STUDY OF THE MECHANISM OF INTERNAL MASS TRANSFER DURING THE DRYING OF VISCOPLASTIC PEAT

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A description is given of the procedure employed in a study of the mechanism of desiccation of cylindrical lumps of peat by the radioactive tracer method under radiative-convective conditions, uncomplicated by moisture exchange with the ground, and the results obtained are analyzed. Drying was performed in an air-conditioned chamber with a normally incident radiation flux.

The radioactive tracer method has been successfully used to study the mechanism of internal mass transfer during the drying of peat. The peat desiccation processes under isothermal conditions [1–4], the mechanism of radiative-convective desiccation of crumbled peat [5–7], and the mechanism of temperature-dependent moisture transport [2] have been particularly well studied.

The aim of the present investigation was to study the mechanism of internal moisture transport and its intensity in various directions in a lump, as well as the rate of evaporation from various areas of the outer surface. The experiments involved: complex observations of changes in specific activity and specific moisture in various layers and at various points of a lump; activity and moisture measurements in various layers and at various points; and measurements of surface activity and surface shrinkage. The influence of temperature on moisture transport was studied by determining the vertical temperature distribution in a lump with the aid of thermocouples.

The procedure of obtaining samples for studying activity and moisture was selected on the basis of preliminary investigations of the moisture field across a cylindrical lump. These tests revealed that the maximum moisture gradients develop in the vertical direction in the upper half of the lump. Substantial moisture gradients are located also in the surface layer of a lump. The sampling method (see Fig. 3a) and the corresponding procedure for measuring surface activity (see Fig. 3b) were selected accordingly. In view of the substantial and nonuniform shrinkage of peat, to ensure adequate sampling the individual layers were marked with a stamp at the end face of a moist lump prior to drying.

Samples for measuring specific activity were prepared in the following manner. After a lump was sectioned in accordance with the sampling method, the samples obtained were dried in a thermostat at t = = 100–105° C to determine their moisture content. Powder samples were then obtained by grinding the dry residue in a mortar. The activity N of absolutely dry peat was measured with an MST-17 counter incorporating a B-3 radiometer. The thickness of the powder layer was in all cases greater than the thickness of the total self-absorption layer of S^{35}.

To measure the surface activity N' of a lump, a plane horizontal screen with a rectangular (4- by

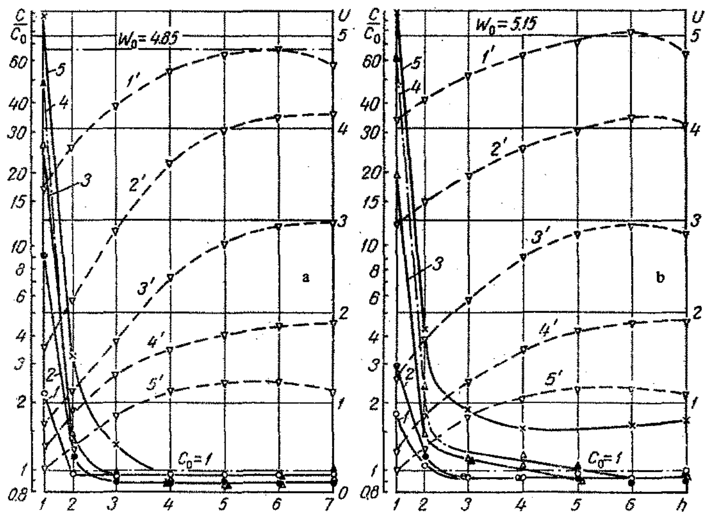

Fig. 1. Curves 1–5 show the tracer concentration (C/C_0) distribution and curves 1'–5', the corresponding moisture (U, in g/g) distribution over the height h during various drying phases: 1–7 along the h-axis are the numbers of the layers marked according to the scheme in Fig. 3a; a) lowland peat, W_0 = 4.85 g/g; b) highland peat, W_0 = 5.15 g/g.

12-mm) collimating slit, oriented along the counter axis, was fixed over the end window of the vertically mounted MST-17 counter. During the activity measurements, the lump was placed on this screen to make it possible to record the beta radiation from the surface area, limited by the dimensions of the slit. Surface shrinkage was compensated for by observing, with a measuring microscope, the changes in the area S of regions bounded by thin (0.1-mm) reference wires. (The initial dimensions of the areas were $S_0 = 6.5 \times \times 6.5$ mm.) Surface shrinkage was measured at the same points at which activity was recorded.

Investigations were performed with two types of peat which differed greatly in their physicochemical properties: lowland "rush-sedge" peat and highland "pine-cotton grass" peat, both with decompositions R = = 45–50%. The highland peat is a high-quality raw material, while the lowland variety, due to its tendency to crack formation, crumbles during field drying and is not suitable for obtaining high-quality products.

The S^{35}-tagged $Na_2S^*O_4$ tracer was introduced in the form of an aqueous solution into the initial peat pulp under vigorous mixing, and was allowed to stand for 10 days to ensure uniform distribution of the tagged atoms. This distribution was checked by taking samples. The peat was dispersed and formed into cylindrical lumps (∅50 × 75 mm) in a worm mechanism. After marking at the end face according to the sampling procedure, we placed the samples in an air-conditioned chamber on a peat monolith with a thin moisture-proof coating. The lumps were spaced 5 mm apart. The daily cycle comprised a period of radiative-convective drying (12 hr; t_c = 28–30° C; φ = 55–40%; v = 0.8 m/sec; q = 0.5–0.6 cal/cm² · min) and a period of convective drying (12 hr; t_c = 18–20° C; φ = 80–85%; v = = 0). These conditions simulated, in the first approximation, the daily field-drying cycle of finely divided peat. Sampling for layerwise moisture and activity was performed three times a day, namely, in the middle of the first period and before changing the drying conditions. The activity of surface areas was measured every 2–3 hr.

Different methods of expressing activity were used in the analysis of the experimental data. The specific activity N of dry pulverized samples defines the tracer content per unit mass of the dry material. The values of N depend on the moisture content W per unit weight (g/g of dry material) of a sample and on the tracer concentration C in interstitial water (g/g of water):

$$N = kCW,$$

where k is a proportionality coefficient, which is invariant for standard sampling and equal radiometric conditions. Treating k as a constant, we get an expression for the relative concentration

$$\frac{C}{C_0} = \frac{N}{N_0} \frac{W_0}{W},$$

where N_0 and W_0 are the initial values of the activity and moisture of a sample, respectively.

It is known from [1, 8] that values of $C/C_0 > 1$ characterize regions of evaporation, while values of $C/C_0 < < 1$ characterize regions of condensation. A constant ratio $C/C_0 = 1$ corresponds to liquid internal mass transport. Constant N and W values in a layer indicate the presence of transit vapor flow.

Let us turn to a discussion of the results obtained (Figs. 1–3). First, we shall clarify the nature of upward internal moisture transport in a lump, and will show that this is the preferred direction. We shall then evaluate the degree to which the various surface areas participate in evaporation. To begin with, it should be noted that, as a rule, the vertical temperature gradients in a lump did not exceed 0.5 deg/cm. Hence, the influence of temperature on moisture transport could be neglected [8], thus simplifying analysis of the effect.

Figure 1 shows the distribution of C/C_0 (on a logarithmic scale) and of the moisture content U (g/g) over the vertical cross section of the samples during the various drying phases. The shape of curves 1 and 1' in Fig. 1a shows that in the initial drying phase, internal mass transfer takes place in the liquid phase, accompanied by evaporation in a thin surface layer. A moisture gradient below the evaporation zone forms owing to shrinkage of the adjacent layers, this process gradually expanding toward the bulk of the lump. Direct measurements of the capillary pressure P_c of the interstitial moisture made with ceramic sensors* in the center and in the upper layer (somewhat below the evaporation zone) of a lump showed that the pressure difference increases abruptly during drying. This is associated with large hydraulic losses during internal mass transfer, and explains why the layers of a lump closest to the meniscus front are the first to be dehydrated and the first to condense owing to shrinkage.

The liquid nature of internal moisture transport, without any appreciable penetration of the evaporation zone into the bulk of a lump, is retained during the further drying process (curves 3 and 4 and 3' and 4'). Only after $U \leq 1$ g/g was reached by the internal layers did vapor diffusion replace liquid transport in these layers (curves 5 and 5'). The zone where transport occurs by diffusion expands gradually into the bulk of a lump during further drying.

The dominant role of liquid transport in the drying of peat is associated with intense shrinkage under the action of capillary pressure increasing beyond the ultimate shearing stress θ of peat [10, 11]. In the course of dehydration of the layers, θ increases more rapidly than P_c. This leads to cessation of shrinkage, to a change in the mechanism of internal mass transport, and to a deceleration of the drying rate. The strong shrinkage of peat, which determines its behavior during the drying process, is associated with a high content of immobilized water in the peat [12].

*The sensors were coupled to low-inertia, automatic null-type strain gauges [9].

The mechanism of moisture transport during desiccation of highland peat is, in general, similar in nature (Fig. 1b); however, the transition to vapor diffusion takes place at a higher moisture content of the layers. The dehydration process during the initial drying phase is much more uniformly distributed over the entire volume of a lump (curves 1 and 2), which is an indication of better moisture transport in highland peat. A confirmation of this is that the pressure difference of interstitial moisture in the upper and central layers of a lump of highland peat is smaller at the same evaporation rate.

Figures 2a and b show the variation of the surface activity of a lump (N'/N'_0) (curves 1) and the mean tracer concentration (C/C_0) in an initially 3-mm thick surface layer (curves 2). All data are given as a function of the mean moisture content (W) of a sample. The moisture content of this layer (curve 3) varies faster than the surface shrinkage (S/S_0) (curve 4), because of the high drying rate and the inhibiting effect of the lower layers on shrinkage. This leads to a recession of the meniscus front in the micropores and to the formation of an evaporation zone, whose position is determined by the conditions under which the liquid flow from the internal layers of a sample is equal to the flow of evaporating moisture.

If during the initial drying phase, curves 1 and 2 have roughly the same shape and, therefore, evaporation proceeds practically from the outer surface, then for $U \leq 2$ g/g, the increase in surface activity starts to exceed that of the mean tracer concentration in the surface layer. At a moisture content of $U \leq 0.8$ g/g in the surface layer, the surface activity N' remains stable after experiencing an abrupt increase (see Fig. 2b). The abrupt increase in surface activity may be associated with the expulsion of concentrated labeled water from the evaporation zone to the surface, or with a decrease in the degree of liquid-phase shielding of soft beta radiation during the desiccation of the surface layer. To assess the influence of the second factor, special tests with filter paper were carried out.* The surface activity of thin paper saturated with labeled water increased after drying by as little as 1.7 to 1.9 times as compared with the activity in the water-saturated state, whereas for peat, an increase by a factor of 10 to 15 is to be observed in a region characterized by a pronounced increase in surface activity. An increase in surface activity is, therefore, associated with the appearance of an evaporation zone and with water transport in the liquid state in this zone toward the outer surface, at a moisture content in the surface layer ranging from U = 2 to 0.8 g/g. Transport appears to be accomplished by means of pellicular moisture and a network of micropores. For U = = 0.8 g/g, the flow of liquid to the outer surface ceases, and transition to diffusion of vapor also in the bulk of the sample sets in simultaneously. The change in the transport mechanism occurs at a mean moisture content of W = 2–2.5 g/g in the sample. This corresponds to the first critical point on the drying-rate curve.

As can be seen from Fig. 2c, surface shrinkage (curve S-I) intensifies at U = 1.3–1.0 g/g. This is associated with the interaction between approaching particles under the action of molecular attraction forces. However, simultaneous increase in the viscosity and strength of the structure inhibits this interaction and leads to cessation of shrinkage.

Intensification of surface layer shrinkage toward the end of the drying process in the presence of substantial moisture gradients in the bulk of a lump contributes to the formation of surface cracks.

The described change in the moisture-transport mechanisms in the evaporation zone does not occur simultaneously all over the external surface. An indication of this, in particular, is the displacement of the specific surface activity curves along the W-axis for various areas of the surface (curves I–IV, Fig. 3). This is associated with the fact that some of the surface areas attain at different times a surface moisture of U = 2 g/g, for which a rapid increase in N' sets in. The values of N' are always stabilized after surface moisture reaches U = 0.7–0.8 g/g. Hence, at $U > 2$ g/g, evaporation proceeds mainly from the outer surface, at $0.8 \leq U \leq 2$ g/g it proceeds from a thin surface zone, while at $U < 0.8$ g/g, the liquid flow toward the outer surface is interrupted. The mean moisture corresponding to these conditions varies as a function of the volume of the lump and the drying conditions. Values of U = 2 g/g correspond to a transition from a coagulation to a condensation structure of the peat, while values of U = 0.8 g/g correspond to a content of physicochemically bound water. This explains the changes in the mechanism of internal mass transport.

The deeper an area of the surface is located (I–V, Fig. 3) the smaller is the amount of water that evaporates from a unit area during the entire drying period. This is confirmed by a decrease in the specific activity peaks* (curves I–IV, Fig. 3b). Consequently, the intensity of evaporation during radiative drying is distributed quite nonuniformly over the cylindrical surface of a lump as a result of the difference in the boundary conditions. These conclusions are confirmed by the curves of the specific activity N of dry samples taken from various areas of the surface layer. A comparison between curves I–III and 1-I, 1-II, and 1-III in Fig. 3 shows that practically the entire tracer is transported together with liquid to the upper portion of a lump. In this process, the greatest amount of water is transported to the uppermost sector I (curve 1-I), a substantially smaller quantity is transported to sector II (curve 1-II), while a rather insignificant amount is transported to sector III (curve 1-III).

*Filter paper was chosen because, in thin layers, surface activity is influenced only by the shielding conditions.

*For lowland peat, smooth increase in surface activity is impaired by crack formation (bend of curves I and II, Fig. 3a).

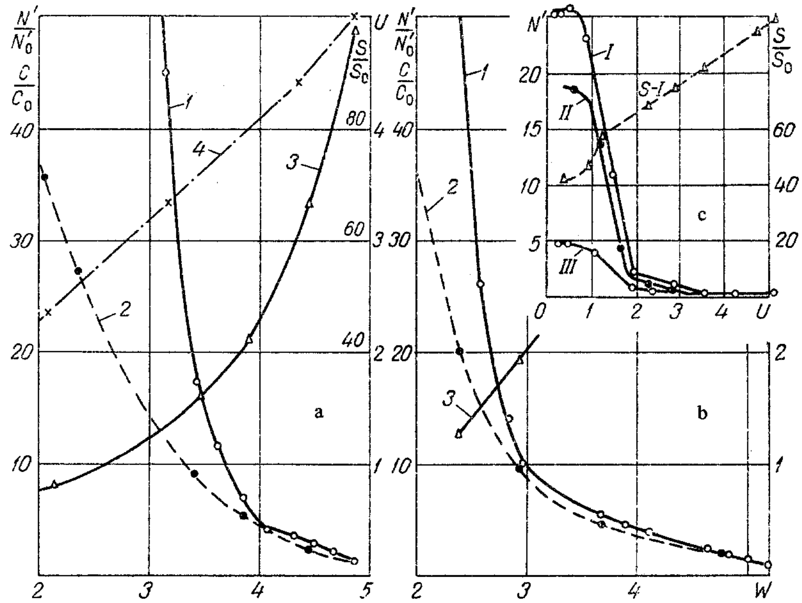

Fig. 2. Variation of (1) surface activity N'/N'_0, (2) tracer concentration C/C_0 in the surface layer and (3) its moisture content U, g/g and (4) surface shrinkage (S/S_0) 100%, as a function of the mean moisture content W, g/g of a sample, which decreases during the drying process: a) lowland peat; b) highland peat; c) specific surface activity N' $(1 \cdot 10^3$ pulse/min) and surface shrinkage $(S/S_0)100\%(S - 1)$ in various sectors of the cylindrical surface (see scheme in Fig. 3) as a function of the moisture content of the surface layer U, g/g.

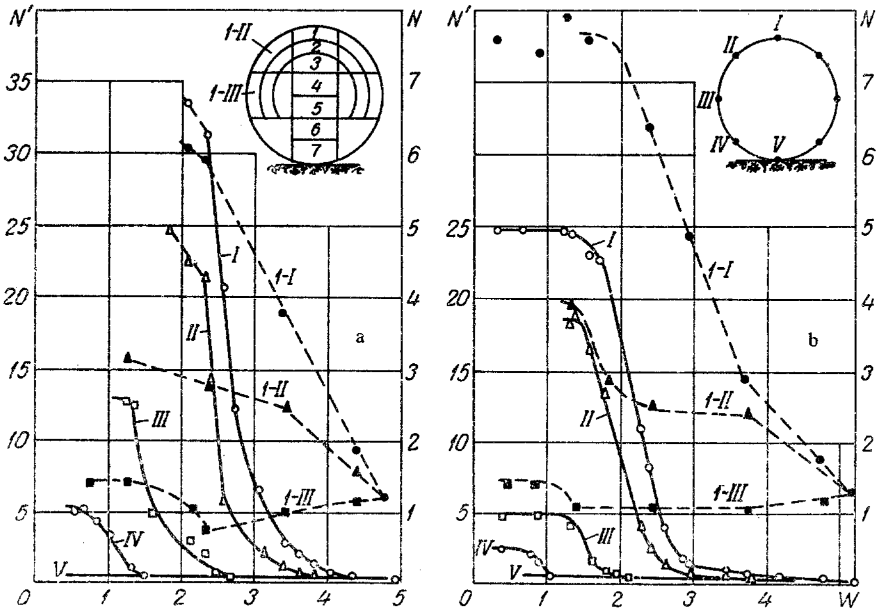

Fig. 3. Variation of the specific surface activity N' $(1 \cdot 10^3$ pulses/min, curves I–V) and the specific activity of dry samples from the surface layer N $(1 \cdot 10^3$ pulses/min, curves 1-I, 1-II, and 1-III) in various sectors of the cylindrical surface as a function of the mean moisture of a sample W, g/g, as it decreases during the drying process; a) lowland peat; b) highland peat.

These curves, just as the surface activity curves, reveal that the change in moisture transport mechanisms does not occur simultaneously in all areas of the surface layer. Indeed, after liquid transport to sector I has ceased (curve 1-I exhibits a peak), an increase in liquid transport to sector II (steeper ascent of curve 1-II), and later to sector III (steeper ascent of curve 1-III), can be observed.

Investigations by the radioactive tracer method of processes involved in the field drying of finely divided peat showed that the drying mechanism in this case does not differ qualitatively from the mechanism of drying in an air-conditioned chamber, which we have studied. Certain quantitative differences may be attributed to the higher moisture gradients that take place in a lump under the more rugged conditions of natural drying. The maximum amount of liquid is transported toward the surface areas that experience the highest solar radiation density.

NOTATION

N is the specific activity of dry powder samples; N' is the specific activity of portions of the outer sample surface; C is the indicator concentration in water; S is the area of sections of the outer sample surface; U is the humidity of the beds; W is the average humidity of a sample; t_c is the air temperature in drying chamber; φ is the air humidity; v is the flow rate; q is the radiation power.

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