Chapter 14
Changing Hydraulic Conductivity After Rupturing Native Structure of Peat Under Limited Evaporation Conditions

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Abstract The qualitative characteristics of peat raw materials in the processes of its mining and field enrichment fully depend on the nature of the biogenic-abiogenic interactions in the peat system, which is a capillary-porous body with a heterogeneous structure and water-peat binding energy changing in a wide range. Energy costs for dehydration of peat capillary-porous bodies of different sizes and configurations are crucial for technologies of peat extraction and processing in terms of ensuring economic efficiency of production. The present paper considers the issue of calculating the characteristics of dehydration of wet peat raw materials with moisture 84–90% under the influence of gravitational and capillary-osmotic forces, as well as through evaporation. As a result of the research, the characteristics of moisture transfer intensity in the biogenic-abiogenic peat system with varying water binding energy are described. For the high-moor peat deposits, the intensity of moisture transfer is described by a linear dependence, for the transitional and low-moor types of peat, the dependence has a minimum at the degree of peat decomposition of 30–32%. The minimum has the role of a generalised point at the decomposition degree of 31%. With the increasing decomposition degree for the high-moor type, the intensity of moisture transfer tends to zero due to the manifestation of the rheological properties of water, i.e. an increase in the limit shear stress and the density of the bound water, as well as the decreasing pore sizes. For transitional and low-moor types, the intensity of moisture transport tends to a constant with an implicit manifestation of the border due to the increase of the resistance factor of moisture transport. It is found that when the filtration equilibrium is reached, the amount of remaining moisture in the technogenic-disturbed biogenic-abiogenic peat system and the critical height of the bulk of peat raw materials will correlate with the moisture conductivity factors, porosity, pore size and height of a bulk. This feature of the changing moisture conductivity is confirmed by the experimental data obtained by the authors to assess the precipitation, the critical thickness of the bulk depending on the initial thickness of

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the peat layer of the disturbed structure and the change in the critical height in the pore radius function, which corresponds to the theoretical data obtained in the work.

Keywords Fuel resources · Green · Peat processing · Dewatering · Environmental management

14.1 Introduction

The concept of increasing share of local fuels in the energy balance is amongst the state energy policy aims; the objective is to ensure the needs of the Russian Federation's regions in fuel and energy resources. Small settlements remote from sources of heat distribution and energy are often faced with the problem of unstable fuel supply to their heat-generating enterprises (Mikhailov 2016). To a greater extent, this applies to towns that use solid and liquid fuels carried from remote sources. The Northwestern Federal District (NWFD) is not an exception; this paper analyses production technologies on its example and provides solutions to improve the quality characteristics of peat products and the productivity of the field stage of its production. The problem of improving the stability of fuel supply in the NWFD can be effectively solved in areas with sufficient reserves of peat fuel resources. The NWFD is amongst the richest in peat regions of Russia, where peat reserves are estimated at 5,791 fields with a total area of about 2.6 million hectares consisting of 7.73 billion tons of balance and 2.27 billion tons of off-balance resources. The reserves of peat at deposits with an area of up to 10 ha make up a sum of 18.8 million tonnes.

A distinctive feature of the NWFD is that the balance reserves of peat deposits make up 25.2% of the total Russian balance reserves of peat and are well studied compared to other regions, so 46.2% of them have A + B categories (According to the classification adopted in Russia, category A corresponds to the explored reserves prepared for mining. Geologically reasonable, relatively proven, contoured workings deposits belong to category B. Category C1 corresponds to the reserves established by the approximate studies of deposits. Category C2 corresponds to the pre-estimated deposits). However, the analysis shows (Fig. 14.1), that the share of reserves of categories A + B is very different by regions in the NWFD.

To date, peat has lost its importance as a reliable fuel for local power generation facilities; it happened primarily due to the peculiarities of extraction and production cycles of peat fuel, where the bulk of the moisture is removed by drying the extracted raw materials directly on the deposit surface. This reduces dramatically the stability of production under severe weather conditions and use of traditional extraction technologies. Present tome, the peat companies in the Russian Federation can be divided into three groups (Table 14.1) according to the volume of production: small, medium and large (Mikhailov et al. 2013).

The total annual volume of peat production in Russia has stabilised at about 2 million tonnes per year. There is a slight tendency of production growth, and only due to small-scale production. Large peat companies, accounting for only 3% of

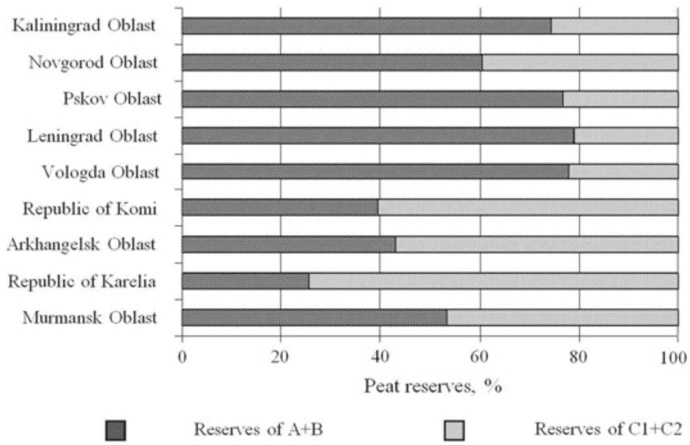

Fig. 14.1 The share of reserves of different categories in total peat balance reserves in the NWFD regions (Mikhailov et al. 2013)

Tables 14.1 Structure of the peat industry in Russia (in the adopted classification)

Peat extraction companies	Production volume, thousand tonnes	Percent from the total number of companies
Small	<5	52
	5–10	39
Medium	10–20	3
	20–40	3
Large	40–60	2
	60–100	0.5
	>100	0.5

the total, produced about 60% of peat, while small and medium −40%. Currently, scholars working on improving the technology of peat mining, pay more attention to the various options for year-round extraction methods and activities to extend the term of peat production. In this regard, the study of interactions occurring in the biogenic-abiogenic peat system under the technogenic impact becomes relevant.

The structure of the extraction process with native structure rupturing of a biogenic-abiogenic peat system is common in all technological solutions, including peat extraction from wetted deposits, followed by dehydration in the field and (or) production facilities. The development of solutions to optimise energy costs for the dehydration of peat raw materials in the design of technological schemes of its production, increasing the load per unit area of the mining field, becomes urgent. Theoretical and experimental studies to identify the potential of moisture removal are the basis of this work; they were conducted to create rational technological methods of field enrichment of peat raw materials of high moisture, based on the maximum intensity of drying in certain weather conditions, as well as optimisation of energy costs for dehydration of peat raw materials.

The solution of the task is provided by a comprehensive study of dehydration of wet peat raw materials with 84–90% moisture under the influence of gravitational and capillary-osmotic forces, as well as by evaporation. In modern economic conditions, the use of intensive technologies of milling and lump peat production is rational only for medium and large peat companies that have a fleet of special peat machines and complexes with prepared production facilities and operating in regions with favourable weather conditions. A striking example of the coincidence of all the factors necessary for the use of technology of milling peat production is the VyatkaTorf JSC, which produced 810 thousand tonnes of peat in 2011.

It should be noted that depending on the meteorological conditions of the area of the enterprise location, the seasonal collection of milling peat in the application of the classical technological scheme of milling peat varies in the range from 200 to 800 t/ha (Vasilyev and Smirnov 2004; Afanasyev et al. 1987). For NWFD conditions, as for other districts, this range is limited by the normative number of cycles for different types of deposits. For products of a nominal humidity of 40% the requirements are as follows. For all types of deposits with the degree of decomposition R_t = 5–15%, mining intensity has to be 100–250 t/ha; with the R_t = 16–20% it has to be 120–300 t/ha; for high-moor and transitional deposits with the R_t = 20–30% it has to be 170–425 t/ha; for high-moor peat with $R_t > 30\%$ and low-moor it has to be 190–425 t/ha. For products with a nominal humidity of 55% the required intensity is 220–550 t/ha (data processed after Afanasyev et al. (1987) on the normative values of the number of cycles and technological indicators of production of milling peat).

It is obvious that ensuring the volume of peat extraction using the existing technology of milling peat requires large production areas, but their preparation, mining and reclamation (Alekseenko et al. 2017, 2018) require significant investments related both directly to the work carried out and rental payments, growing with the increase in the developed areas. Prospects of increasing productivity and reducing the cost of peat production should be sought in the best use of meteorological conditions and increasing the load per unit area of the mining field by technological methods (Afanasyev et al. 1987; Antonov et al. 1981; Sokolov et al. 1988). It should be noted that consumers of peat raw materials and products impose a set of requirements for the characteristics of field peat products that are not provided with intensive production technologies. Peat, as a complex biogenic-abiogenic system, transforms during the execution of technological operations can both improve and worsen its consumer properties. The direction of the vector of change in the properties of the peat system is determined only when taking into account the whole range of factors of biogenic-abiogenic interactions that occurred during its natural formation and technological transformation in the course of technological mining operations.

For small peat companies, the most promising technology for peat extraction is the open-pit method for harvesting raw materials of increased moisture (Mikhailov et al. 2013; Kosov 2005; Kremcheev and Afanasyev 2012; Kremcheev 2014; Naumovich 1984; Kremcheev and Nagornov 2017), in which all production tasks are solved in a small field area with a minimum set of general-purpose technical means (swamp excavator, tractors with semi-trailers, front-end loader, etc.), its organisation is possible with minimal investment. In addition, the method has the following advantages: reduction of adverse environmental impact; expansion of the production season; optimal use of weather conditions; increase of economic efficiency of production up to 20 times compared to milling and lump technology (Mikhailov and Selennov 2009; Selennov and Mikhailov 2009); increase in the number of usable peat deposits; rapid reclamation of areas that absorb CO_2.

When using the open-pit method, it will be easier for small peat mining companies to follow the basic principles of environmental management in the extraction of peat raw materials: to follow the international principles of reasonable use of peat deposits; to ensure diversification of production with rational directions of extraction and use of peat; to provide extended mining of peat deposits; to flexibly apply innovative technological solutions in the extraction of peat raw materials, ensuring minimal environmental impact; to produce a phased reclamation and re-waterlogging of peat deposits, providing a reduction in fire risk in the post-production period and (or) improve the efficiency of peat accumulation process.

The flow sheet for the production of peat crumb and lump fuel can be implemented with a number of basic technological modules, interconnected by transport links. Crumb-shaped peat is both a product (milling peat) and a raw material for further year-round processing in workshop conditions and production of, e.g. lump-shaped fuel, peat briquettes, pellets or products demanded by the agriculture. With the transition to exclusively workshop conditions for the production of peat fuel, it is possible to significantly simplify the technology of extraction of raw materials, reducing the need for the preparation of fields for the extraction and drying of peat in the field, stockpiling, storage and transportation of products, as well as to significantly lessen the dependence of the production cycle on weather conditions, fire hazard, etc.

The conceptual scheme of interaction between the modules of small and medium-volume peat production and material flows within the energy cluster of distributed energy is presented in Fig. 14.2. The modular scheme of peat production in the structure of the distributed energy cluster includes mining, transport and processing modules (Kremcheev et al. 2012).

The mining module includes a quarry and zones of gravity dehydration and drying. The plot of gravity peat dewatering is arranged in the vicinity of an excavation area or on special platforms, where peat dehydration occurs in bulks until the critical height determined by the equilibrium condition of moisture under the action of gravitational, capillary and osmotic forces, taking into account evaporation.

Areas of peat drying can be of two types. The first type provides the stages of dehydration by evaporation from the side surface of the stacks of raw materials of an optimal size during the transfer of high moisture peat, followed by its use for the production of peat compositions or in the processing module. The second type is used to obtain the crumb-shaped peat, including conditioned moisture, by drying peat of optimal grain size in thick layers with a layer-by-layer cleaning in larger rolls and hauling during their drying-free time to the pile permanent storage or to the first-type site. The finished crump-shaped peat products with allowable moisture

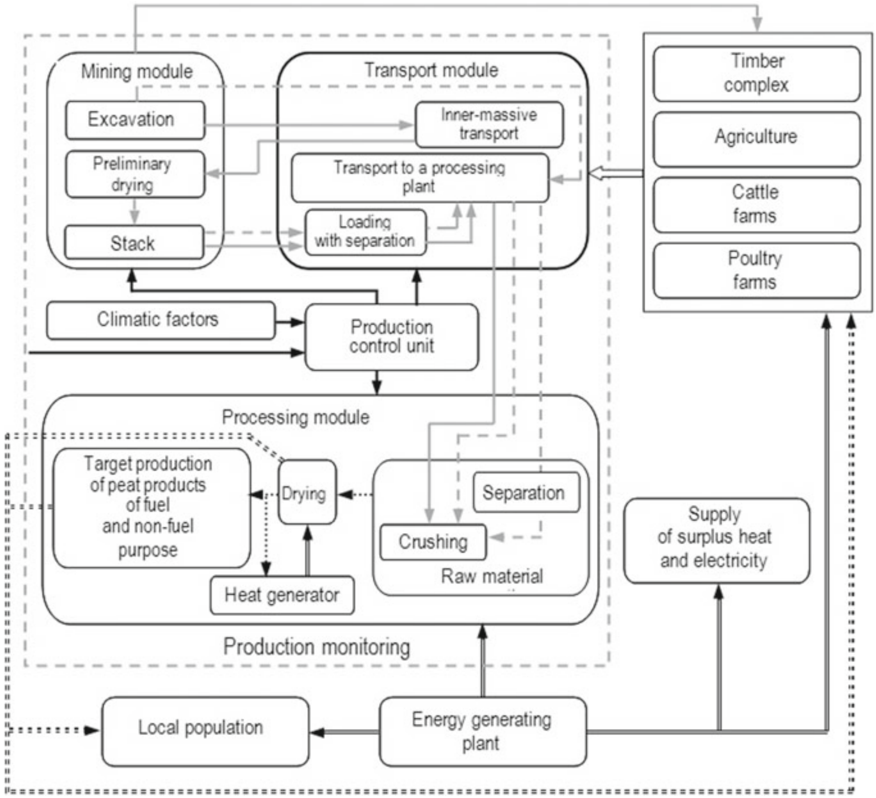

Fig. 14.2 Conceptual diagram of flows of raw materials, production and management of effects within the cluster of distributed energy

level are shipped to the consumer mainly for fuel purposes (*GOST R 50902-2011. Fuel peat for pulverised burning. Technical conditions*).

The processing module includes a preparation site for peat raw materials of increased moisture, providing two major processes, i.e. separation and crushing. Under the first process, peat raw materials are purified from large inclusions of wood and permafrost with its partial grinding. After separation, if necessary, the peat raw material is crushed to obtain a given particle-size distribution. The peat lumping provides obtaining agglomerates of fuel with desired characteristics (size, mass, strength, etc.). A screw extrusion method is a widespread technology for obtaining agglomerated peat fuel. The drying area is necessary for concluding drying of the peat fuel to a moisture content of not more than 45% (in accordance with the requirements of *GOST R 51062-2011. Lump peat fuel for household needs. Technical conditions*). Since the drying process is the most energy-intensive, it is rational to use a heat generator operating on the same peat fuel in the drying module to increase energy efficiency and energy independence of production.

The use of modular production technology with developed transport links will allow, if necessary, to respond quickly to changes in the characteristics of peat raw materials without changing the quality of the products. On the basis of previous studies, the target range of humidity for peat raw materials entering the shop module for the production of peat fuel products by extrusion, ranging from 60 to 70% (Kremcheev and Kremcheeva 2016; Lishtvan et al. 1983), has been established. In some cases, this range can be extended to 55–75% in case of product diversification. Thus, the task of the field stage of peat enrichment in open-pit mining is the decrease of moisture from 90–93 to 55–75%.

Due to the fact that for the proposed small-scale extraction technologies, the critical parameters are the rhythm and mode of moisture removal from the disturbed peat system, the issue of generalisation of theoretical information on moisture filtration in native and disturbed peat systems is getting more relevant, as well as the development of a mathematical apparatus that allows, on the basis of a priori information, to solve the problem of optimising the energy costs of dehydration of peat raw materials with moisture $W = 84$–90% under the action of gravitational P_g and capillary-osmotic P_k forces.

The aim of the research is the experimental-theoretical evaluation and ranking of the parameters of the biogenic peat system affecting moisture transfer, which in turn will allow development of a set of technological solutions to control the process of removing moisture from disturbed peat systems in small-scale field technologies of peat extraction and processing.

14.2 Approaches and Methods

Peat raw materials are considered as a biogenic-abiogenic system, the native structure of which is broken as a result of the influence of actuating elements of peat machines at the stages of extraction, transportation and preparation for the process of field enrichment, which are the main parts of the production process along with the field dehydration. The developed provisions are general and applicable for any peat type during its field dehydration.

When solving the problem of fluid motion estimation in biogenic-abiogenic peat systems of the disturbed structure at the first stage, the processes of accompanying moisture evaporation from the peat layer were not taken into account. The analysis of results of theoretical and experimental studies of changes in the properties of peat raw materials in the process of dehydration, taking into account moisture evaporation is performed by assessing the critical thickness of the peat layer during the dehydration of H_{cr} and balancing the gravitational and capillary-osmotic forces ($P_k = P_g$). The critical thickness is the value at which the technological scheme of peat extraction with the subsequent moisture removal from the peat layer of the disturbed structure during field dehydration is possible only with the use of mechanical pressing followed by final drying of raw materials by thermal methods in the factory or drying in the field. These stages of dehydration are amongst technological methods of changing the properties of peat raw materials (moisture W, density γ, porosity n, moisture transfer intensity i_i, total moisture capacity W_{tc}, strength R_i, etc.), determining, along with the degree of decomposition R_t, the quality of diverse peat-based products (Afanasyev and Churaev 1992; Afanasyev et al. 1987; Lazarev and Korchunov 1982; Semensky 1939; Shakhmatov 2011).

14.3 Results

Drying in the factory is one of the final stages of peat processing by weather-independent technologies. Implementation of this process in the factory without pre-drying in the field can be justified from an energy point of view, provided that at this stage at $W = 82–84\%$ peat is mechanically pressed (Lazarev and Korchunov 1982). The field stage of high humidity peat dewatering is much cheaper than the factory one, but it is a bit longer in terms of the technological cycle time. Questions of the physics of the biogenic-abiogenic interactions in peat systems are largely researched by V. M. Naumovich, L. S. Amaryan, V. I. Goryachev, etc.

Since the process of gravitational peat dewatering takes place irrespectively of a processing technology for peat raw materials of high humidity, in this Chapter the water transfer in a disturbed biogenic-abiogenic peat system is substantiated by gravitational and capillary-osmotic removal of moisture through the application of the model, providing a determination of the maximum values of the moisture transfer factor through filtration factors and the thickness of a dehydration layer subjected to a critical height reduction value. The results of experimental and theoretical studies are usually used in the evaluation of filtration processes (Amaryan and Bazin 1965; Gamayunov et al. 1998; Jordán et al. 2016; Kashchenko 2010; Kashchenko and Kovalev 2011; Korchunov et al. 1960; Kremcheev and Ivanov 2016; Kutais 1955; Nerpin and Khlopotenkov 1970; Sudnitsyn 1964; Vakhromeev et al. 1984; Vitkov et al. 1994), basing on the application of different models (Kashchenko 2010; Korchunov et al. 1960; Nerpin and Khlopotenkov 1970; Sudnitsyn 1964; Vitkov et al. 1994). The model analysis was described in a number of papers (Kashchenko and Kovalev 2011; Korchunov et al. 1960; Nerpin and Khlopotenkov 1970; Vitkov et al. 1994). Peat systems were studied using theoretical and experimental studies based on the potential theory of moisture transfer, taking into account the agreed models of moisture movement in films and capillaries (Amaryan and Bazin 1965; Gamayunov et al. 1998; Korchunov et al. 1960; Kremcheev and Ivanov 2016; Kutais 1955; Sudnitsyn 1964; Volarovich and Churaev 1960). These models give the greatest convergence of simulation results in comparison with the experiment (Gamayunov et al. 1998; Kashchenko and Kovalev 2011; Korchunov et al. 1960; Nerpin and Khlopotenkov 1970). Works on the study of the filtration properties of peat using radioactive isotopes (Afanasyev and Churaev 1992; Churaev 1960; Volarovich and Churaev 1960) made in the radiochemical laboratory of the Kalinin Polytechnic Institute (the Tver State Technical University nowadays) and in the Radchenkotorf Scientific Centre JSC are also of great interest, as well as the use of salt labels in the All-Russian Research Institute of Hydraulic Engineering and Land Reclamation named after A. N. Kostyakov.

Peat raw material, being extracted from a deposit, where stored as a biogenic-abiogenic native substance, passes from the two-phase state (liquid–solid) to the three-phase (liquid–solid–gas), which determines a significant difference between the processes of moisture movement in an undisturbed deposit and peat system subjected to dehydration in the process of extraction with field enrichment. The principal difference between the mining of peat and other minerals is the specific structure of the biogenic-abiogenic peat system and the complexity of water removal during the field enrichment, which is one of the stages of its production.

Water occurs in various physical states in nine stable isotopic types. In a water molecule, hydrogen and oxygen atoms create dipoles, which are combined into associates with the general formula H_2O and form a cyclic, chain and branched structure (tetrahedral associate) with covalent and hydrogen bonds. There is another division of the water molecule structure: angular, ball and tetrahedral.

Water, interacting with the solid phase and air, changes its physical and technological properties, which are different for free and bound water (Afanasyev and Churaev 1992; Gamayunov 2004). For instance, water in the free state is subject to gravity forces that transmits the hydrostatic pressure, almost not being compressed. In the bound state, the structure and density of water is affected by the mineralogical composition of peat, due to the primary (<15% ash) and introduced (secondary) ash, consisting of oxides of SiO_2, CaO, Fe_2O_3, Al_2O_3 (about 80% of ash) and such ions as Ca^{2+}, $Fe^{2+, 3+}$, Mg^{2+}, K^+, Na^+, etc. In this case, the density of bound water ρ_W, depending on the temperature T, passes through a maximum at $T \cong 310.5$ K for each period of structure formation and differs from $\rho_W = 1 \times 10^3$ kg/m^3 ($T = 277.14$ K) as higher, as higher is the degree of peat decomposition or its dispersion (Gamayunov 2004).

From the point of view of the porous structure, pores with a radius $r > 10^{-5}$ m are not capillary ones and therefore according to N. N. Fedyakin (Afanasyev and Churaev 1992; Gamayunov 2004) water in the pores will be almost free in terms of the surface tension factor σ and the viscosity η. Thus, according to A. V. Lykov, pores can be considered to be capillary for a porous peat body with a size of $l = 0.1$ m if their radius does not exceed 10^{-5} m. For a larger body, such as of $l = 1.0$ m, capillary pores are reduced and their radius should be 10^{-6} m.

In bodies with capillary structure, liquid forms a continuous tube of $h = l$ height. This fact is reflected in the hypothesis of S. N. Nerpin and E. M. Khlopotenkov on continuity of pores of the same diameter in the soil (Nerpin and Khlopotenkov 1970) and on the distribution of water-bearing pores in the soil (S. V. Lundin, L. V. Sverdlova), which indicates the presence of minimum volumes in the system, the pore characteristics of which do not change regardless of the location or orientation. For peat systems, this condition applies peculiarly to the porous particles with pores of a smaller diameter of non-particle (large) pores.

Capillarity can be determined by the ratio of pressures $P_g \ll P_k$. In this regard, both large and narrow (capillary) pores can be distinguished in peat bodies of the disturbed structure (Afanasyev and Churaev 1992; Churaev 1960; Volarovich and

Churaev 1960), which will determine the initial conditions of dehydration at $P_g > P_k$. The intensity of moisture transfer i_g is determined by the action of gravity forces until the height h_i of the bulk of the waterlogged peat of the disturbed structure reaches, due to height reduction, the critical height of H_{cr}, at which the values of gravitational and capillary-osmotic forces are aligned, and the flow of gravitational moisture becomes zero.

Regardless of a flow sheet used in the preparation of peat raw materials to dehydration, there is a violation of the structure of a peat deposit and its transition to a three-phase state in which, along with the forces of gravity $P_g = \rho_W g h_i$, capillary forces act in opposite directions $P_k = (2\cos\Theta)/r$ (Fig. 14.3). According to the laws of thermodynamics (Antonov et al. 1981; Gamayunov 2004), the increase in the entropy dS/d in time caused by external $dS_{e/}d$ and internal $dS_{i/}d$ conditions of heat and mass transfer is defined as:

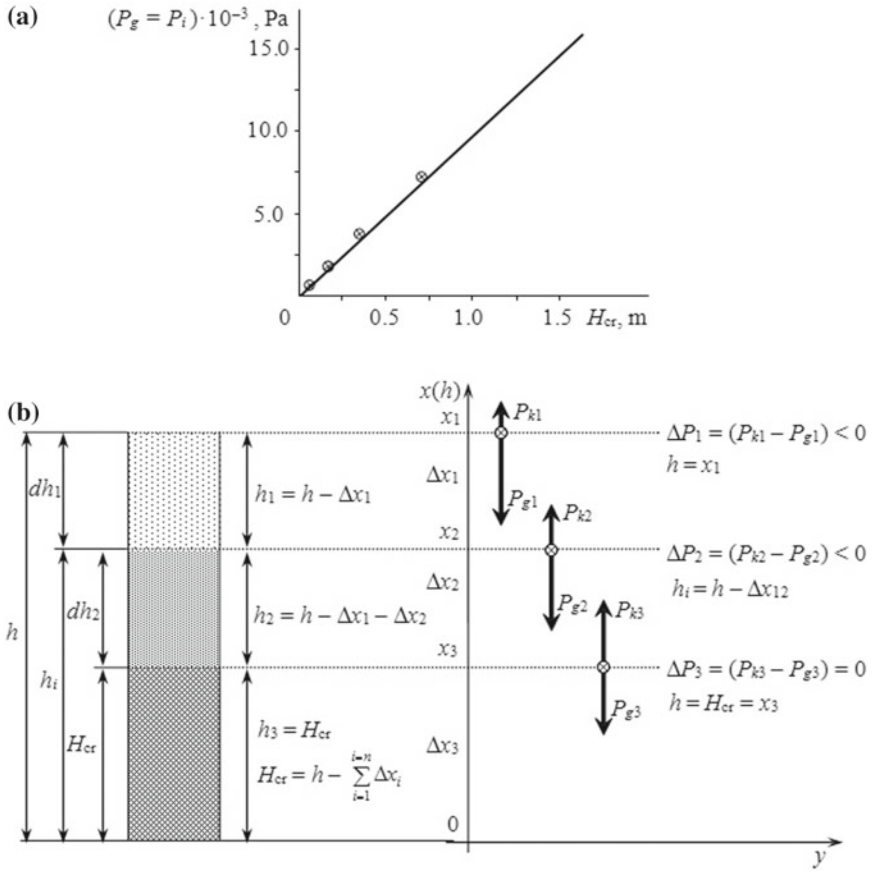

Fig. 14.3 The change of the pressure gradient $\Delta P = P_{ki} - P_{gi}$ (***a***) and the layer height (***b***) at dehydration of peat raw materials to $h = H_{cr}$ at $T = 273$ K

$$\frac{dS}{d\tau} = \sum_{i=1}^{n} J_i X_i, \tag{14.1}$$

where J_i is the flux density of the ith substance; X_i is the thermodynamic driving force.

It is experimentally found that J_i is proportional to X_i:

$$J_i = L_i X_i, \tag{14.2}$$

where L_i is the proportionality factor.

For the case of moisture transfer at T = const, the dependence (14.2) can be represented according to the Fick's laws of diffusion for the case of water evaporation from a watered surface

$$i_\mathrm{i} = -D\frac{\partial c}{\partial x}, \tag{14.3}$$

which after conversion (Antonov et al. 1981) takes the form of

$$i = -a_\mathrm{m}\gamma_\mathrm{c}\frac{dW}{dx}, \tag{14.4}$$

where $\partial c/\partial x$, dW/dx are respectively gradients of concentration of water vapour and moisture in the peat; D, a_m are the diffusion factors of vapour through air and moisture in the peat; $c = \gamma_\mathrm{c} W$; γ_c is the density of dry matter of peat at $W = W_i$.

The use of Eqs. (14.3) and (14.4) in our case is difficult since there is the uncertainty of driving forces X_i due to the decreasing height of peat raw materials in a bulk. At the same time, the use of the Darcy's equation in different forms (Amaryan and Bazin 1965; Kremcheev 2011, 2013; Kremcheev and Ivanov 2016; Kutais 1955; Nerpin and Khlopotenkov 1970; Vakhromeev et al. 1984; Vitkov et al. 1994) is not possible because of the impossibility of accounting for the capillary forces and vertical pressure h/l (Kutais 1955) when evaluating the hydraulic conductivity of peat raw materials.

Therefore, the use of Eq. (14.2) when assessing the hydraulic conductivity of peat allows choosing as a driving force the pressure difference $P_i = P_k - P_g$, related to the difference between the coordinates $\Delta x_i = x_i - x_{i+1}$ (Fig. 14.2). Without taking into account moisture evaporation from the surface or the associated internal evaporation, the equation of moisture conductivity will have the form:

$$i_g = -F_\mathrm{m}\frac{d}{dx}\left(P_k - P_g\right) = -F_\mathrm{m}\frac{dP_i}{dx}, \tag{14.5}$$

where F_m is the factor of moisture conductivity characterizing the flow of moisture at $(dP/dx) \to 1$, s; i_g is the intensity of the flow of moisture, kg/(m^2 s).

After substituting the expressions for P_k and P_g into Eq. (14.5), we obtain

$$i_g = -F_{\mathrm{m}} \frac{d}{dx}\left(\frac{2\sigma \cos \Theta}{r} - \rho_{\mathrm{W}} g h\right). \tag{14.6}$$

Provided *dh/dx* = 1 (Fig. 14.2) Formula (14.6) can be written as:

$$i_g = -F_{\mathrm{m}}\left(\frac{2\sigma \cos \Theta}{rh} - \rho_{\mathrm{W}} g\right), \tag{14.7}$$

where σ is the surface tension factor, N/m; *r* is the pore radius, m; Θ is the solid phase wetting angle, degree; *g* is the gravitational acceleration, m/s^2; ρ_{W} is the density of the associated fluid, kg/m^3.

Knowing such characteristics of a biogenic-abiogenic peat system as the factor of moisture conductivity, pore radius and layer height, all other things being equal, it is possible to determine the intensity of the flow of gravitational moisture in peat (peat raw materials) of the disturbed structure.

Analysis of Formula (14.7) shows that at the initial stage of dehydration of raw materials with a moisture content of $W \geq 82$–88% gravity can be taken as the main thermodynamic driving force. Then Eq. (14.7) takes the form:

$$i_g \cong -F_{\mathrm{m}} \rho_{\mathrm{W}} g, \tag{14.8}$$

that according to (14.6) will be:

$$i_g \cong -F_{\mathrm{m}} \frac{dP_g}{dx}. \tag{14.9}$$

Comparison of Eqs. (14.8) and (14.9) leads to the following condition

$$\frac{dP_g}{dx} = \rho_{\mathrm{W}} g. \tag{14.10}$$

So, if ρ_{W} = const, then dP_g/dx = const. This condition is approximate, since according to the data of the A. E. Afanasyev and A. S. Efremov, ρ_{W} = var and depending on the temperature, takes values in the range of $\rho_{\mathrm{W}} = (0.81 - 1.32) \times 10^3$ kg/m^3, respectively, at T = 273–311 K, i.e., each period of the structure formation of a peat body has its maximum defined by interaction type in a biogenic-abiogenic system and degree of peat processing, defined by parameters of an actuating unit of mining machines.

With the decreasing degree of peat processing and the increasing moisture content, the density of the liquid goes down, and with the increasing decomposition and processing degrees and the decreasing moisture content, the density rises compared to free water (Afanasyev and Churaev 1992; Gamayunov 2004). According to the known values of the intensities of the gravitational flow of moisture, Formula (14.8) can be used to find the values of the moisture transfer factors under the condition

$$P_k << P_g, h_i > H_{\text{cr}}.$$

At the height of the layer of peat raw material equal to the critical, the moisture flow pauses, and in accordance with the studies of Kutais (1955), the system passes into the filtration equilibrium. According to Korchunov et al. (1960), this state is determined by the equality of the full potential $\text{P} = 0$ due to the same values of the capillary $\text{F}_\text{c} = P_k/\rho_\text{W}$ and the gravitational $\text{F}_\text{g} = gH$ potentials,

$$\text{F}_c = \frac{P_k}{\rho_g} - gH \to 0. \tag{14.11}$$

From these conditions

$$P_g = P_k, i_g = 0, h_i = H_{\text{cr}} \tag{14.12}$$

we find the relationship between the effective pore radius r and the height (thickness) of the peat layer of the disturbed structure. From Eq. (14.6) it follows that

$$\frac{2\sigma \cos \Theta}{rh} = \rho_\text{W} g. \tag{14.13}$$

Then

$$h = H_{\text{cr}} = \frac{2\sigma \cos \Theta}{r\rho_\text{W} g}. \tag{14.14}$$

Equation (14.14) is similar to the Jurin's law on the capillary rise of the liquid. We estimate h using Eq. (14.14) for the average summer drying conditions in the peat industry.

The dependence $H_{\text{cr}} = f(r)$ has a hyperbolic form and corresponds to the expression (14.14). The dependence $H_{\text{cr}} = f(1/r)$ is linear in coordinates. Thus, with increasing thickness of the H_{cr} layer, the effective pore radius decreases; this is confirmed by filtration research (Kashchenko and Kovalev 2011; Korchunov et al. 1960; Nerpin and Khlopotenkov 1970).

As a result of data analysis (Afanasyev 2005) it is revealed that at the pore size $r_k = 20$ microns, capillary pressure tends to become gravitational, i.e. water absorption tends to the minimum value. In our case, this pore size corresponds to the peat bulk height of 0.692 m at the temperature of 273 K. With this, we believe that dewatering D_w and water absorption A_w for the porous body model differ only in the direction of the moisture flow and can be related by the ratio

$$D_\text{w} = 1 - A_\text{W}, \tag{14.15}$$

where $D_w = l_0/l$, i.e. is the ratio of the length of the water-filled section l_0 of the dead-end capillary to the total length of the capillary l; $A_w = l_i/l$ is the ratio of the length of the water-filled section of the capillary l_i to the total length of the capillary l.

Obviously, when using real media, more reliable results can be obtained, but taking into account all factors such as surface roughness, tortuosity, narrowings, expansions, hydrophilicity, air content and other physical, chemical and mechanical characteristics of the porous structure that change the resistance to moisture transfer, is quite a difficult task. In this regard, Formula (14.14) for the critical height, obtained from the condition of equality of capillary and gravitational pressures, was amended by a factor β, taking into account the features of the structure and indirectly reflects the resistance of moisture transfer,

$$H_{\text{cre}} = H_{\text{crt}}\beta = \beta\frac{2\sigma\cos\Theta}{r\rho_W g}, \tag{14.16}$$

where H_{cre}, H_{crt} are experimental and theoretical values of the critical thickness of a peat layer, respectively. The expression (14.16) can also be written for the current values of the height of the layer exposed to precipitation,

$$h_{\text{e}} = h_{\text{t}}\beta. \tag{14.17}$$

Thus, the expression for calculating the intensity of the moisture flow in the peat takes the form:

$$i_g = -F_{\text{m}}\beta\frac{P_k - P_g}{H_{\text{cr}}} = F_{\text{ef}}\frac{P_k - P_g}{H_{\text{cr}}}, \tag{14.18}$$

where $F_{\text{ef}} = F_{\text{m}}\beta$ is the effective moisture transfer factor; F_{m} is the factor of moisture conductivity; β is an empirical factor dependent on peat characteristics, clarified by the results of specific experimental studies of a biogenic-abiogenic system with the use of expressions (14.16) and (14.17), $\beta = h_{\text{e}}/h_{\text{t}} = H_{\text{e}}/H_{\text{t}}$, so for real environments, the values of H_{cr} and the intensity of moisture transfer i_g will be different in comparison with the theoretical values obtained for the capillary model,

$$i_g = -F_{\text{m}}\left(\frac{2\sigma\cos\Theta}{rh_i} - \rho_W g\right). \tag{14.19}$$

The theoretical estimation of the moisture conductivity factor is based on the expression

$$F_{\text{m}} = \frac{i_g}{\left(\frac{2\sigma\cos\Theta}{rh_i} - \rho_W g\right)} = k_h i_g, \tag{14.20}$$

where F_h = const at given constant values r, h_i, is determined from the angular dependence factor $F_{\mathrm{m}} = f(i_g)$,

$$F_h = \frac{dk_{\mathrm{B}}}{di_g} = \left(\frac{2\sigma\cos\Theta}{rh_i} - \rho_{\mathrm{W}}g\right)^{-1}. \qquad (14.21)$$

The use of this equation is reduced to the theoretical estimate of F_h, and the moisture transfer intensity is calculated through the maximum value of the filtration factor F_{f}

$$i_g = \rho_{\mathrm{W}}F_{\mathrm{f}} \qquad (14.22)$$

for the initial state of waterlogged peat of the disturbed structure or determined experimentally for different conditions of dehydration. The value of moisture transfer intensity in Eq. (14.22) will reflect the maximum value of moisture flow. Therefore, from Eq. (14.20) we obtain an expression for the maximum value of the moisture conductivity factor F_{m} = max. As a result, Eq. (14.20) taking into account (14.22) takes the form:

$$F_{\mathrm{m}} = \rho_{\mathrm{W}}F_{\mathrm{f}}\frac{dF_{\mathrm{m}}}{di_g}. \qquad (14.23)$$

After the reexpression, we obtain a differential equation of the form

$$\frac{dF_{\mathrm{m}}}{di_g} - \lambda_p F_{\mathrm{m}} = 0, \qquad (14.24)$$

where $\lambda_p = (\rho_{\mathrm{W}}F_{\mathrm{f}})^{-1}$, m^2 s/kg, λ_p characterises the inverse of the moisture transfer intensity.

We divide the variables and integrate (14.24):

$$\int_{k_1}^{k_2}\frac{dF_{\mathrm{m}}}{F_{\mathrm{m}}} = \lambda_p\int_{i_1}^{i_2}di_g$$

We finally get

$$F_{\mathrm{m}2} = F_{\mathrm{m}1}\exp\left[-\lambda_p(i_1 - i_2)\right], \qquad (14.25)$$

where indices 1 and 2 reflect the minimum (initial) and maximum (current) values of the parameter, respectively.

The dependence (14.25) is similar to the coupling equation of the filtration factor F_{f} with the porosity factor ε, which has the form (Afanasyev 2005) for small pressure changes in a peat deposit:

$$F_{f2} = F_{f1}\exp[-\alpha_f(\varepsilon_1 - \varepsilon_2)], \tag{14.26}$$

where F_{f1}, ε_1 are the initial and F_{f2}, ε_2 are the current values of the parameters.

Porosity factor ε is linked to the general porosity n by a ratio

$$\varepsilon = \frac{n}{n-1}. \tag{14.27}$$

Factor α_f characterises the decrease in water permeability (in our case, moisture conductivity) of peat during its compaction (reduction of the effective pore radius) and depends on the composition and structure of peat ($\alpha_f = 1$–3). As the degree of peat decomposition increases and the porosity coefficient decreases, the values of α_f increase (Kremcheev and Ivanov 2016): $\alpha_f = 0.123\exp(0.057R_t)$, $\alpha_f = (17.1/\varepsilon_2) - 0.39$.

In this case, the last equation differs in the factors $\alpha_f = (21.6/\varepsilon_2) - 1.7$, that is due to the smaller sample of data in comparison with (Kremcheev and Ivanov 2016).

As a result of generalisation of the available theoretical data and the results of experimental studies, the data characterising moisture transfer in different peat types were obtained (Table 14.2).

Therefore, factors α_f and λ_r are similar, as they are associated with the intensity of moisture transport and its changes due to varying effective radii of pores and the critical layer height that creates the pressure on the peat structure. As a rule, with the growth of the critical layer height and, consequently, pressure, the pore size decreases (Bazin et al. 1981).

Using Formula (14.22), the expression (14.27) can be written through the moisture transfer intensity i_g

$$i_2 = i_1\exp[-a(\varepsilon_1 - \varepsilon_2)], \tag{14.28}$$

where $i_1 = \rho_W F_{f1}$, $i_2 = \rho_W F_{f2}$. This approach allows estimation of the factor of moisture conductivity F_m for peat raw materials of the damaged structure of different types without considering evaporation.

Analysis of the expression (14.20) shows that for the current layer height, equal to the critical one, the filtration factor, the intensity of moisture transfer due to gravity forces and the moisture conductivity coefficient tend to zero. Then the coefficient of moisture conductivity will be associated simultaneously with the pore radius (Table 14.2) (Bazin et al. 1981; Kremcheev et al. 2014). To show the relationship between the moisture conductivity factor and the filtration properties of both native and ruptured biogenic-abiogenic peat system, we solve Eq. (14.25) with respect to $i_2 - i_1$ and equate it to Eq. (14.28). The result is

$$\left(\frac{F_{m2}}{F_{m1}}\right)^{\frac{1}{\lambda_p i_1}} = \exp[-\alpha_f(\varepsilon_1 - \varepsilon_2)], \tag{14.29}$$

and Eq. (14.25) thus takes the form

Tables 14.2 Changing the characteristics of moisture transfer of different peat types

Peat type	Decomposition degree R_t, %	Total moisture capacity		The filtration factor $F_f \cdot 10^{10}$, m/s	Moisture transfer intensity $i_g \cdot 10^6$, kg/(m^2·s)	Total porosity n	Porosity factor ε_2	Factor of moisture conductivity $F_m \cdot 10^{10}$, s	Filtration rate α_f	$1/\varepsilon_2$
		W_{tc}, kg(w)/kg(s)	ω_{tc}, %							
Low-moor										
Woody-sedge	36	9.4	90.4	2.51	0.27	0.904	9.4	0.255	0.96	0.106
Sedge-hypnum	22	11.7	92.1	3.36	0.36	0.921	11.7	0.342	0.43	0.085
Sedge	28	10.4	91.2	1.99	0.21	0.912	10.4	0.203	0.61	0.096
Hypnaceous	26	10.4	91.2	1.42	0.15	0.912	10.4	0.145	0.54	0.096
Transitional										
Woody-sedge	39	9.8	90.7	2.07	0.22	0.907	9.8	0.211	1.14	0.102
Scheuchzeria	26	10.7	91.4	1.83	0.2	0.914	10.7	0.187	0.54	0.093
Woody	44	7.6	88.4	4.18	0.45	0.884	7.6	0.426	1.51	0.131
Woody-sphagnous	35	8.9	89.9	2.05	0.22	0.899	8.9	0.209	0.904	0.112
Sedge-sphagnum	28	11.1	91.7	0.65	0.07	0.917	11.1	0.066	0.61	0.09
High-moor										
Scheuchzeria-sphagnous	23	10.3	91.2	0.46	0.05	0.912	10.3	0.047	0.456	0.097
Cottongrass-sphagnous	31	11.2	91.8	0.44	0.047	0.918	11.2	0.045	0.72	0.089
Pine-cottongrass	39	11.2	91.8	0.023	0.0025	0.918	11.2	0.002	1.14	0.089
Magellanicum	16	13.5	93.1	0.72	0.077	0.931	13.5	0.073	0.31	0.074

Notes 1. The fluid density is taken after (Afanasyev et al. 1985) for $T = 293$ K, $\rho_W = 1.075 \times 10^3$ kg/m^3

$$i_2 = i_1 \exp\left[\frac{1}{\lambda_p i_1}\left(\ln\frac{F_{\mathrm{m1}}}{F_{\mathrm{m2}}}\right)\right]. \tag{14.30}$$

Therefore, it is possible to use filtration characteristics for the estimation of hydraulic conductivity of peat through the change of the porosity factor (Eq. 14.29) and to express the intensity of moisture transport through $F_{\mathrm{m}i}$ and $\lambda_r = 1/(\rho_{\mathrm{W}} F_{\mathrm{f}})$ (Formula 14.30) based on the dependence α_{f} on the degree of peat decomposition, i.e. one of the integrating indicators that determine its physical and mechanical properties. Equations (14.29) and (14.30) can be simplified by dividing the exponential function into a series and using its first two parts. Given $\lambda_r = (\rho_{\mathrm{W}}\, F_{\mathrm{f}})^{-1}$ Formulae (14.29) and (14.30) take the form:

$$\left(\frac{F_{\mathrm{m2}}}{F_{\mathrm{m1}}}\right)^{\frac{1}{\lambda_p i_1}} \approx [1 - \alpha_{\mathrm{f}}(\varepsilon_1 - \varepsilon_2)], \tag{14.31}$$

$$i_2 \approx i_1\left[1 + \frac{1}{\lambda_p i_1}\left(\ln\frac{F_{\mathrm{m1}}}{F_{\mathrm{m2}}}\right)\right]. \tag{14.32}$$

Thus, it is possible to estimate the moisture conductivity by changing the filtration factors at the initial ($R_k \to 0$) and final ($i_g \to 0$) stages of dehydration under the condition of limited evaporation (i.e. the intensity of evaporation from the wet surface of peat or water $i_{\mathrm{and}} \to 0$).

Taking into account Formulas (14.19) and (14.22) we obtain

$$\rho_{\mathrm{W}} F_{\mathrm{f2}} = F_{\mathrm{m2}} \rho_{\mathrm{W}} g. \tag{14.33}$$

Hence, the maximum moisture conductivity factor can be recorded as:

$$F_{\mathrm{m2}} = \frac{F_{\mathrm{f2}}}{g}. \tag{14.34}$$

Taking into account Formula (14.31), it can be written that

$$F_{\mathrm{m2}} \approx F_{\mathrm{m1}}[1 - \alpha_{\mathrm{f}}(\varepsilon_1 - \varepsilon_2)]^{\lambda_p i_1}, \tag{14.35}$$

must have a minimum (Fig. 14.4) with the growth α_{f} (decomposition degree) and the decrease of the initial porosity factor. The change in F_{m2} according to the formula (14.34) is shown in Table 14.2 depending on the type and decomposition degree of peat, the current porosity factor, the total moisture capacity and the intensity of moisture transfer.

Analysis of Table 14.2 shows that the maximum value of the moisture conductivity factor for the high-moor peat is the lowest ($F_{\mathrm{m2}} = (0.002 - 0.073) \times 10^{-10}$ s) compared with the transitional ($F_{\mathrm{m2}} = (0.066 - 0.426) \times 10^{-10}$ s) and low-moor ($F_{\mathrm{m2}} = (0.145 - 0.342) \times 10^{-10}$ s) decreases with the increasing degree of peat decomposition (Fig. 14.4). Within each group of peat (except the high-moor type)

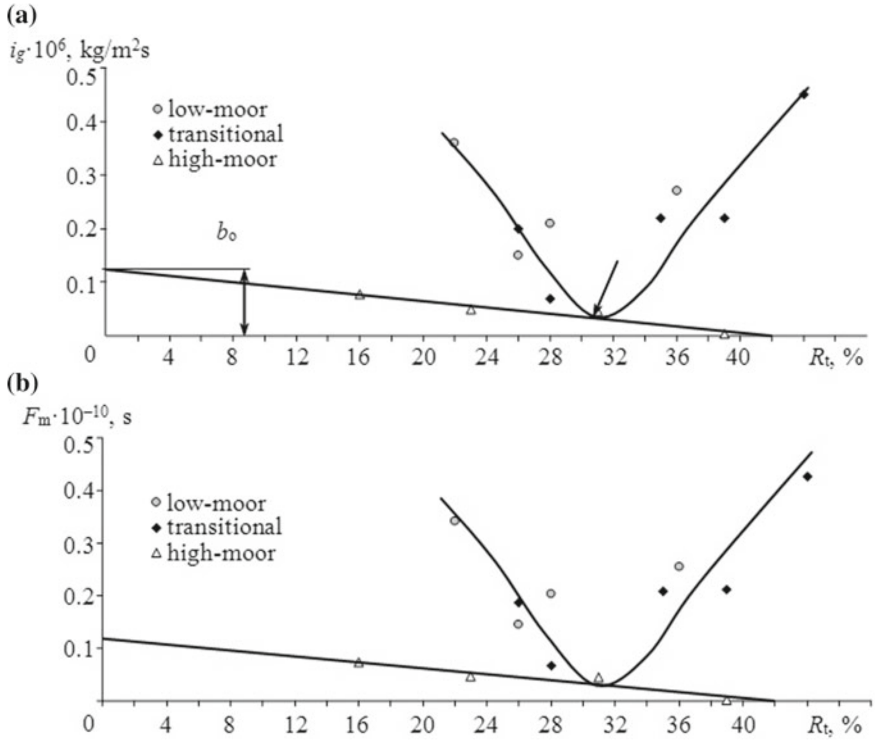

Fig. 14.4 Dependence of the maximum intensity of moisture transfer (**a**) and the moisture conductivity factor (**b**) on the degree of peat decomposition without taking into account evaporation for high-moor, low-moor and transitional peat types at $T = 293$ K

(Table 14.2, Fig. 14.4) F_{m2} increases with the degree of peat decomposition $R_t >$ (30–32)%. At lower values of decomposition degree, the value of the moisture conductivity factor decreases with the increase in the decomposition degree. In particular, for the pine-cottongrass peat, the value $\alpha_f = 1.14$ ($R_t = 39\%$), and for the magellanicum $\alpha_f = 0.31$ ($R_t = 16\%$) for the corresponding porosity factors ε_2, equal to 11.2 and 13.5 respectively, i.e. the data fit in those limits that are given Kremcheev and Ivanov (2016) for different permeability categories (high $\alpha_f < 0.35$, medium $\alpha_f = 0.35$–0.75, low $\alpha_f > 0.75$). Therefore, moisture conductivity, according to Eq. (14.29), will vary as well as filtration characteristics for one type of peat ($\alpha_f = f(R_t)$), i.e. will be minimal.

14.4 Discussion

The main factors affecting the moisture transfer are the decomposition degree, which varies by 2.43 times, the porosity factor, which varies by 1.2 times and the moisture conductivity factor, which changes by 36.5 times (Table 14.2). Thus, the high-moor peat is an exception due to the high structure heterogeneity due to the possible presence of a boundary horizon of increased decomposition, alternating with the usual structure with a reduced decomposition degree. Even with the same decomposition degree of peats of different types, values of F_{m2} differ by magnitudes of order, that is also true for filtration factors F_{f}, and intensity of moisture transfer at low changing ε_2, n, $_{\mathrm{tc}}$. This circumstance is due to the decrease in the pressure gradient dP/dx (Bazin et al. 1981) at decreasing capillary pressure due to the hydrophobisation of the solid phase, which has a high bitumen content (Afanasyev et al. 1988; Bazin et al. 1981).

The water of the high-moor peat contains various dissolved organic substances: monosaccharides, pentoses, uric and humic acids, bitumens, high and low-molecular organic and mineral substances. The latter can be in colloidal, molecular and ionic states (Lishtvan and Korol 1975). These structural features of solid and liquid phases lead to peat compaction, which is an easily deformable system. Even at a pressure of $P_g \approx 50$ kPa (Kremcheev and Ivanov 2016), peat thickness decreases, which leads to an increase in the resistance to moisture flow (expression 14.18).

Consequently, the size of capillaries (pores) decreases with the increasing decomposition degree. This circumstance contributes to the rise of capillary-osmotic and surface forces; and leads to variations in the values of F_{m2} (Fig. 14.4). By analogy with the filtration factor (Kremcheev and Ivanov 2016), they vary between 10 and 60%. For the transitional and low-moor peats the values of α_{f} are within the same limits as for the high-moor type with increased moisture conductivity factors (10–100 times) and slightly different porosity factors $\varepsilon_2 = 7.6$–11.1 for the transitional type $\varepsilon_2 = 9.4$–11.2 for the low-moor type as compared with the high-moor one $\varepsilon_2 = 10.3$–13.5. Hence, the moisture conductivity is largely responsible for the composition of the transferred moisture with little change in the characteristics of the solid phase. This fact is confirmed by the physicochemical properties of the dispersed medium of peat of the transitional and low-moor types (Kremcheev and Ivanov 2016; Lishtvan and Korol 1975).

Thus, water mineralisation level in high-moor peat deposits is 40–70 mg/dm^3, and for transitional and low-moor it increases 1.8–2.6 times and 4.2–10 times, respectively. Calcium and its water-soluble compounds are predominant in the mineral part. Calcium is amongst the key structure-forming peat components, providing changes in pore size. Calcium cations determine the biochemical process. They neutralise the acidity. Moreover, ion exchange processes occur mainly in an acidic medium under pH < 7. The pH values of marsh waters increase from the high-moor to transitional and to low-moor peat deposits, i.e. with a decrease in their acidity, which corresponds to a higher calcium content (up to 15–85 mg/dm^3) in the low-moor ones as compared to the high-moor marsh waters (up to 15 mg/dm^3) (Kremcheev and Ivanov 2016).

The features typical for the intensity of moisture transfer, reflected by the dependences $i_g = f(R_t)$ are noted in Fig. 14.4. For a high-moor deposit, it is linear

$$i_g = b_0 - \alpha_W R_t, \tag{14.36}$$

where $b_0 = 0.13 \times 10^{-6}$ kg/(m^2 s); $\alpha_W = di_g/dR_t$ is the angle dependency factor (14.36), $\alpha_W = di_g/dR_t = 0.33 \times 10^{-8}$ kg/(m^2 s %).

For the transitional and low-moor peat types, the dependence (14.36) is minimal at the peat decomposition degree of 30–32%. The minimum has the role of a generalised point at $R_t = 31\%$. We call it the average effective binding degree of decomposition R_d; on its basis it is possible to reach any peat type: $R_d = 31\%$, $i_g = 0.037 \times 10^{-6} \pm 0.008 \times 10^{-6}$ kg/(m^2 s). At the same time, for the high-moor type at $R_t \to 0$, $i_g = 0.13 \times 10^{-6\,\mathrm{kg}}$/(m^2 s) (extrapolated value), and for the transitional and low-moor type it is much larger (Fig. 14.4). With the increasing degree of decomposition for the high-moor type, the intensity of moisture transfer tends to zero due to the rheological properties of water, i.e. the increasing limiting shear stress and the density of the bound water and the decreasing pore sizes (Afanasyev and Efremov 2011). For the transitional and low-moor types, the intensity of moisture transport tends to a constant with an implicit manifestation of the border due to the increasing moisture transport resistance factor β.

14.5 Conclusion

The data obtained during the complex of theoretical and experimental studies allow drawing the following conclusions. When the filtration equilibrium is reached, when $i_g \to 0, P_k \to P_g, h_i \to H_{cr}$, the volume of remaining moisture in a pile and its critical height will be correlated with the factors of hydraulic conductivity, porosity, pore size and the height of the peat bulk, i.e. the remaining moisture mass will be maximal in the high-moor peat M_h, medium in the transitional one M_m and minimal in the low-moor peat M_l. The lowest values of the moisture conductivity factor correspond to the high-moor peat deposits; this explains the retention of higher water volumes at the filtration equilibrium with this type of peat compared to others. This feature of the change in moisture conductivity is confirmed by experimental data on the assessment of precipitation, the critical thickness of the bulk depending on the initial thickness of the peat layer of the disturbed structure and the change in the critical height in the function of the pore radius, which corresponds to the theoretical data.

This circumstance is one of the determining when choosing a set of technological methods for dewatering peat in continuous production with stable quality indicators. The results obtained in the study of interaction in the biogenic-abiogenic peat systems of different genesis, allow developing algorithms for directional changes in the quality characteristics of field peat products depending on the requirements of consumers.

The scientific results of the research and methodological approaches proposed in the work are used in the practice of the peat mining enterprises, in the educational process of the Saint Petersburg Mining University, the Tver State Technical University and the Belarusian National Technical University.

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