Effect of decomposition on physical properties of fibrous peat

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Organic matter in peat deposits undergoes slow microbial decomposition, which causes permanent material change, including reduction in volume of solids, and is a significant factor in the development of creep settlements for such deposits. Microorganisms accountable for decomposition are readily available in peat, although generally less populous compared with other soils on account of the unfavourable environment. This paper presents a novel experimental-laboratory study that stimulates the growth of microorganisms in a fibrous peat and hence its decomposition rate. The carbon/nitrogen ratio and pH value of the peat were adjusted within optimum ranges for microbial activity to occur by blending sufficient amounts of pulverised fuel ash and urea with the wet peat. This process did not adversely affect indigenous microbial populations within the peat. Blended material was incubated aerobically and anaerobically at 30°C over periods of up to 126 days. Microbial populations increased by approximately 3500- and 1800-fold under aerobic and anaerobic incubation, respectively, which was an indicator of increased decomposition rate. Water content, specific gravity of solids, volatile organic content and fibre content were measured both before and after incubation treatment. Fibre content was found to be approximately inversely proportional to incubation period, with relatively greater reductions in fibre content occurring for blended material under aerobic conditions.

Notation

B–Ae blend of peat, PFA and urea under aerobic incubation
B–An blend of peat, PFA and urea under anaerobic incubation
 G_s specific gravity of solids
 H_n humification number
 n number of data points/values
P–Ae peat under aerobic incubation
P–An peat under anaerobic incubation
 R^2 coefficient of determination
 w water content

Introduction

Peat (mire) deposits are formed by the gradual accumulation of the remains of dead plant vegetation at various stages of decomposition under waterlogged conditions. These deposits can build up over time where there is a reservoir of water to promote new plant growth in the uppermost layer (*acrotelm*) and preserve the dead plant remains in underlying layers (*catotelm*). Decomposition of peat occurs naturally, with plant matter and molecules broken down into finer detritus and simple molecules (e.g. carbon dioxide and water). The process is accompanied by permanent material changes, including

progressive destruction of constituent fibres; disappearance of physical structure/fabric; reduction in water-holding capacity; weakening of adsorption complex; gas generation and reduction in volume of the solids (Mesri and Ajlouni, 2007; O'Kelly and Pichan, 2013; Wardwell *et al.*, 1983). After larger particles have been broken down by earthworms/insects/snails etc. during the initial stages of decomposition, indigenous microorganisms including bacteria and fungi continue the decomposition process by secreting chemicals that digest organic matter into detritus (Hobbs, 1986; Pankratov *et al.*, 2011).

Since different types of microorganisms live in different environments, their actual population can vary widely, depending on soil type and depth (Barns and Nierzwicki-Bauer, 1997). In many soil deposits, estimated total microbial populations are of the order of 10^9 – 10^{12} /kg soil at near the ground surface (Mitchell and Santamarina, 2005). However, the microbial population and activity in peat material have hardly been explored and are less well understood (Hingley, 1993; Hunter *et al.*, 2006; Pichan and O'Kelly, 2013), although it is known that microbial populations possessing versatile cellulolytic and hydrolytic capabilities for

degrading cellulose, soluble phenolics, pectin, starch, chitin and other biopolymers are present in peat (Pankratov *et al.*, 2011).

Nevertheless, the unfavourable environment of waterlogged conditions, lack of available nutrients, high acidity and low temperature in peat ecosystems inhibit the growth and activity of most microbial populations, which retards the decomposition process. However, peat is not inert, but undergoes a slow but steady rate of decomposition over an extended period of time. Since microorganisms generally have very rapid rates of generation, mutation and natural selection, which allows very fast adaptation and extraordinary biodiversity to develop under ideal environments (Mitchell and Santamarina, 2005), the decomposition rate can accelerate once the limiting factors have been altered accordingly, either naturally or as a result of anthropogenic activity. For instance, in peat ecosystems, the decomposition rate can accelerate markedly with increased oxygen concentration caused by intermittent fluctuations of the groundwater table (Pichan and O'Kelly, 2013). Recent developments in microbiology have also indicated that biological activity can be promoted by injecting nutrients (e.g., glucose) or by changing environmental conditions (Mitchell and Santamarina, 2005). Preliminary laboratory trials on the feasibility of artificially induced decomposition in fibrous peat by Pichan and O'Kelly (2012, 2013) have indicated that its main decomposition limiting factors of carbon-to-nitrogen (C/N) ratio and pH level can be adjusted within reported optimum ranges of 25–30:1 and 7.0–7.5, respectively (Wardwell *et al.*, 1983), by mixing sufficient amounts of basic and nitrogenous materials with the peat.

From a geotechnical engineering perspective, unexpected or accelerated decomposition in peat deposits can prove problematic, particularly for fibrous peats. Once such deposits have been exposed to conditions more favourable for accelerated decomposition to occur, the settlement rate may increase substantially, which may be significant over the design life (Landva *et al.*, 1983), potentially impacting on the serviceability limit state of engineering structures bearing on the peat strata. Colleselli *et al.* (2000) and Wong *et al.* (2009) have reported that, for peats, the higher the fibre content, the greater the tertiary (creep) settlement component. Tertiary compression, which occurs in addition to secondary compression after substantial dissipation of the excess pore water pressures (Dhowian and Edil, 1980), may substantially increase the long-term settlement rate. Some researchers have reported that tertiary compression is a manifestation of the loss of organic solids (reduction in volume of the peat solids) over time due to the decomposition process. In order to mitigate against this risk, the writers proposed a novel approach (Pichan and O'Kelly, 2013) whereby microbial decomposition in bearing peat strata is artificially induced in situ in advance of the main construction works. Such treatments may reduce long-term settlements for fibrous peat deposits since natural decomposition is a significant factor in the development of secondary and tertiary creep settlements (O'Kelly and Pichan, 2013). The breaking down of the cells and baffle walls that reinforce the peat fibres has been reported to reduce subsequent deformation of the degraded fibres under applied loading (Farrell, 2012; Landva and La Rochelle, 1983).

Hence, more decomposed peats generally undergo lower amounts of primary consolidation and secondary compression settlements under loading compared with lesser decomposed peats (Drexler *et al.*, 2009; Franzen, 2006; Mesri and Ajlouni, 1997; O'Kelly, 2005a, 2006; O'Kelly and Pichan, 2013), with more decomposed peats also less prone to further decomposition occurring.

This paper presents the results of an experimental laboratory study on artificially induced decomposition in a fibrous Irish peat. Although mainly concentrating on microbiology aspects, this paper also investigates its effects on some physical properties of the peat, namely, water content, specific gravity of solids, volatile organic content and fibre content. However, the actual compression response under loading, with and without stimulated decomposition, was not directly measured in this study.

Experimental method

Experimental materials

The test materials in the present study were a moderately decomposed peat sampled from a depth of 1.7 m below the ground surface at Ballydermot raised bog, County Kildare, Ireland; a pulverised fuel ash (PFA) obtained from Lanesborough peat-burning power station, County Longford, Ireland; and nitrogenous fertilizer (i.e., urea). Details on the geotechnical and hydraulic properties of the Ballydermot peat deposit have been reported by Osorio *et al.* (2010), Osorio Salas (2012) and Pichan and O'Kelly (2012, 2013). Two batches of the peat material were obtained from the same depth but slightly different locations at the Ballydermot bog. The sampled peat was immediately placed in airtight containers in order to prevent aerobic decomposition of the material from occurring prior to incubation treatments in the laboratory.

The parental vegetation of the peat consisted of *Sphagnum* (S), *Carex* (C), *Lignidi* (W) and *Phragmites* (Ph). Based on the moderate degree of humification of the plant structures (H_{5-6}), water content ranging between 1000% and 2000% (B_4), high fine fibre content (F_3), moderate coarse fibre content (R_2) and no wood or shrub remnants present, the peat was classified as SCWPh- H_{5-6} - B_4 - F_3 - R_2 material according to the modified von Post peat classification system (Landva and Pheeney, 1980). Most of the plant matter present was in a moderately decomposed condition, although peat fibres with their characteristic highly porous and open cellular structure were still recognisable under microscope examination.

Test programme

Assessment of potential growth of microorganisms in natural peat

The potential growth of indigenous microbial populations present in the peat was assessed for different incubation temperatures and environments in order to establish the ideal conditions for cultivation of microorganisms in peat. In this regard, a standard plate-count technique, described previously by Pichan and O'Kelly (2013), was used. In summary, separate dilutions containing randomly selected

samples of the wet test materials were prepared and plated onto a semi-solid medium of Tryptic soy agar tenfold diluted (TSA 1/10). Sets of duplicate test specimens were then incubated both aerobically and anaerobically at constant temperatures of 10°C, 20°C, 30°C and 40°C. Lastly, the population or concentration of microorganisms/cells present in the specimens was assessed by counting the number of colony-forming units (CFUs) that had developed on the plates after a 10-day incubation period, with the results expressed as CFU per gram of peat solids in the plated specimens.

Incubation treatment of test materials

Specimen preparation

The PFA material was obtained in a granular form (well-graded very sandy silt of high plasticity) and is highly alkaline, with a measured pH value of 11.8. The urea was composed of approximately 46% nitrogen and is highly soluble in the pore water. In the laboratory, specific amounts of the PFA and urea were mixed with the wet peat in order to adjust the peat's pH value and C/N ratio within reported optimum ranges (7.0–7.5 and 25–30:1, respectively) for microbial decomposition to occur. Pichan and O'Kelly (2013) have reported how the required amounts of PFA and urea can be determined experimentally. Firstly, samples of peat incorporating different amounts of PFA material were prepared, with the materials mixed together at the peat's natural water content. By measuring the pH value of the different mixtures, the relationship between %PFA additive and pH value could be determined. Hence the precise amount of PFA necessary to achieve a pH value within the optimum range for decomposition could be established. Next, with the pH value adjusted accordingly, samples of the peat–PFA mixture were prepared with different amounts of urea and the C/N ratio of the different blends was determined by elemental analysis. Pichan and O'Kelly (2013) have also discussed potential environmental issues relating to in situ mixing of PFA and urea with peat. In the present study, the total carbon and nitrogen contents of the peat were measured using an Elementar VARIO El cube instrument at $54.23 \pm 1.25\%$ and $1.25 \pm 0.03\%$ ($n = 3$, where n is the number of tests), respectively, giving a mean C/N ratio for the natural peat of $\sim 43:1$. Using these experimental data and the method of Barbarick (2006), we determined the amount of urea additive required to produce a material having a C/N value within the optimum range for decomposition. Previous work by the authors (Pichan and O'Kelly, 2013) had identified that the ideal mixture for the sampled Ballydermot peat material comprised 75.8% peat, 22.7% crushed PFA and 1.5% urea, on a dry mass basis, which produced values of pH and C/N of 7.3 and 30:1, respectively. Addition of more than 23% PFA produced a progressively stronger alkaline blend which would inhibit growth of the microorganisms and microbial activity.

Referring to Table 1, two sets of five test specimens were prepared from the blended 75.8% peat, 22.7% PFA and 1.5% urea mixture; one set decomposed aerobically and the other decomposed anaerobically (denoted by specimen sets B–Ae and B–An, respectively) over incubation periods of between 7 and 126 days. Another two sets of five specimens prepared from the remoulded peat (i.e., without any additives) were also tested under aerobic

Type of incubation	Material condition	Incubation time: day				
		7	14	42	84	126
Aerobic	Peat	P–Ae ₇	P–Ae ₁₄	P–Ae ₄₂	P–Ae ₈₄	P–Ae ₁₂₆
	Blended	B–Ae ₇	B–Ae ₁₄	B–Ae ₄₂	B–Ae ₈₄	B–Ae ₁₂₆
Anaerobic	Peat	P–An ₇	P–An ₁₄	P–An ₄₂	P–An ₈₄	P–An ₁₂₆
	Blended	B–An ₇	B–An ₁₄	B–An ₄₂	B–An ₈₄	B–An ₁₂₆

Table 1. Test conditions and specimen notation

and anaerobic conditions as controls (denoted by P–Ae and P–An, respectively). As mentioned earlier, two batches of peat material were obtained from the Ballydermot bog sampling area. Specimen sets P–Ae and B–Ae were prepared using peat material from the first batch, with specimen sets P–An and B–An prepared from the second batch. The peat was remoulded and the test materials mixed together in the laboratory using a 4.5-L paddle-mortar mixer, with each test specimen prepared using approximately 3.0 kg of the wet peat at its in situ water content.

Incubation of test specimens

The test specimens were individually sealed inside heavy-duty black plastic bags and stored for set periods of between 7 and 126 days inside a specially constructed incubation chamber (Figure 1) which was set to maintain a constant incubation temperature of 30°C. The chamber, internally 2.4 m long, 0.6 m high by 0.5 m wide, was constructed using 50-mm-thick, high thermal performance rigid insulation with foil facing (thermal conductivity of 0.021 W/mK). The internal temperature was maintained by a 360-W thermostat-controlled aluminium tubular heater, 1.8 m in length, which was fitted along the bottom of the chamber. The incubation bags containing the test specimens were placed on a grillage, located 150 mm above the chamber base, which allowed circulation of the heated air to occur within the chamber. The shortest incubation period of 7 days used was sufficient for indigenous microorganisms within the peat to adapt to the controlled experimental conditions (Pichan and O'Kelly, 2013). The sealed incubation bags prevented the test specimens from drying out and also from exposure to light which may have otherwise influenced the biological activity occurring over the incubation period. This feature was necessary in order to simulate the near-saturated and dark conditions for in situ peat at depth.

The anaerobic specimen sets, B–An and P–An, were vacuumed before the start of the incubation treatment in order to remove any air (oxygen) from inside of the incubation bags. An aerobic condition for specimen sets B–Ae and P–Ae was created by periodically injecting fresh air into the incubation bags, purging any biogas generated up to that point and providing ample supply of oxygen for aerobic decomposition to occur throughout the incubation period.

Figure 1. Chamber for incubation of test materials. (1) Walls constructed from 50-mm-high thermal performance rigid insulation board. (2) Incubation bag containing aerobic specimen. (3) Grillage located 150 mm above chamber base. (4) 360-W tubular heater located in cavity below the grillage. (5) Thermostat control.

Physical properties of test specimens

The degree of decomposition of peat can be assessed using a range of different methods, including measurement of various physical and (or) chemical properties and also by chemical extraction of soluble materials (Chambers *et al.*, 2011). In the present study, values of gravimetric water content, loss in dry mass on ignition (LOI), specific gravity of solids, and fibre content were determined for the peat and blended materials in accordance with BS1377 (BSI, 1990a, 1990b). Measurements were taken before the start of the incubation treatments, which served as baseline readings, and again at the end of the different incubation periods. Note that the geotechnical definition of water content is used in this study; that is, the mass ratio of the pore water phase to dry solids phase, expressed as a percentage. Water content determinations were performed by oven drying representative samples at a temperature of 105–110°C over a 48-h period. Although some of the organic matter in peat is susceptible to slight charring or oxidation at this elevated drying temperature range (O'Kelly, 2004), the values of water content determined under these test conditions are sufficiently accurate (Skempton and Petley, 1970; O'Kelly and Sivakumar, 2014). The volatile organic content was determined by LOI tests, whereby samples of the powdered oven-dried material were ignited in a muffle furnace at 440°C over an 18-h period (BS1377-3: BSI, 1990b). For the test materials under investigation, it is reasonable

to assume that the measured LOI values are a good approximation of volatile organic content, although this test method does not make any distinction between the types of organic matter present. Values of the specific gravity of solids were determined using the small pycnometer method (BS1377-2: BSI, 1990a). The constituent fibres were separated by washing representative samples on the 150- μ m sieve, with the fibre content (FC) determined by expressing the oven-dried mass of retained material as a percentage of the total dry mass of the sample (ASTM D1997; ASTM, 2008).

Evaluation of decomposition rate

Various methods exist for the determination of the decomposition rate of organic matter in soils, including litter-bag techniques (French, 1988; Thormann *et al.*, 2001), measurement of gas volume released (Nachimuthu *et al.*, 2007; O'Kelly, 2005b; Roppola *et al.*, 2008) and cotton strip assay (French, 1988; Nachimuthu *et al.*, 2007). Although these techniques have proven effective in monitoring the decomposition rate of peat in the field, they were deemed unsuitable for the present laboratory setup. Reasons included difficulties in continuous measurement of the volume of biogas generated inside the incubation bags and also because of the relatively small test-specimen size (approximately 3 kg in wet mass) and hence volume of biogas that would be produced over time. Instead, the decomposition rate was evaluated based on measured microbial populations, assessed using the plate-count technique described earlier. Immediately after the incubation treatments, samples were randomly selected from the different test specimens and plated since some types of microorganisms are particularly sensitive to changes in environment. All plates were incubated aerobically at a constant temperature of 20°C, which had been established in this study as ideal conditions for cultivation of microorganisms. Note that the plate-count technique typically only detects up to about 5% of the total population of viable microorganisms present in the soil sample on account of the controlled test conditions, in particular the specific nutrients supplied in the medium and the fixed incubation temperature of 20°C used (Pichan and O'Kelly, 2013). Although optimum growth for other microbial populations present in the samples would occur under different incubation environments, the experimental results, nevertheless, sufficiently reflect the availability of microorganisms in the peat.

Experimental results and discussion

Potential growth of microbial populations in peat

Table 2 presents the data of mean microorganism counts, expressed as CFU per gram of dry solids, for the peat material sampled from the Ballydermot bog. Incubation temperature and aeration considerably influenced the growth rate of microorganisms in the peat, which were mostly facultative in character (i.e., can live with or without oxygen), with greater numbers of colonies forming under aerobic incubation at a temperature of 20°C or 30°C. Fewer but approximately similar numbers of colonies formed under anaerobic incubation at temperatures in the range 10°C to 40°C. Hence, from the available data, it would appear that aerobic incubation

Incubation	Mean population of microorganisms: CFU/g peat solids			
	10°C	20°C	30°C	40°C
Aerobic	8.8×10^6	1.9×10^7	1.3×10^7	1.3×10^6
Anaerobic	6.1×10^6	4.2×10^6	6.0×10^6	7.4×10^5

Table 2. Mean microorganism counts for natural peat

at temperatures of between approximately 20°C and 30°C is ideal for the cultivation of indigenous microorganisms in the natural peat material. This is consistent with the findings of pilot studies performed on the same peat material by Pichan and O'Kelly (2013).

Rates of decomposition for peat under different incubation conditions

Table 3 lists the mean microbial populations measured shortly after preparation of the peat and blended test specimens, but prior to the start of the different incubation treatments at 30°C. These mean population values, which were determined under aerobic conditions at 20°C, ranged between 3.7×10^5 and 1.1×10^6 CFU/g for the peat and between 3.2×10^4 and 8.5×10^5 CFU/g for the blended material.

Specimen	Population of microorganisms: CFU/g peat solids	
	Mean	Average
P-Ae ₇	9.1×10^5	6.0×10^5
P-Ae ₁₄	5.4×10^5	
P-Ae ₄₂	7.0×10^5	
P-Ae ₈₄	4.7×10^5	
P-Ae ₁₂₆	3.7×10^5	
B-Ae ₇	8.5×10^5	6.3×10^5
B-Ae ₁₄	8.2×10^5	
B-Ae ₄₂	6.9×10^5	
B-Ae ₈₄	5.1×10^5	
B-Ae ₁₂₆	2.9×10^5	
P-An ₇	1.1×10^6	7.4×10^5
P-An ₁₄	6.0×10^5	
P-An ₄₂	8.7×10^5	
P-An ₈₄	6.3×10^5	
P-An ₁₂₆	4.8×10^5	
B-An ₇	8.1×10^4	6.4×10^4
B-An ₁₄	8.1×10^4	
B-An ₄₂	6.9×10^4	
B-An ₈₄	5.5×10^4	
B-An ₁₂₆	3.2×10^4	

Table 3. Initial microorganism populations in test specimens

Since the plated samples had been randomly selected from the different test materials, the relatively large variation in the measured numbers of colonies may be explained by the large spatial variations in microbial populations that naturally occur within peat (Barns and Nierzwicki-Bauer, 1997). However, the mean microorganism counts recorded for the peat in Table 3 are consistent with reported values for peats of $\sim 2.6 \times 10^5$ CFU/g (Hunter *et al.*, 2006) and within the range 2.2×10^5 to 1.5×10^6 CFU/g (Pichan and O'Kelly, 2013). Average values listed for the different specimen sets in Table 3 are used later in the paper as reference values for evaluating the decomposition rate.

From the data in Table 3, it would appear that the addition of PFA and urea materials to the peat did not have significant adverse effects on existing populations of indigenous microorganisms in the peat. Some of these microorganisms are expected to be key decomposers with cellulolytic potential (e.g., *Firmicutes*, *Bacteroidetes*, *Acidobacteria* and *Cytophaga*) as well as fungi capable of degrading celluloses in peat (Hunter *et al.*, 2006; Pankratov *et al.*, 2011). However, it was not possible to determine the actual types (species) of microorganisms in the peat using the technique employed and it was considered beyond the scope of this study. It was also not possible to determine the rate of nutrient decrease in the TSA 1/10 medium during the plate-count tests, which could potentially be correlated with the rate of microbe growth.

Data of mean microorganism counts for the peat and blended materials after different incubation periods at 30°C are presented in Figure 2. Compared with peat, microbial population values were significantly greater for blended material, with the measured ranges for both materials consistent with reported total microbial populations occurring near the ground surface of the order of 10^6 – 10^9 /g for many soil deposits (Mitchell and Santamarina, 2005). For a given material, microbial population values were also consistently greater for aerobic than for anaerobic conditions, since microorganisms generally have higher rates of generation, mutation and natural selection in an aerobic environment.

Figure 2. Microbial populations plotted against incubation period

Referring to Figure 2, the microbial populations in all test specimens increased significantly during the early stages of incubation; that is, between 0 and 7-day readings. This presumably occurred due to the steep increase in temperature between ambient laboratory temperature of 20°C and the higher incubation chamber temperature of 30°C. Compared with the peat, the blended material had significantly higher microbial populations, with a peak value of $\sim 1.2 \times 10^9$ CFU/g measured after 42 days under aerobic incubation at 30°C. This value was approximately 1800 and 3500 times greater than the average initial values measured for the peat and blended materials, respectively, under aerobic conditions at 20°C (Table 3). The microbial populations within the aerobic blended material appear to remain approximately steady over the course of the 126-day incubation period. For anaerobic blended material, the trend in the data suggests a gradual approximately steady increase in microbial populations with incubation period over the same time period. In contrast, after the initial 7-day incubation period, the microbial populations in the peat appeared to reduce steadily for both aerobic and anaerobic conditions, with approximately similar populations of $\sim 2.5 \times 10^6$ and 6.8×10^6 CFU/g dry peat present for the 126-day incubation period. This population range is approximately seven times greater than the average initial (pre-incubation) values measured for the peat under aerobic incubation at 20°C (Table 3).

From the above findings, it was anticipated that recorded increases in microbial populations for both the peat and blended materials could provide sufficient quantities of key decomposers necessary to bring about discernible changes in the physical properties of these materials and, furthermore, that relative changes in microbial populations could act as qualitative indicators of the decomposition rate.

Physical properties of the test materials before incubation treatment

Table 4 presents the mean and standard deviation (SD) values of water content, specific gravity of solids, LOI and fibre content determined before the start of the incubation treatments for the specimen sets of remoulded peat and blended material. As mentioned earlier, the peat material had been obtained in two batches, taken from the same depth but slightly different locations at the Ballydermot bog. The first batch from which peat and blended specimens undergoing aerobic treatment were prepared had mean values ($n = 5$, where n is the number of tests) for water content w of 1168% (SD = 59%), LOI of 98.4% (0.1%), specific

Figure 3. Water content plotted against depth profiles at the Ballydermot bog (Osario Salas, 2012)

gravity of solids G_s of 1.44 (0.02) and was moderately acidic, with a pH of 5.3 (0.1). The second batch from which specimens undergoing anaerobic treatment were prepared had mean values for w of 1481% (SD = 90%), LOI of 98.1% (0.1%), G_s of 1.42 (0.02) and pH of 5.4 (0.1). Undisturbed (intact) peat had a mean value for fibre content of 77.8% (SD = 6.8%). Remoulding of the peat during specimen preparation caused considerable mechanical tearing and breakage of the fibres, reducing its fibre content to approximately 50–55%. The fibre content of the blended material was even lower at 40.2% (SD = 3.5%, $n = 9$), simply on account of its 22.7% PFA and 1.5% urea components by dry mass. These additives had been pulverised in an attempt that they would not be the cause of significant tearing or abrasion of the peat fibres during material preparation.

Differences in measured water contents for the two batches of sampled peat, but also between sub-samples taken from the same batch, were significant. However, this is expected on account of the heterogeneity of peat deposits, with significant variations of in situ water content expected to occur, even over very short distances, in the case of fibrous peat. Hobbs (1986) explained this by considering the plant growth patterns, with plant vegetation of different character living in communities, and the non-uniform

Material	Incubation	Water content: %	Specific gravity	Loss on ignition: %	Fibre content: %	pH
Peat	Aerobic	1168 ± 59	1.44 ± 0.02	98.4 ± 0.1	51 ± 4	5.3 ± 0.1
	Anaerobic	1481 ± 90	1.42 ± 0.02	98.1 ± 0.1	54 ± 4	5.4 ± 0.1
Blended	Aerobic	881 ± 39	1.66 ± 0.02	72.7 ± 1.0	39 ± 2.6	7.3 ± 0.2
	Anaerobic	1047 ± 55	1.65 ± 0.03	76.9 ± 2.4	41 ± 2.6	7.2 ± 0.1

Table 4. Physical properties of test materials before incubation

decomposition rate that occurs throughout the bulk mass. Landva (1980), for instance, found that the water content at any selected depth within a 75-m-by-15-m test area at Escuminac (NB, Canada) varied by at least 600 percentage. This natural heterogeneity is also evident from the significant differences between water contents determined from peat cores recovered from two 100-mm-diameter cable percussion boreholes, BH1 and BH2, at the sampling area on the Ballydermot bog site (Figure 3). Within the 3.8- to 4.0-m-deep peat layer, water contents reduced approximately linearly from 1340% to ~600% with increasing depth from 1.5 to ~4.0 m below the ground surface. Closer examination indicates that differences of up to 88 percentage occurred between measured water contents for specimen pairs sampled from the same core and depth in the peat deposit.

The measured specific gravity of solids values for the peat are within the reported range of 1.4 to 1.5 for cellulose and lignin (Hobbs, 1986), and are also consistent with its extremely high LOI value of ~98%. Compared with the peat, the blended material had significantly lower values of water content, LOI and fibre content, but higher values of pH and specific gravity of solids (Table 4). This is simply explained by the dry inorganic PFA additive that had been mixed with the wet peat. From the known mix proportions, measured specific gravity of solids of 2.59 for the PFA material and assuming that the urea goes into solution, the specific gravity of solids for the blended material was calculated as 1.67. This value is in good agreement with the mean initial specific gravity of solids value of 1.65 (SD = 0.03, $n = 10$) measured for aerobic and anaerobic specimen sets B-Ae and B-An.

Physical properties of test materials after incubation treatment

Figures 4–7 present the measured values of water content, LOI, specific gravity of solids and fibre content plotted against incubation period at a temperature of 30°C for the peat and blended materials. Overall, it would appear that water content, LOI and specific gravity of solids were practically independent of incubation period,

Figure 4. Water content plotted against incubation period

Figure 5. Loss on ignition plotted against incubation period

Figure 6. Specific gravity of solids plotted against incubation period

whereas fibre content was approximately inversely proportional to incubation period. Each of these material relationships is discussed in turn below.

The sealed incubation bags used for both aerobic and anaerobic treatments created a closed system in that the original mass of pore water within the test specimen remained in place and was added to by some additional pore water generated from the decomposition process. Significant increases in microbial populations have been shown to occur during the incubation period for both peat and blended material. Hence it would be expected that water content would increase somewhat with incubation period. However, statistical analysis of the data in Figure 4 using the analysis of variance method indicated an F -ratio value of less than 0.38, which suggests that measured water content values were practically independent of incubation period. This may be explained as follows. For peat, the original mass of pore water is extremely large compared with that generated as a result of the incubation treatments; for example,

Figure 7. Fibre content plotted against incubation period: (a) incubated specimens; (b) incubated and compressed specimens

for the first and second batches of sampled peat, the original mass of pore water was approximately 11.7 and 14.8 times that of the dry solids respectively. Some simple calculations will show that the water content of treated specimens for which reductions of up to approximately 10% in dry solids mass had occurred would still fall within the 95% confidence interval for the untreated specimen. Hence the authors postulate that the microbial populations produced over an incubation period of up to 126 days were not sufficient to cause greater material change, with all of the data comfortably falling within the 95% confidence interval.

Fresh organic matter is broken down and mineralised during the decomposition. In theory, the transformation of organic matter into humic substances and conversion into gases caused by an increase in the degree of decomposition ultimately reduce the organic content, thereby marginally increasing the specific gravity of solids (Pichan and O'Kelly, 2013). However, in the present study, volatile

organic content was assessed based on the mass of combustible material (expressed as a percentage of the total sample dry mass) for a furnace temperature of 440°C. Therefore this test method does not make any distinction between the different types of organic matter present. Hence, given the nature of the test method used and the extremely high LOI value of ~98% measured for untreated peat, it is unsurprising that incubated peat had similar values (Figure 5). Statistical analysis indicated an *F*-ratio value of 0.60, indicating that LOI was practically independent of incubation period.

The specific gravity of solids value for peat is strongly dependent on its mineral content. Based on the proportion of ash residue after combustion at 440°C, the sampled peat had a mineral content of less than 2% by dry mass. Hence, again it is unsurprising that, for incubated peat, the specific gravity of solids value remained practically unchanged (Figure 6), with an *F*-ratio value of 0.65.

It has been well documented in the literature (e.g., Mesri and Ajlouni, 2007; O'Kelly and Pichan, 2013; Wardwell *et al.*, 1983) that the decomposition process causes progressive degradation of constituent fibres and hence a reduction in fibre content. Overall, this trend is evident in Figure 7 for both the peat and blended material, particularly for aerobic incubation, with best-fit trend lines indicating a general trend of decreasing fibre content with increasing incubation period. However, reported values in Figure 7 for the rate of reduction in fibre content with increasing incubation period are indicative only, given the relatively small number of data points and extreme variability expected for peat. Nevertheless, greater rates of reduction in fibre content occurred under aerobic conditions, with gradients of 0.049 and 0.043 for the peat and blended material trend lines, respectively (Figure 7a). The slightly lower value determined for the blended material is simply explained on account of the lower initial fibre content of these test specimens. When considered in terms of the percentage reduction in the initial fibre content values of 51% and 39% (see Table 4), the gradient of 0.043 for the blended material should be factored by approximately 1.3 to 0.056, confirming that the blended material provides more favourable conditions for decomposition to occur. As expected, for the anaerobic condition, the effect of the incubation treatment was significantly reduced, particularly for unblended peat.

Repeat tests were performed to confirm these observations (see Figure 7b). In this instance, specimens prepared from the incubated peat and blended material were compressed one-dimensionally in a consolidometer apparatus (O'Kelly, 2009) under an applied vertical stress of 14 kPa. The 150-mm-diameter specimens, each precisely 2.2 kg in wet mass, were formed by loosely placing and levelling the test material within the confining ring of the apparatus, without applying any compactive effort, thereby causing minimal disturbance to the peat fibres during the specimen preparation. A vertical stress of 14 kPa was applied on the basis that it had been established as the pre-consolidation pressure for the in situ peat (Pichan and O'Kelly, 2013). By the end of these 21-day-duration compression tests, large axial strains of 36–44% had occurred for both the peat and blended specimens. The fibre content of these

compressed specimens was then determined in accordance with ASTM D1997-91 (ASTM, 2008). For these specimens, the best-fit trend lines in Figure 7b indicate a stronger relationship and greater rate of decrease in fibre content with increasing incubation period for both the peat and blended material. This may be explained as follows:

- The measured fibre content values represent the combined effects of the incubation treatment and stress-induced changes. Fibres degraded or weakened as a result of the incubation treatment would have been more susceptible to mechanical degradation and breakage during the one-dimensional compression and structural rearrangement of the peat fibres occurring under the large strains.
- Before these fibre content tests were performed, the test specimens would have also undergone some further decomposition over the course of the 21-day compression tests. In the confining ring of the consolidometer apparatus, the test specimens would have experienced anaerobic conditions at ambient laboratory temperature of 21°C. The stress level would not have affected the decomposition process (O'Kelly, 2005b).

Other factors affecting the variance between specimen data for a given test material are:

- The relatively small size (mass) of the test specimens and natural heterogeneity of the test materials, with different test specimens and also sub-samples taken from these specimens for physical testing showing considerable variation in initial properties, even under the controlled material/specimen preparation conditions. Peat is a particularly challenging material to work with on account of its inherent variability, difficulties in sampling and handling, extremely high water content and presence of fibres.
- The degree of heterogeneity occurring between the untreated peat test specimens is likely to change, and by an unknown amount, for the different incubation periods. This occurs on account of the non-uniform decomposition rate for plant vegetation of different character comprising the peat material. Hobbs (1986) reported that the decomposition process can be rather patchy, particularly during the early stages.

Recommendations for future studies

This experimental study has demonstrated that the existing microbial populations and activity in peat can be increased markedly by altering moisture aeration status, temperature, pH and carbon/nitrogen ratio within reported optimum ranges for decomposition to occur. The decomposition process caused progressive degradation of the constituent fibres, which was reflected by an approximately inverse relationship between fibre content and incubation period over the 126-day testing programme. The optimum condition for aerobic microbial activity requires a degree of saturation of 60–80% (Mitchell and Santamarina, 2005), although it is questionable whether this was consistently achieved throughout the

aerobic test specimens for the present experimental setup. Hence, the decomposition rate could be increased further by incorporating established technologies of biosparging, bioventing and bacterial seeding. These would ensure sufficient and more uniform supply of oxygen within the peat and also increase the proportions of key decomposers in order to stimulate extra microbial growth. Further microbiological studies should be performed to identify the types and species of existing microorganisms in peat and the favourable environment conditions for their growth. The study also demonstrated that peat has potential for extreme variability, particularly more fibrous peats, even under controlled material and specimen preparation conditions. This can be addressed somewhat in future studies by testing greater numbers of specimens having larger size (mass). In relation to the determination of fibre content, chemical analysis may prove more insightful in assessing the levels of microbial activity and resulting effects on physical properties; for example, measurement of chemical properties by quantitative measurements of extracted humic substances (Rochus and Sipos, 1976). Measurement of volatile organic content using LOI tests could be complemented with data from dichromatic-oxidation tests (Landva *et al.*, 1983). Measurements of the reduction in test-specimen mass over the course of the incubation treatments could be used to assess the level of destruction of the fibres due to increased microbial activity (Thormann, 2011). Image analyses using various image-processing techniques suggested by Zainorabidin *et al.* (2010) could also be used to investigate potential changes in fibre structure and of the peat fabric occurring as a result of increased levels of decomposition. Additional microbiological studies could also be performed in order to identify the types and species of indigenous microorganisms in the peat and establish favourable/optimum environments for their growth. The peat test material considered in the present study was initially in a moderately decomposed state (H_{5-6} on the von Post peat classification system). The effect of the incubation treatments may have been more dramatic had the peat been initially in a lesser decomposed state (higher fibre content). Hence further studies are recommended to investigate the effects of stimulated microbial decomposition under different incubation treatments on the engineering properties of peats having a range of botanical compositions and for different initial decomposition states.

Summary and conclusions

The hypothesis of this experimental laboratory study was that microbial populations in peat and hence its decomposition rate can be stimulated by altering moisture-aeration status, incubation temperature, pH and carbon/nitrogen ratio within reported optimum ranges for decomposition to occur. As a demonstration, the pH and carbon/nitrogen ratio of a fibrous Irish peat were adjusted accordingly by mixing peat-pulverised fuel ash material and urea with the peat. This process did not appear to adversely affect indigenous microbial populations present within the sampled peat, which were significantly enhanced by aeration and by maintaining an incubation temperature in the range 20–30°C. Water content, specific gravity of solids and volatile organic content were found

to be practically independent of incubation period on account of the extremely high water content and almost exclusively organic nature of the sampled peat. For 30°C, microbial populations in blended material incubated aerobically and anaerobically were found to increase by approximately 3500- and 1800-fold, respectively, and remained steady over the duration of the 126-day incubation period considered. Fibre content was approximately inversely proportional to incubation period, suggesting that increased microbial populations were responsible for increased decomposition rates, particularly for blended material under an aerobic condition. Under compression loading, peat fibres degraded or weakened as a result of the incubation treatment were also more susceptible to mechanical degradation and breakage.

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