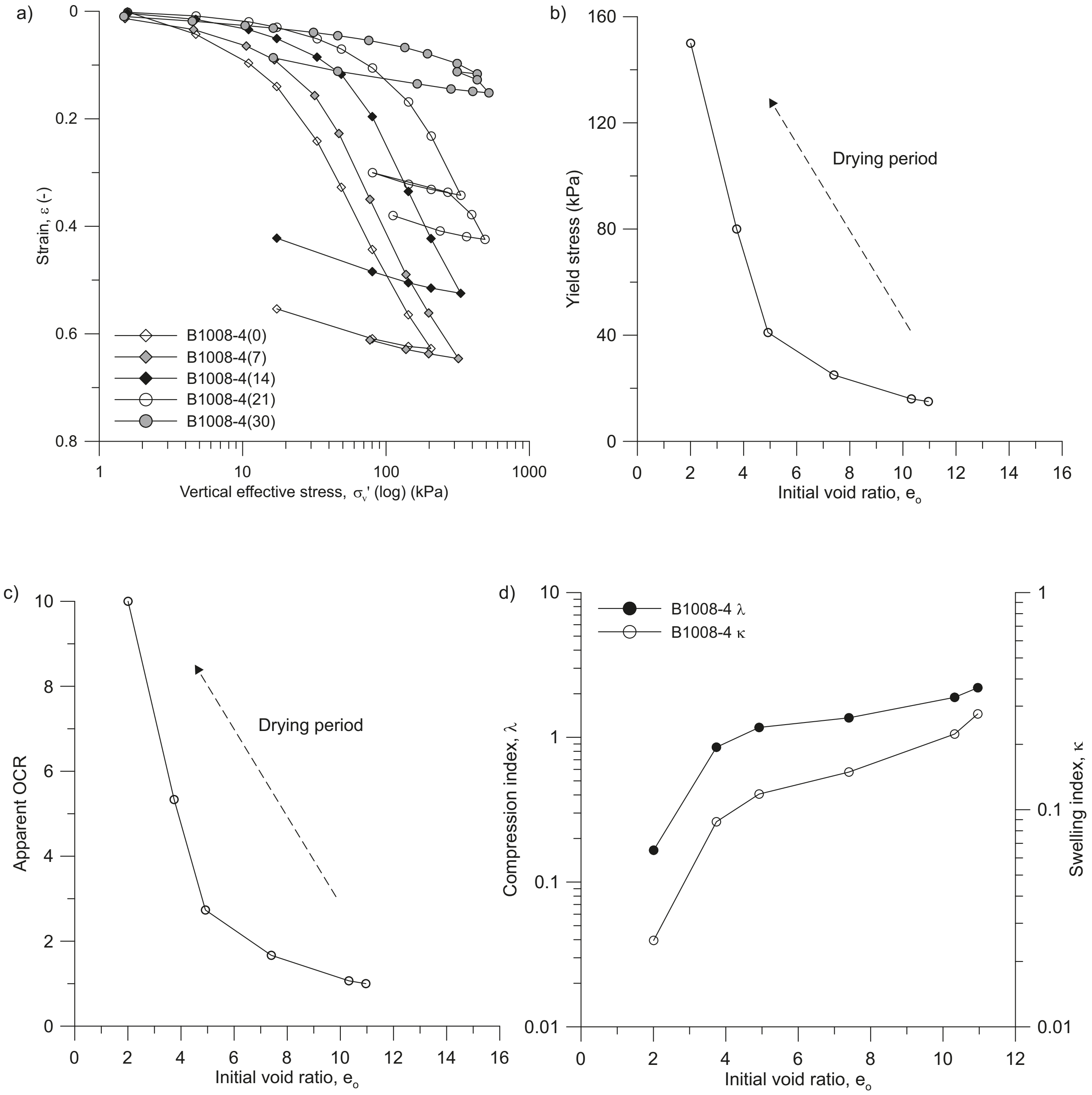


Compressibility and saturated hydraulic conductivity

The compression curves of sample (B1008-4) tested in the natural state and after drying and re-saturation are shown in Fig. 2*a* as a function of the linear strain ε. The compression curves show a typical "S" shape with a marked change in the slope corresponding to the yield stress, typically identifying a "structured" soil. The yield stress of the natural sample B1008-4(0) is around 15 kPa. The initial fabric of the natural sample is expected to remain relatively intact up to the yield stress and to be disrupted progressively once the preconsolidation pressure is overpassed, causing the overall compressibility to increase substantially. The results in Fig. 2*a* show that the drying process modifies dramatically the saturated compression behaviour of peat by increasing the yield stress and largely decreasing the compressibility. The yield stresses corresponding to the different drying durations are depicted in Fig. 2*b* as a function of the void ratio at the beginning of the oedometer tests (initial void ratio after drying and re-saturation). They were derived using Casagrande's (1936) graphical construction and are reported in Table 1. The same data are used in Fig. 2*c* to give a picture of the apparent overconsolidation ratio (OCR) induced by drying.

The saturated compressibility of the different samples after drying is compared using the loading index $\lambda = -\Delta e/\Delta \ln\sigma'_{\mathrm{v}}$

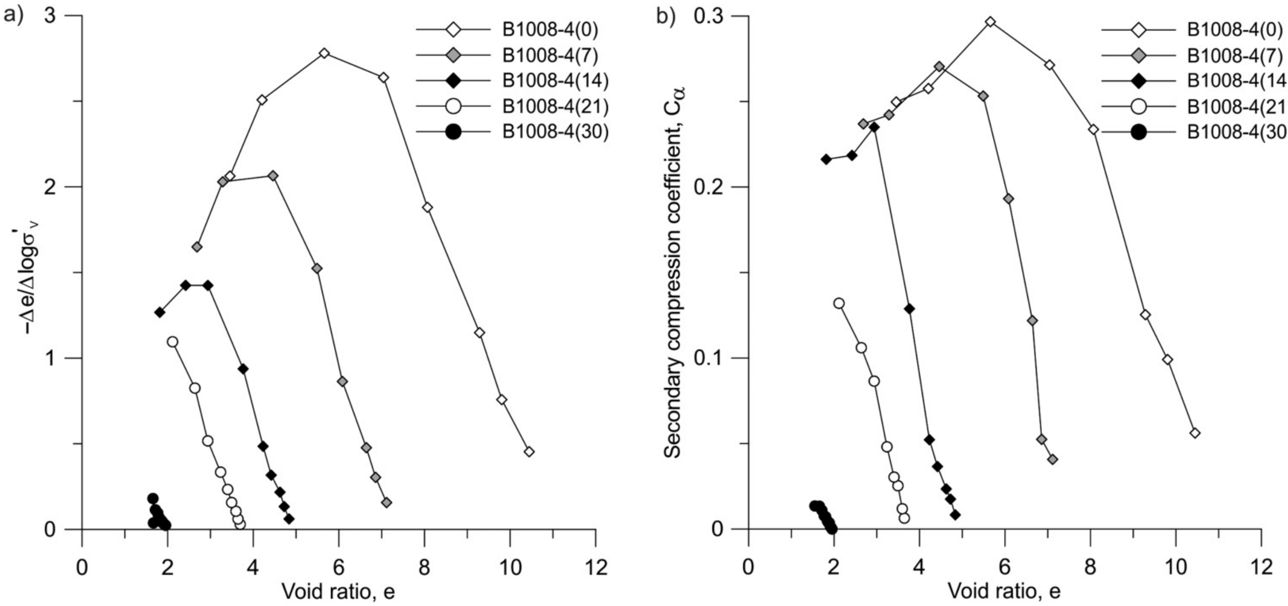
Fig. 2. Effect of drying on the compressibility of natural peat (*a*) compression curves; (*b*) yield stress; (*c*) apparent OCR; (*d*) compression index.



and the swelling index κ for unloading. The correlation between λ and κ and the initial void ratio is shown in Fig. 2*d*. Both λ and κ decrease with the drying period; however, the rate at which they decrease is not constant. Two regions can clearly be identified, which are delimited by an initial void ratio $e_0 = 5$ ($w = 300\%$), below which λ and κ start decreasing at an increased rate. The same pattern is observed in Fig. 2*b* for the yield stress, which shows a dramatic increase below the same void ratio. These results confirm that different fabric modifications occur and different compression mechanisms can dominate the hydro-mechanical response depending on the void ratio range. The value $e_0 = 5$ seems to discriminate between two modes of behaviour, which are detected both at the macroscale in terms of compression behaviour and at the physical level, with a change in the trend in the state parameters (e.g., fibre content and liquid limit).

Figure 3 shows how the compressibility ($C_c = -\Delta e/\Delta \log\sigma'_v$, Fig. 3*a*) and the creep ($C_\alpha = \Delta e/\Delta \log t$, Fig. 3*b*) coefficients change upon loading. Again, two patterns can be identified, depending on the void ratio reached after the drying period. Above an initial void ratio $e_0 = 5$, the compression and the creep coefficients initially increase at a decreasing void ratio, suggesting disruption of the initial fabric. Below a threshold void ratio, where both primary and secondary compressibility reach maximum values, they both start

Fig. 3. Compression behaviour of natural peat samples with different drying periods: (*a*) $-\Delta e/\Delta \log\sigma'_{\mathrm{v}}$; (*b*) C_{α}.

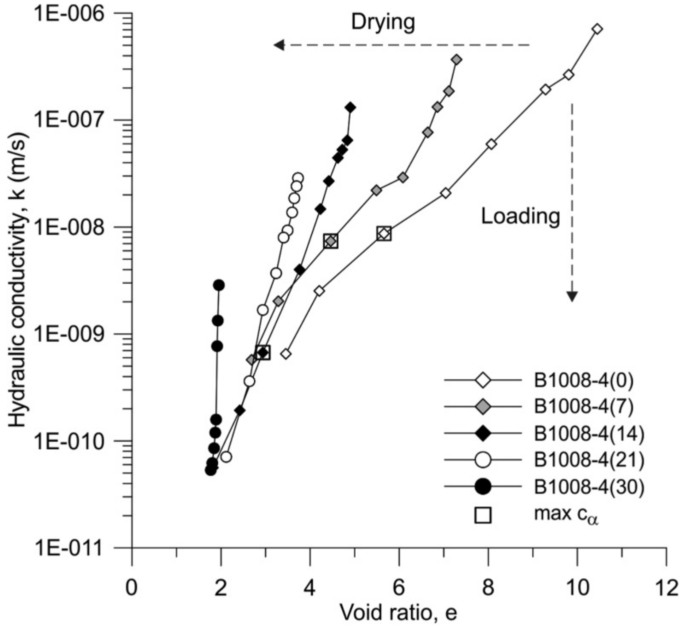


decreasing sharply towards the values that characterize samples that had been brought to initial void ratios smaller than $e_0 = 5$.

The behaviour of the samples still having an initial void ratio higher than $e_0 = 5$ after drying is consistent with previous investigations on natural peat samples (Lancellotta 2008; Madaschi and Gajo 2015), which highlighted that maximum compressibility occurs at stresses 2–3 times higher than the yield stress. However, the samples that were dried at void ratios below $e_0 = 5$ show compression and creep coefficients that are lower than those of the sample having a more open structure, but both increasing monotonically at decreasing void ratio. The result seems to suggest that a second level of the soil fabric exists, which is still sensitive to mechanical loading.

Figure 4 shows how the vertical hydraulic conductivity, k, changes with the void ratio and drying duration. The intact peat has a high hydraulic conductivity in the order of 10^{-6} m/s due to relatively large open pores. Compression causes a substantial reduction of the larger pores (Yamaguchi 1992) with the hydraulic conductivity decreasing by several orders of magnitude with decreasing void ratio. On the contrary, the reduction in hydraulic conductivity due to drying is modest, although the total void ratio decreases substantially, until the initial void ratio reaches values below $e_0 = 5$. The result highlights that, although during drying the total porosity of the peat decreases, the amount of large pores, which are dominant on the hydraulic conductivity, does not.

Fig. 4. Effect of drying on the saturated hydraulic conductivity.



Under load, the hydraulic conductivity decreases by several orders of magnitude, and all the curves describing the change in k with the void ratio tend to converge to the same final value. Also, the change in hydraulic conductivity follows two different patterns. If the initial void ratio of the sample is above $e_0 = 5$, an S-shaped curve is observed with a transition point where $\partial^2 k/\partial^2 e = 0$. If $e_0 < 5$, the decrease in hydraulic conductivity is almost linear in the semi-log plot, and no clear transition in the hydraulic conductivity change rate can be detected. It is interesting to note that the void ratio at which $\partial^2 k/\partial^2 e = 0$ corresponds to the highest secondary compression coefficient for all the samples (Fig. 3*b*). The results seem to confirm that secondary compression in this peat is likely to be associated with very slow expulsion of water from micropores, accompanied by structural rearrangement of the fabric (Berry and Poskitt 1972; Hobbs 1986; Boylan et al. 2008).

Fabric of natural peat samples

Three predominant characteristics were investigated when classifying peats: (*i*) the amount of organic matter from highly broken down formless botanical tissues; (*ii*) fibres; and (*iii*) inorganic grains. Water in peat can be present in three states: water in interconnect interparticle pores, which can actively transmit water; water within organic matter and fibrous components; and absorbed water (bounded water). The fibres of peat consist of cellular structures forming a two-level structure characterized by macro- and micropores between and within fibres, respectively. (Hoag and Price 1997; Quinton et al. 2009). The dual-porosity structure of peat has been confirmed by many researchers (Hayward and Clymo 1982; Yamaguchi et al. 1985; Kazemian et al. 2011). Among them, Landva and Pheeney (1980) and O'Kelly and Pichan (2013) showed by means of SEM that the highly porous, cellular structure of the constituent fibres is mostly full of water.

Figure 5*a* plots the variation in water content of the peat samples studied in this investigation with drying duration. The water content gradually decreases from $w = 700\%$ to values lower than $w = 100\%$ over the drying periods. Although the room conditions were kept constant, the evaporation rate slowed down after day 15, and 10 days were necessary for the last drying step, from $w = 148\%$ to $w = 76\%$. The reason for the reduced evaporation rate can be detected by looking at the data in Fig. 5*b*, where the shrinkage curve is plotted. Two phases can be distinguished, delimited by the void ratio $e = 5$. Above this void ratio, the samples shrunk due to water having high mobility draining from the large pores and can be re-saturated up to values higher than $\mathrm{Sr} = 0.9$. During the second stage of drying, the moisture loss exceeded the volume change, and the peat started desaturating irreversibly, reaching a final degree of saturation around $\mathrm{Sr} = 0.5$ upon rewetting. The evaporation rate decreases substantially when the water within the fibres, which has much lower mobility, starts draining from the sample.

To assist in the interpretation of the data and to visualize the change in fabric due to the ongoing drying process, the microstructure was investigated by means of micro computer tomographic (micro-CT) images. The micro-CT was performed on the undisturbed samples after different drying periods. It is worth noting that saturated undisturbed samples of peat are virtually impossible to analyse due to the very low-density contrast between the organic constituents and water. To be able to visualize some fabric features, X-ray tomography was performed on two samples having water contents $w = 340\%$ and $w = 150\%$, respectively. The sample with $w = 340\%$ still has a void ratio above $e = 5$, while the sample with $w = 150\%$ has a void ratio $e \approx 3.7$.

The comparison between the X-ray tomographies allows us to show how the fabric is progressively affected during drying processes. Figure 6*a* shows a cross section of the undisturbed sample B1008-4, having an organic content $\mathrm{OC} = 90.6\%$ and a fibre content $\mathrm{FC} = 36\%$ (see Table 1). Typical aggregated structures of natural organic matter and fibrous texture are identified, with a predominant amount of fine fibres and a few big reed fibres. The skeleton of the peat sample is mainly composed of organic aggregates, with fibres randomly distributed in between. Figure 6*b* shows a vertical section of an X-ray tomography taken on the natural sample after 3 days of air drying. Organic peds with small inner pores can be distinguished, together with the hollow structure of the fibres. Large interped pores are visible between the organic peds and between the organic peds and the fibres. A schematic diagram of the natural peat fabric is shown in Fig. 6*c*, showing organic peds forming the skeleton of the peat sample, and fibre with cellular structure and inorganic particles randomly distributed in between. Two main types of pores are represented: (*i*) the interparticle pores and (*ii*) intra-particle pores within organic peds and fibres.

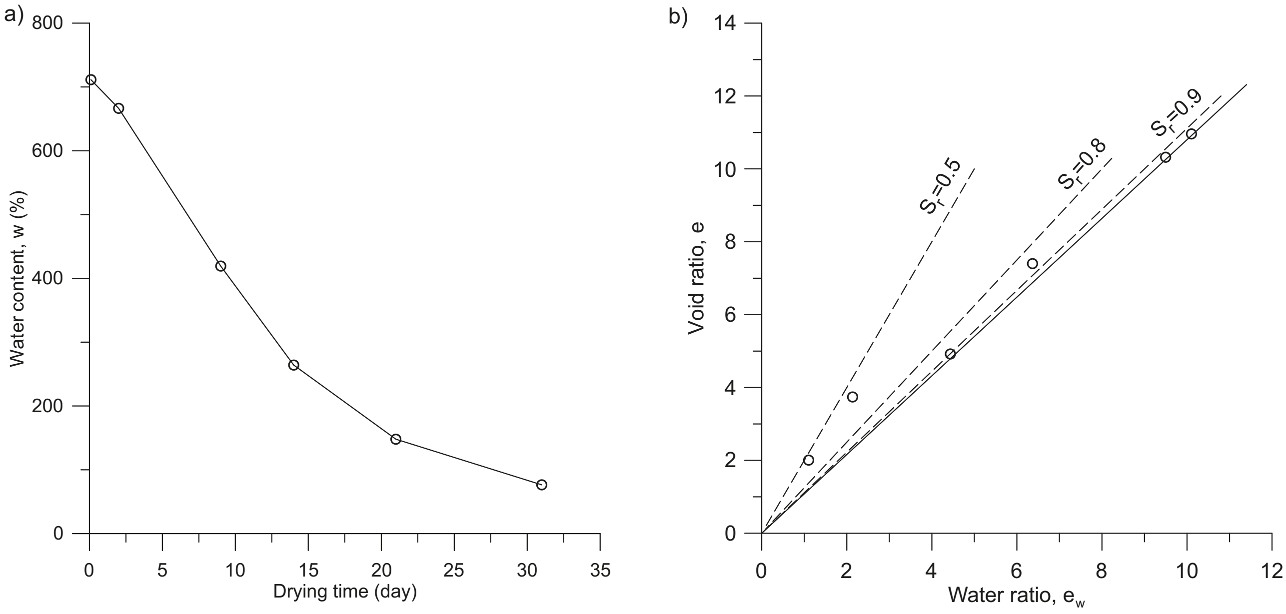
A comparison between the fabric of the two samples having $w = 340\%$ and $w = 150\%$ is shown in Fig. 7. At the beginning, the organic peds become more densely packed and new interparticle pores are created, together with cracks, which explains why the saturated hydraulic conductivity is not affected substantially, in spite of a reduction in the void ratio from 12.0 to 4.0 and clear alteration of the pore structure. When the organic peds and fibres start desaturating, irreversible shrinkage occurs, and the fabric formed by the aggregation of organic peds and fibres becomes denser and denser over further drying. The intra-ped and intra-fibre pore desaturation is an almost irreversible process; the organic components start becoming hydrophobic, and these pore classes cannot be re-saturated easily.

Discussion

All the data presented so far consistently identify a delimiting void ratio $e_0 = 5$, which discriminates between macro- and micro-fabric dominated responses during drying. However, the two fabric levels interact with each other in a loading process, with different characteristic time scales. Consolidation of peats is believed to occur due to dissipation of excess pore pressure of the interparticle water together with macro-fabric rearrangement (Adams 1963; Barden 1965), while secondary compression is due to the very slow drainage of water from the intraparticle pores, still accompanied by fabric rearrangement. These data seem to confirm the interpretation, showing that the engineering properties of peats are changing both at the macropore and the micropore levels, although at different rates and with different dominant physical mechanisms.

Both fabric levels undergo substantial modification during drying, as already observed on other multimodal active porous materials (e.g., Romero et al. 2011). However, in the case of peats, these changes are mostly irreversible due to drying affecting the water retention potential of the organic constituents. The yield stress after drying increases faster when the micro-fabric starts being affected in spite of a smaller change in void ratio, which highlights the role of fabric in the complex response of fibrous peats. When the organic aggregates are still saturated, the macro-fabric dominates the compression response, the yield stress of the macro-fabric increases, and the increase in the post-yield compressibility shows a maximum potential for spatial rearrangement of the aggregates and fibres. When the aggregates start desaturating, the stiffness increases and the organic

Fig. 5. Drying process: (*a*) decrease of water content with drying time; (*b*) shrinkage curve.



aggregates end up behaving as coarse particles, which cannot deform easily. As a consequence, the yield stress increases faster.

The role of fabric

Three other test series were performed on reconstituted samples, to provide further insight into the role of the fabric and the different organic components on the hydro-mechanical response and to quantify how sensitive it is to drying–wetting processes. The first test series aimed at analysing the role of fabric at constant organic and fibre contents. The second and the third test series focused on the contribution of organic content and fibre content separately.

Microstructure

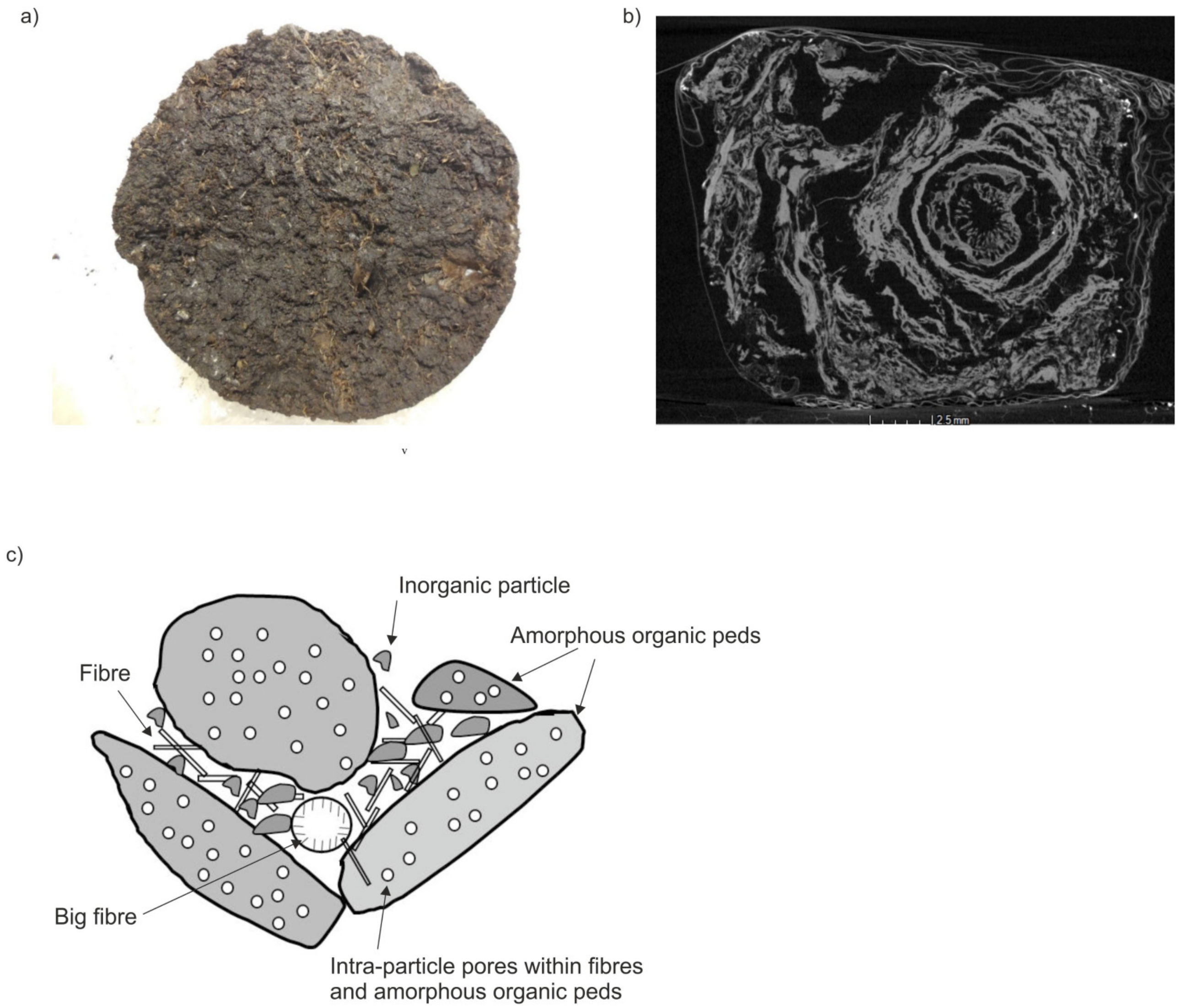
The role of the natural fabric of peat samples was investigated by comparing the previous results on undisturbed samples (B1008-4) with data of similar tests performed on reconstituted samples of the same peat (B1009-3). As shown in Table 1, samples B1008-4 and B1009-3 have similar organic contents, which are 90% and 88%, respectively. The comparison of the result between the natural and reconstituted samples aimed at quantifying the effect of the initial natural physical state and arrangement of organic aggregates, fibres, and inorganic grains.

The comparison between the cross section image and the micro-CT scan of the reconstituted sample (Fig. 8) and those of the natural sample (Fig. 7) shows that the intact fabric of the natural soil was completely changed by reconstitution. A massive texture, a more densely packed arrangement, with interparticle pores filled by organic matter can be appreciated.

The compression curves of the intact and reconstituted samples before drying and after drying over different periods are compared in Fig. 9*a*. As before, the samples were all re-saturated before the start of the compression tests. Different from the natural samples, the compression curves of the reconstituted samples are almost linear in the semi-log plot. A yield stress can be identified only after significant drying has occurred, although for higher stresses than the corresponding natural samples. The compressibility of reconstituted samples is higher for small stresses, while the samples become stiffer than the corresponding natural samples at increasing stresses. The comparison clearly shows that natural samples can sustain a higher void ratio during compression, thanks to their initial fabric, as already observed in many much stiffer natural soils and weak rocks (see, e.g., Burland 1990; Leroueil and Vaughan 1990). However, when the yield stress of the current fabric is reached, the compressibility increases due to substantial fabric rearrangement, and delayed strains are recovered. On the contrary, reconstituted samples, which are initially more compressible, do not show any sensitive behaviour upon loading due to their massive structure.

The data plotted in Figs. 9*b* and 9*c* seem to confirm that primary and secondary compression are mutually affected by hydro-mechanical coupling at the different fabric levels. The natural samples have a more open fabric, which gives the soil higher primary compressibility (Fig. 9*b*) allowing the micropores to drain faster over primary compression and anticipating most of the deformation due to loading. The reconstituted samples have a more massive structure, which is characterized by much lower hydraulic conductivity (Fig. 9*d*). The latter is believed to be responsible for delaying compression, which is reflected eventually in a higher secondary compression coefficient (Fig. 9*c*). As the two sets of samples have the

Fig. 6. Fabric of natural peat: (*a*) cross section photo; (*b*) micro-CT scan; (*c*) schematic diagram. [Colour online.]



same organic composition, the result highlights the role of fabric on the secondary compressibility, which is not only a function of the organic content.

The data in Fig. 9*d* confirm the dramatic role of the initial fabric of the soil in its hydraulic conductivity, which changes by three orders of magnitude on average by remoulding the initial fabric of the soil. As expected, the preferential flow path offered by the interparticle pores gives the natural samples much higher short-term hydraulic transmissivity to the soil, irrespective of the previous drying duration. Similar to the natural samples, the void ratio reduction upon drying does not affect the hydraulic conductivity of the reconstituted samples to a large extent, which remains almost the same irrespective of the drying duration, while it decreases substantially over loading.

The previous results demonstrate the dramatic role of the arrangement between organic peds, fine fibres, and inorganic granular matter in peats in their observed hydro-mechanical behaviour. However, they do not tell yet whether total organic matter or fibres are most relevant in terms of composition. Therefore, further tests were performed to discern the relevance of fibres over total organic content on the observed results. It is worth noting that this last series of tests was performed on remoulded samples only, as the composition of the soil cannot be changed unless the soil is reconstituted.

Total organic content

The literature on organic soils tends to claim the organic content to be the key factor in the engineering and index properties of peats. Skempton and Petley (1970) established a correlation between organic content and specific gravity. Hobbs (1986) stated that the water holding capacity, the liquid limit, the hydraulic conductivity, and the cation exchange capacity depend on the amount of organic matter. To better quantify the influence of the total organic content on the coupled hydro-mechanical response of the studied peat, data from two reconstituted sample sets from the same peat having similar fibre content but different total organic content are compared. The two sample sets B1009-3 and

Fig. 7. CT scan of air-dried natural peat sample with $w = 340\%$: (*a*) lateral view, (*b*) top view; and $w = 150\%$: (*c*) lateral view, (*d*) top view.

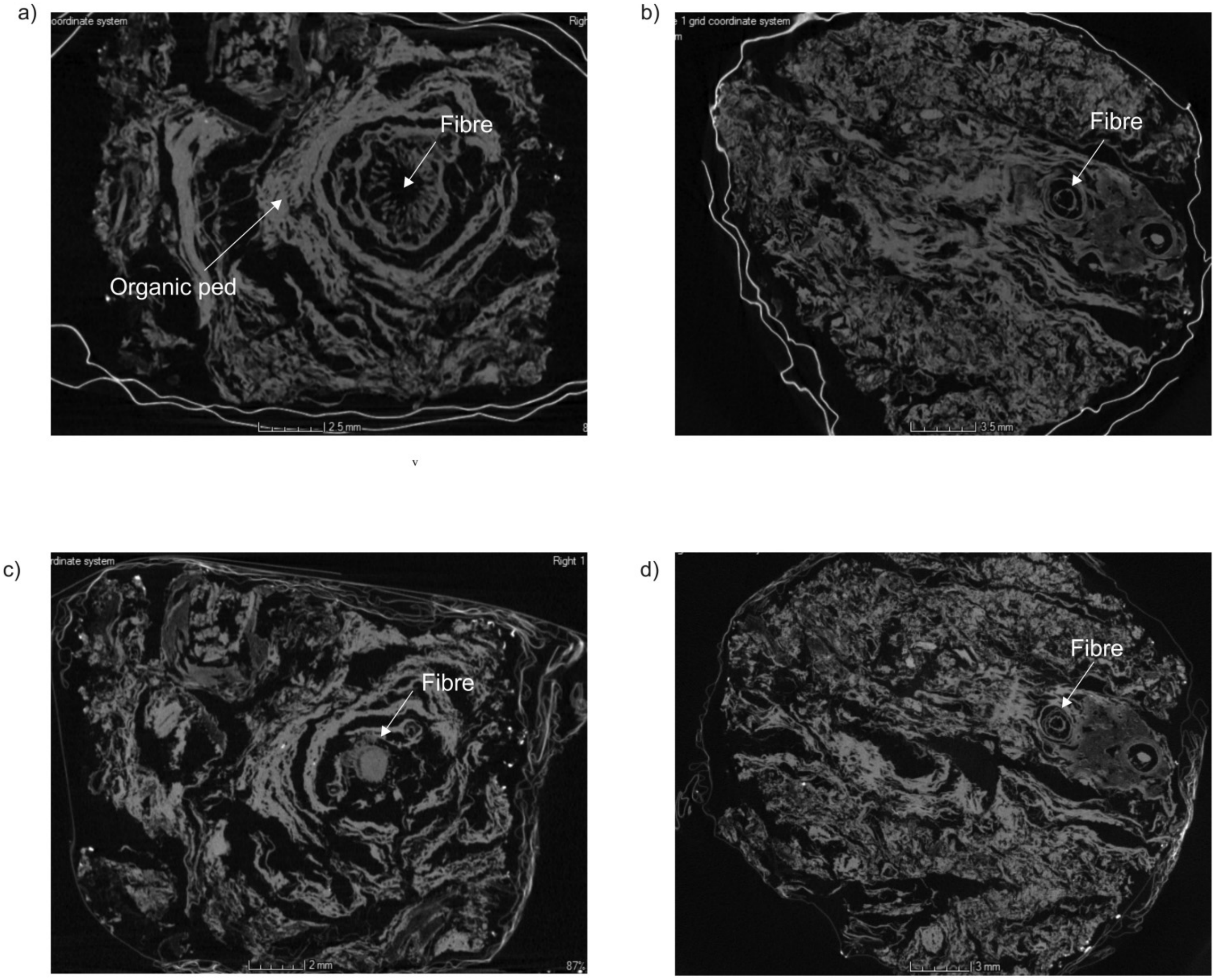
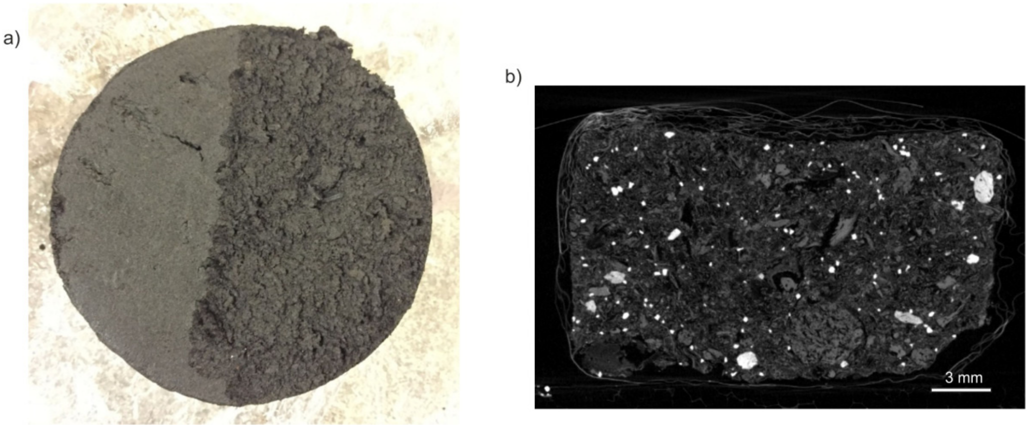


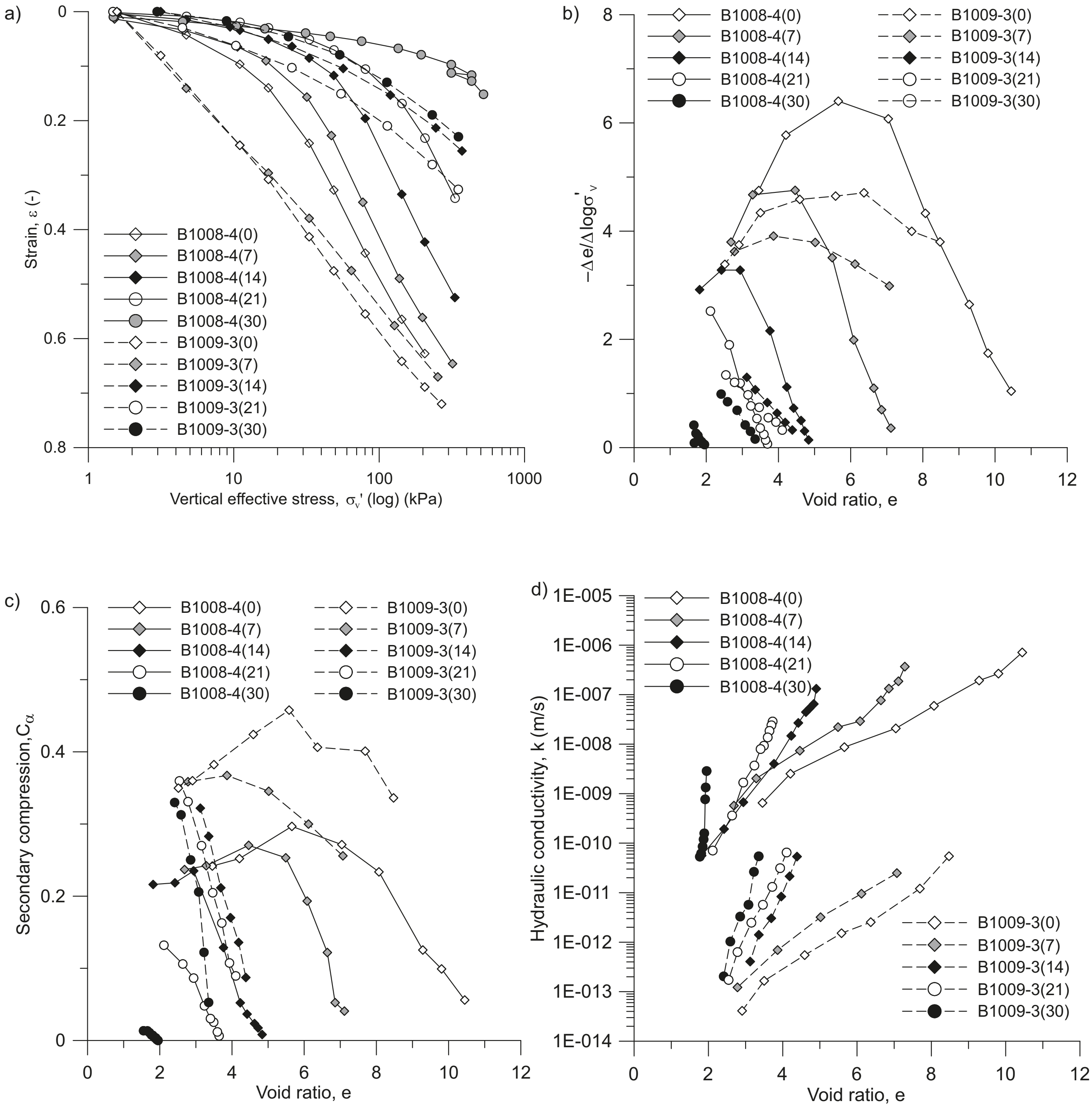
Fig. 8. Fabric of reconstituted peat sample (*a*) cross section image; (*b*) micro-CT scan. [Colour online.]



B1009-5 have on average an organic content around 88% and 73%, respectively. The classification data listed in Table 1 confirm that the higher the organic content, the higher the water content and the lower the bulk density.

The compression curves of B1009-3 and B1009-5 after different drying durations and re-saturation are compared in Fig. 10*a*. The pattern of the curves is similar, although the sample having the lowest organic content shows higher

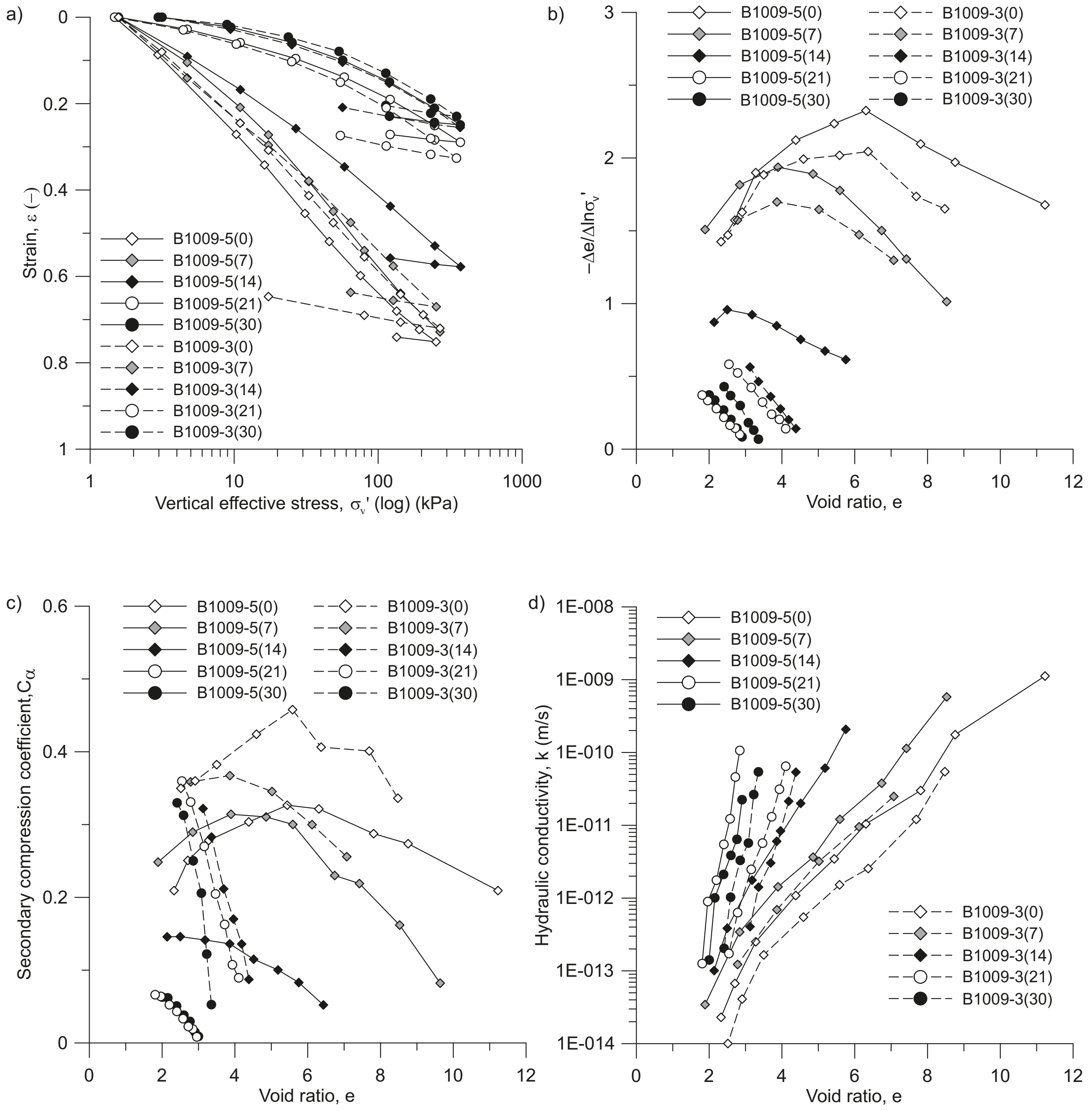
Fig. 9. Effects of initial fabric on (*a*) compression curves; (*b*) $-\Delta e/\Delta \log \sigma'_{\mathrm{v}}$; (*c*) C_{α}; (*d*) *k*.



compressibility on average. The step-by-step compressibility of the two sample sets is compared in Fig. 10*b*, confirming the higher primary compressibility of the sample having the lowest organic content. However, the void ratio corresponding to the peak in compressibility is the same for the two samples, irrespective of the organic content, which suggests that another fabric feature can equally affect the multilevel hydro-mechanical response. This is confirmed by the data on secondary compressibility and hydraulic conductivity in Fig. 10*c* and 10*d*, which show that decreasing the organic content decreases the secondary compressibility and increases the hydraulic conductivity. The data confirm that the organic content has an important role in delaying compression, besides affecting the total compressibility of the peat samples. Although in this case the data are not conclusive, it seems that a void ratio $e = 5$ can equally discriminate between macro- and microporosity.

To verify the latter statement, the compression and swelling indexes λ and κ of the different specimens tested after drying and rewetting are plotted in Fig. 11 for the three samples B1008-4, B1009-5, and B1009-3. The data show that the intact initial fabric is responsible for the higher normally consolidated compressibility of the natural sample. The corresponding compressibilities of the reconstituted samples are similar, irrespective of the total organic content. While the organic content does not dominate primary compression

Fig. 10. Effect of organic content on (*a*) compression curves; (*b*) $-\Delta e/\Delta \log\sigma'_{\mathrm{v}}$; (*c*) C_α; (*d*) *k*.



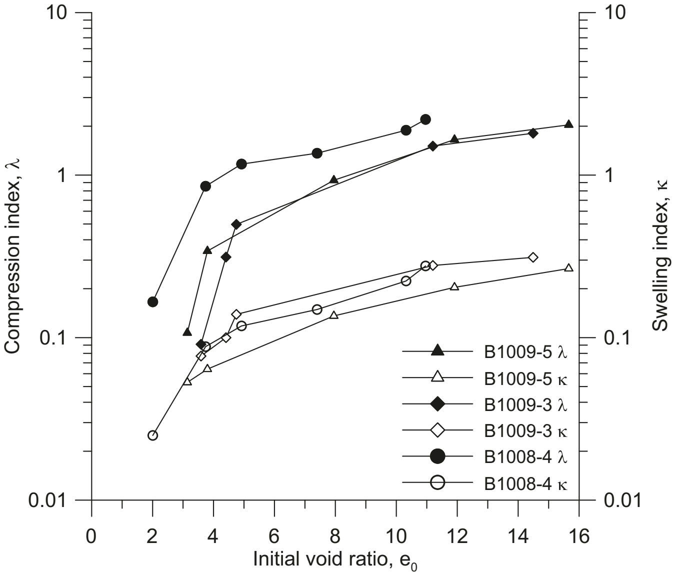
more than the initial fabric, it seems that it might affect the void ratio at which a change in the deformational response is observed. For the two samples having an OC ≈ 90% (B1008-4 and B1009-3), a substantial reduction of λ is observed starting at a void ratio $e \approx 5$, while for the sample having OC < 75%, a similar reduction can be estimated to start at $e \approx 4$, which suggests that the organic content determines the microscopic void ratio. The same void ratios discriminate the swelling index trend.

Fibre content

By comparing the identification and classification data after drying (Table 1 and Fig. 1), it can be observed that the fibre content decreases substantially with drying, while the total organic content remains almost unaltered. Drying breaks down the cellulose within the plant tissues, which produces a reduction in the size of the fibres, without any significant loss of total organic material. To isolate the effect of fibres on the compression behaviour of drying peat, a last sample set was prepared starting from remoulded samples of peat having high fibre content and comparing their behaviour with that of companion samples in which the fibres had been removed before preparation.

The properties of the last sample set are summarized in Table 2. The fibre content of the two original samples was 45% and 50%, respectively. The fibres were removed from the peat

Fig. 11. Effect of drying on the compression index and swelling index.



samples by washing them over an ASTM No. 100 sieve (opening size 150 μm) and using demineralized water. Removing the fibres decreases the total organic content of the samples. However, the organic content of the two samples without fibres remains around 80%, which is in the range investigated with sample set B1009-3 and B-1009-5. Specific gravity also increases due to the removal of fibres, which are made by cellulose and lignin, having the lowest density amongst the peat constituents.

The compression curves for the samples with and without fibres are plotted in Fig. 12*a*. It can be seen that eliminating the fibres reduces the compressibility of the samples. As reported in Table 2, the compression index decreases from 1.576 to 1.087 and from 1.744 to 0.836, respectively, and the same trend is observed for the swelling index. The most relevant observation coming from the elaboration in Fig. 12*b* is that removing the fibres tends to attenuate the fabric effects, with small variations in the step-by-step compressibility. Also, the data in Fig. 12*c* show that fibres play a relevant role in secondary compression, with the latter reducing significantly when the fibres are removed. Consistently, the hydraulic conductivity increases by nearly one order of magnitude in the macroporosity range, while the difference decreases once the macropores are compressed.

Summary and conclusions

Peats are characterized by high shrinkage potential, and understanding how the physical and geotechnical properties of natural peat will change as a consequence of drying and wetting cycles will help in addressing the challenges posed by increasing climatic stresses. To this aim, a dedicated experimental investigation was planned on natural and reconstituted peat samples, which were left drying during increasing periods. Afterwards, they were re-saturated and tested in one-dimensional compression to investigate how the engineering properties of peat are affected by drying. Micro-CT scans were used to help in visualizing the changes in fabric during drying.

The data collected on natural peat samples suggested to deepen the investigation by looking at the separate role of fabric, organic content, and fibres in the engineering response. In fact, although it is well known that organic content and fibres are dominant on the engineering behaviour of peats, scarce attention was devoted in previous investigations on the separate roles of the different fabric elements. The results suggest that distinguishing the role of the fibrous component of peat amongst the organic components helps in understanding the modifications occurring after drying and wetting cycles.

The compression behaviour of natural peats is a multiscale time-dependent fabric modification process, as already well known since decades. The data provided by this investigation seem to substantiate that primary compression mainly affects the interped and fibre pores (macropores), while creep is mostly associated with delayed compression of the microfabric. The latter occurs thanks to a decrease in the microporosity, including intra-organic ped and intra-fibre pores. The intact fabric gives natural peats higher primary compressibility and lower secondary compressibility than those of reconstituted samples of the same peat, highlighting that these two features are not a function of organic content exclusively. The fibres play a very significant role in the observed response, largely delaying the compression at comparable organic content.

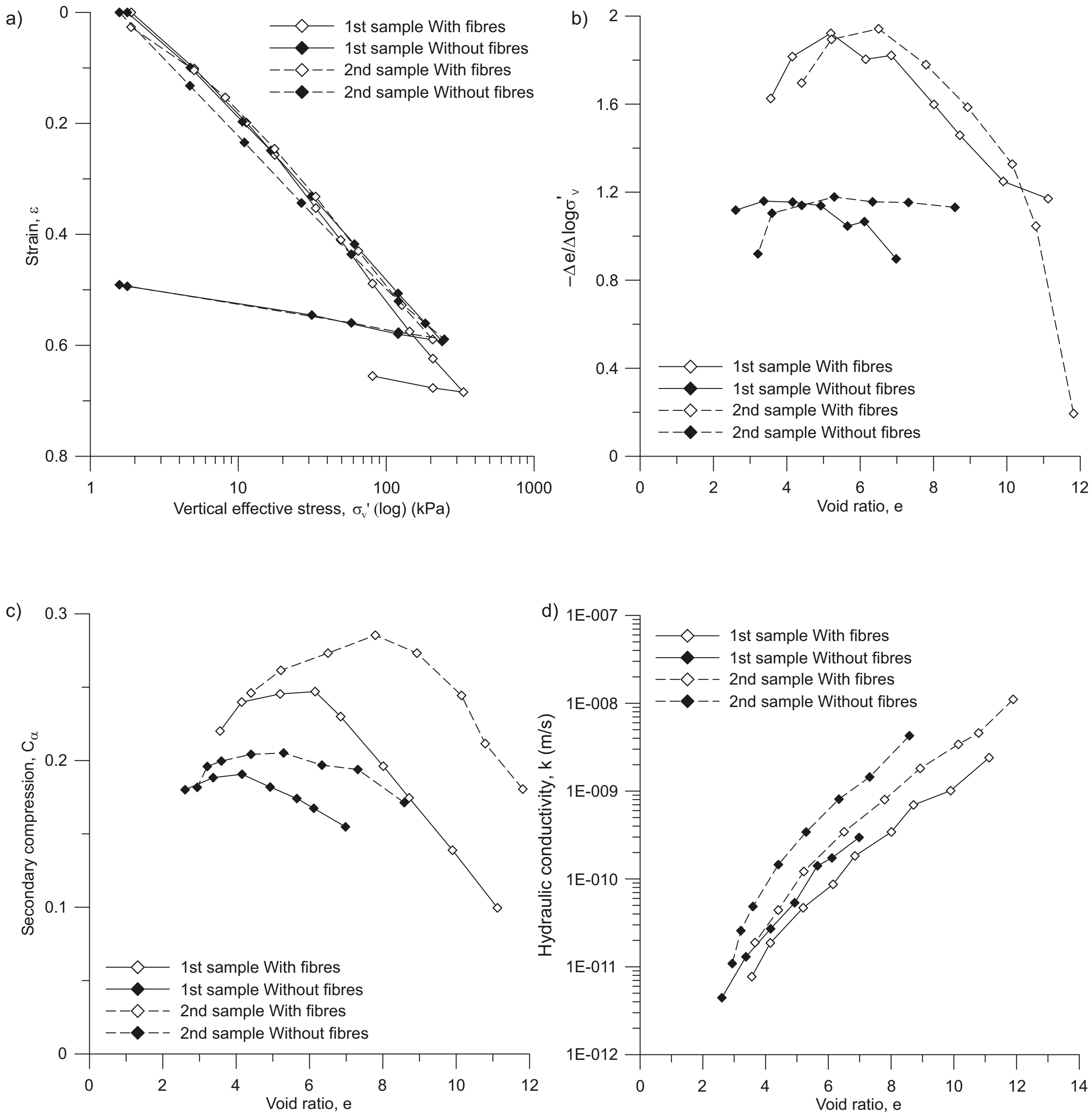
This framework helps in understanding the modifications induced by drying and wetting cycles on the engineering response of peats. Drying in peats starts affecting the macropores only. If shrinking is allowed, irreversible reduction of the volume occurs at constant saturation. A threshold void ratio discriminating between micro- and macroporosity was consistently found from the various data elaborations, which seems to be a unique function of the organic content, and above which the response of natural samples is dominated by the macrostructure response. Above the same threshold, the saturated hydraulic conductivity is not affected substantially by drying, due to enlargement of the macropore sizes and crack formation, even at decreasing total porosity. However, drying breaks the fibres into smaller pieces, which is accompanied by substantial irreversible changes in volume and liquid limit, in turn dramatically increasing the yield stress and reducing both the primary and the secondary compressibility. The reduction in fibre content itself decreases both primary and secondary compressibility and seems to smooth down the relevance of the contribution of fabric to the response.

As expected, reconstituted samples exhibit lower primary compressibility, higher secondary compressibility and lower hydraulic conductivity than the corresponding natural samples, as a consequence of the different fabric. However, the threshold void ratio at which the microstructure starts dominating the behaviour is the same for the two sample sets, as it depends on the organic content.

Table 2. Index properties, compression index, and swelling index for peat samples with and without fibres.

Sample	Water content (%)	Void ratio	Fibre content (%)	Organic content (%)	G_s	λ	κ
1st with fibres	913	13.5	45	87.45	1.478	1.576	0.253
1st without fibres	711	10.6	0	80.00	1.490	1.087	0.210
2nd with fibres	925	13.9	50	90.37	1.502	1.744	0.199
2nd without fibres	762	11.7	0	80.43	1.534	0.836	0.177

Fig. 12. Effect of fibres on (*a*) compression curves; (*b*) $-\Delta e/\Delta \log\sigma'_v$; (*c*) C_α; (*d*) *k*.



Overall, the data presented highlight that the natural fabric dominates the consequences of drying and wetting cycles over the engineering response of fibrous peats. Organic content does not seem to be exhaustive information on the peat fabric and does not allow uniquely identifying the compression and hydraulic parameters. The fibres, even the small ones, which are randomly distributed in the peat matrix, seem equally relevant in governing the hydro-mechanical response upon compression, and they should be carefully accounted for in inferring descriptive parameters for the engineering behaviour of peats from their classification data.

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