DEFORMATION AND FILTRATION IN CLAY MATERIALS CONSTITUTING TO THE SAFETY BARRIERS OF RADIATION HAZARDOUS FACILITIES

Martynov K. V., Zharkova V. O., Zakharova E. V.
A. N. Frumkin Institute of Physical Chemistry and Electrochemistry, Russian Academy of Sciences, Moscow, Russia

Article received on October 1, 2021

The paper focuses on the compression tests implemented to study one-dimensional deformation in dry and water-saturated state and pressure filtration in samples of dispersed materials developed as a construction material for waterproof barriers. These materials are made of kaolin, polymineral and bentonite clays and their mixtures. For the studied samples, the paper presents the plotted dependences between deformation, swelling pressure, capillary suction, permeability coefficients and the skeleton density (dry density). The study has confirmed that kaolinite containing materials tend to compaction and the montmorillonite – to swelling. The compression characteristics of a polymineral clay material and mixed materials do not always depend on the mineral composition alone. Swelling pressure manifests itself in case of bentonite and polymineral clay-based materials and is practically absent in materials made of kaolins and their mixtures with 30 wt.% bentonite. The permeability coefficients increase along with the growing ratio of kaolinite and montmorillonite contents, whereas it is the additivity that is characteristic for mixed materials.

Keywords: radioactive waste, waterproof barrier, kaolin, bentonite, effective pressure, skeleton density, odometer, deformation, swelling pressure, capillary suction, permeability coefficient.

To limit the spread of radiation contamination from radioactive waste disposal facilities (RWDF) and to isolate radiation-hazardous facilities, safety barriers made of clay materials are installed. These barriers perform three functions: provide adequate mechanical stability of the facility structure and the barrier itself, exclude the possibility of advective radionuclide transfer due to low water permeability of barrier materials and delay diffusion transfer of sorbed and non-sorbed radionuclides. In terms of the first two functions, the most important indicators are the characteristics of material deformation and pressure filtration.

These are actively studied by international researchers [1, 2]. However, with rare exceptions [3], their attention is mainly focused on compacted materials based on bentonite clays. National practice also provides for the use of dispersed mixed materials based on industrial kaolin clays with some addition of bentonites, as well as local polymineral clay raw materials [4]. In any case, the properties of dispersed materials, even those being considered similar in their mineral composition, depend on the raw material sources and the processing methods applied, including mixing, drying, grinding and segregation by particle size (categorization) [5]. Therefore, to demonstrate the safety of each facility, the knowledge on the properties of specific materials that can be used in its construction is essential.

This study is focused on the compression and filtration characteristics of some clay materials produced based on the raw materials from industrial
deposits with different mineral clay compositions used at the facilities of the State Corporation Rosatom and considered potentially suitable for the production of safety barriers.

Objects and methods of research

Samples of dispersed materials based on clays of various mineral compositions were studied: white kaolinite (KGPO-25) and black refractory kaolin clay (T-2) from the Kampanovsk deposit, polymineral clay from the Kantatsk deposit (KK), waxy bentonite from the Kamalinsk deposit (VB) (all of the deposits are located in the Krasnoyarsk Territory), bentonite from the 10th Khutor deposit (KhBGP) (Republic of Khakassia), as well as 30:70 wt. % mixtures of Khakass bentonite with kaolin clays. KGPO-23, T-2, CBGP materials are industrial products, the rest, including mixtures, was manufactured in the laboratory. The content of crystalline phases in the samples (Table 1) was measured by X-ray quantitative phase analysis (XQPA) on an X-pert Pro X-ray diffractometer (PANalytical, Netherlands).

Table 1. Mineral composition of the studied materials according to the XQPA data, wt. %

<table>
<thead>
<tr>
<th>Materials</th>
<th>Montmorillonite</th>
<th>Kaolinite</th>
<th>Illite</th>
<th>Quartz</th>
<th>Feldspar</th>
<th>Carbonates</th>
<th>Other*</th>
</tr>
</thead>
<tbody>
<tr>
<td>KGPO-23</td>
<td>5</td>
<td>48</td>
<td>2</td>
<td>27</td>
<td>10</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>T-2</td>
<td>8</td>
<td>39</td>
<td>5</td>
<td>36</td>
<td>7</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>KK</td>
<td>15</td>
<td>24</td>
<td>5</td>
<td>25</td>
<td>11</td>
<td>2</td>
<td>18</td>
</tr>
<tr>
<td>VB</td>
<td>76</td>
<td>4</td>
<td>1</td>
<td>16</td>
<td>3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>KhBGP</td>
<td>71</td>
<td>4</td>
<td>1</td>
<td>12</td>
<td>9</td>
<td>3</td>
<td>-</td>
</tr>
<tr>
<td>B30K70</td>
<td>33</td>
<td>41</td>
<td>2</td>
<td>12</td>
<td>11</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>B30T70</td>
<td>35</td>
<td>32</td>
<td>2</td>
<td>28</td>
<td>2</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>B30K7K</td>
<td>36</td>
<td>35</td>
<td>2</td>
<td>22</td>
<td>4</td>
<td>1</td>
<td>-</td>
</tr>
</tbody>
</table>

*Including amorphous matter.

Virgin compression method according to GOST 12248.4-2020 [6] and filtration tests according to GOST 25584-2016 [7] were implemented to measure deformation and pressure filtration parameters of samples under load at room temperature under one-dimensional deformation on an automated testing complex ASIS (Research and Production Enterprise Geotech, Penza) [8] included into the State Register of SI FIF OEI under No. 61952-15. The device provides axial static load of up to 50 kN, supplies liquid in the amount of up to 250 cm³ to a filtration 71.5 × 20.5 mm oedometer fitted with a linear deformation sensor, liquid pressure control in the supercharger of up to 2 MPa and measures the filtrate volume. All measuring sensors have errors specified in the passport and are subject to annual verification. The control software provides full control automation over the course of the experiments and records the results obtained.

Experimental techniques and methods used to calculate deformation and filtration characteristics were described in [8—10]. The initial samples were dispersed materials with a moisture content of 3—8 wt. % measured according to GOST 5180-2015 [11]. Directly in the oedometer of the compression-filtration device the samples were saturated with water at a minimum axial load and a water pressure in the blower being sufficient to stop the sample deformation and to reach stationary filtration. Unlike the capillary suction, this method provides 100% water saturation of the samples. The compression-filtration device allowed to study sample deformation both under increasing (compression) and decreasing (decompression) load modes, which facilitates the measurements of such an important compression characteristic as swelling pressure. Both types of compression tests provided for staged changes in the loading. In the decision-making on the transition mode to the next loading stage, the strain stabilization criterion was considered important. For the studied samples, the value of 0.01 mm within 30 minutes was established as a stopping criterion for the deformation by the experimental method.

The measured characteristic, i.e., the linear deformation of the sample, was recalculated via the dry unit weight determined taking into account the initial moisture (mass of solid particles, i.e., the mass of the sample minus pore water, or dry mass) into a change in the density of the sample’s dry unit weight (ρ, g/cm). This parameter shows the volumetric material deformation, which can more easily describe the properties of clay-based safety barriers than the linear deformation and its derivatives: the compressibility coefficient and the deformation modulus provided for in GOST 12248.4-2020. It’s considered even more challenging to describe the properties of barrier materials using these characteristics, since clay material deformation is seen as a non-linear dependence between the pressure and the matrix [12].

To provide visual representation of clay material deformation, compression curves for the studied samples can be depicted on straight or inverted graphs showing the dependence between the changing density of the matrix (ρ) and the pressure acting on the matrix (P). In the latter case, compression curves, including those describing such important characteristics as swelling pressure and capillary suction, can be represented as matrix density functions [9] (Figure 1).
Disposal of Radioactive Waste

In the absence of pore pressure, the pressure acting on the matrix corresponds to the axial pressure acting on the sample ($P_0$). In the presence of a pore pressure gradient (during filtration tests, the pressure of the liquid at the odometer’s outlet is equal to the atmospheric pressure), the pressure acting on the matrix corresponds to the effective pressure ($P_e$):

$$P_t = P_e = P_0 - P_l/2,$$

where $P_l$ is the pressure in the supercharger.

Compression curves for dry (CDM) and water-saturated (CSM) material (Figure 1a) correspond to deformation curves described by power functions (Figure 1b). Deformation and filtration in clay materials are strongly affected by the swelling of smectite minerals (montmorillonite) in the presence of water and the interaction of clay mineral surfaces with pore water causing capillary absorption. The physical basis of these phenomena is well illustrated in [2], whereas [13] presents the changes in relevant compression-deformation characteristics.

Similar to deformation curves, swelling and capillary absorption are described using swelling and capillary pressure dependences on the matrix density, which can be derived from compression curves and approximated by power functions [9] (Figure 1b). Swelling pressure ($P_s$) corresponds to the decompression curve of a water-saturated material (DSM) in the area where the volume increases, i.e., the density of the sample matrix decreases (Figure 1a):

$$P_s = P_{DSM}.$$ 

Capillary pressure (suction) ($P_c$) is equal to the compression curve displacement along the pressure axis when the sample is saturated with water taking into account the swelling pressure:

$$P_c = P_{CDM} - P_{CSM} + P_{DSM}.$$ 

This interpretation reflects the compression influence caused by different forces acting on the matrix. The load acting on the sample causes compression, i.e., positive deformation. Capillary forces act in the same direction. Swelling, on the contrary, leads to expansion, i.e., to a negative deformation of the matrix.

The technique providing the filtration tests with clay materials and the calculation of relevant characteristics is described in sufficient detail in [8, 10]. To calculate the water filtration coefficient considered as the main indicator, two or three series of experiments were implemented involving several material samples given different loads and pressures for each sample: these were selected in a way to cover the possible variation range of material matrix density in the safety barrier. The filtrate volume considered sufficient for a reliable assessment of the filtration coefficient should be equal to at least one pore volume of the sample, i.e., for a standard odometer, 10—20 cm$^3$ for materials of different matrix densities. For low-permeability materials, depending on the load and pressure levels, one experiment can last from several weeks to several months to gain the required filtrate volume. Based on the volume of liquid $V$ (cm$^3$) filtered over time $t$ (s) and the Darcy model for one-dimensional filtration, the filtration coefficient (m/s) was calculated:

$$K_f = (V/Lp_i)/(tS\Delta P),$$

where $L$ is the sample thickness (cm), $p_i$ is the density of the liquid (for water at room temperature, 1 g/cm$^3$), $S$ is the cross-sectional area of the sample (cm$^2$), $\Delta P$ is the pore pressure drop in the sample. In addition, observance of a stationary mode is seen as a must to provide the correctness of the data obtained to calculated the filtration coefficient according to the Darcy equation.
Graphical representation of the filtration coefficients was obtained based on the dependences between the material matrix densities, which were approximated by exponential functions. This representation allows to predict filtration coefficients for barriers based on the expected density of the barrier material.

In addition to actual filtration characteristics, these tests resulted in data on the deformation of water-saturated materials: these were presented as dependences between the matrix density and the effective pressure (pressure on the sample matrix). Since filtration experiments usually take much more time compared to the compression tests, whereas Table 2 shows the equations for presentation allows to predict filtration coefficients for barriers based on the expected density of the barrier material.

Results and discussion

Figure 2 presents the deformation characteristics for the studied materials according to the compression tests, whereas Table 2 shows the equations for curves approximating these characteristics. The dependences of the compression characteristics were approximated by power functions.

For all materials, water saturation causes noticeable volumetric deformation: at an equal load, matrix density increased by about 0.1 g/cm³ for bentonite materials and by 0.2 g/cm³ for kaolin materials and mixtures (Figures 2a and 2b).

Both in dry and water-saturated state under pressure kaolin materials (KGPO-23, T-2) with a predominance of kaolinite over other clay minerals, are compacted better than bentonite materials (VB, KhBGP), in which montmorillonite is seen as the main mineral. Compression curves (deformation and swelling) for materials composed of bentonite and kaolin clay mixtures (B30K70, B30T70) practically match with the curves of their kaolin component. Thus, bentonite added to the studied kaolin clays in the amount of up to 30 wt.% practically does not change their deformation characteristics, even though the montmorillonite content in mixtures is practically comparable with the kaolinite one.

At the same time, in terms of compression characteristics, Kantatska kaolin (KK), which is a polymineral clay with a ratio of montmorillonite and the sum of kaolinite and illite being equal to 1:2 differs remarkably from the kaolin materials KGPO-23 and T-2. Its compression curves are intermediate between kaolin and bentonite materials. The compression curves for a mixture of Kantatska kaolin with Khakass bentonite (B30KK70) shift even more towards bentonite materials, demonstrating the additivity of its compression characteristics. In this mixture, as in others, montmorillonite and kaolinite are present in approximately equal amounts. Thus, the compression characteristics of mixed materials depend not only on their mineral composition and cannot always be calculated as weighted average values.

In a clay barrier, swelling pressure may occur after water saturation if, under this process, either the materials were compacted to levels exceeding the bulk density or pre-compacted materials were used. Based on the comparison of deformation characteristics in the dry state (Figure 2a), one can see that different matrix densities can be obtained at the same pressure of preliminary dry compaction for bentonite and kaolin materials. At a compaction pressure of 10 MPa, they correspond to approximately 1.5 g/cm³ for VB and KhBGP bentonite materials and 1.7 g/cm³ for KGPO-23 and T-2 kaolin materials and their mixtures with bentonite. Under water saturation, for bentonite materials such a

<table>
<thead>
<tr>
<th>Material</th>
<th>( P_{\text{cmv}, \text{MPa}} )</th>
<th>( P_{\text{cmw}, \text{MPa}} )</th>
<th>( P_{\text{cmr}, \text{MPa}} )</th>
<th>( P_{\text{cmr}, \text{MPa}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>KGPO-23</td>
<td>1.05 \times 10^{-1} \rho_t^{1.79}</td>
<td>1.53 \times 10^{-1} \rho_t^{1.51}</td>
<td>1.08 \times 10^{-1} \rho_t^{1.74}</td>
<td>1.08 \times 10^{-1} \rho_t^{1.27}</td>
</tr>
<tr>
<td>T-2</td>
<td>2.93 \times 10^{-1} \rho_t^{1.57}</td>
<td>2.97 \times 10^{-1} \rho_t^{1.90}</td>
<td>3.84 \times 10^{-1} \rho_t^{1.15}</td>
<td>2.94 \times 10^{-1} \rho_t^{1.16}</td>
</tr>
<tr>
<td>KK</td>
<td>1.01 \times 10^{-1} \rho_t^{1.88}</td>
<td>9.36 \times 10^{-4} \rho_t^{1.60}</td>
<td>1.3 \times 10^{-5} \rho_t^{1.75}</td>
<td>9.33 \times 10^{-3} \rho_t^{1.15}</td>
</tr>
<tr>
<td>VB</td>
<td>2.03 \times 10^{-1} \rho_t^{1.56}</td>
<td>5.81 \times 10^{-3} \rho_t^{1.64}</td>
<td>7.39 \times 10^{-9} \rho_t^{1.59}</td>
<td>1.39 \times 10^{-2} \rho_t^{1.14}</td>
</tr>
<tr>
<td>KhBGP</td>
<td>7.26 \times 10^{-1} \rho_t^{1.57}</td>
<td>2.59 \times 10^{-6} \rho_t^{1.36}</td>
<td>2.12 \times 10^{-2} \rho_t^{1.23}</td>
<td>6.29 \times 10^{-4} \rho_t^{1.50}</td>
</tr>
<tr>
<td>B30K70</td>
<td>3.85 \times 10^{-1} \rho_t^{1.49}</td>
<td>2.17 \times 10^{-4} \rho_t^{1.68}</td>
<td>6.56 \times 10^{-10} \rho_t^{1.52}</td>
<td>3.68 \times 10^{-1} \rho_t^{1.47}</td>
</tr>
<tr>
<td>B30T70</td>
<td>3.34 \times 10^{-1} \rho_t^{1.49}</td>
<td>6.14 \times 10^{-4} \rho_t^{1.46}</td>
<td>6.41 \times 10^{-10} \rho_t^{1.43}</td>
<td>2.72 \times 10^{-1} \rho_t^{1.50}</td>
</tr>
<tr>
<td>B30KK70</td>
<td>3.46 \times 10^{-1} \rho_t^{1.61}</td>
<td>4.65 \times 10^{-3} \rho_t^{1.51}</td>
<td>2.5 \times 10^{-4} \rho_t^{1.80}</td>
<td>2.76 \times 10^{-1} \rho_t^{1.12}</td>
</tr>
</tbody>
</table>
Disposal of Radioactive Waste

Figure 2. Dependences between the deformation pressure of clay materials in dry (a) and water-saturated (b) states, swelling pressure (c) and capillary suction pressure (d) on the matrix density according to the compression tests: symbols stand for the experimental data, curves – for approximations by functions from Table 2

Matrix density corresponds to a swelling pressure of 0.5—1.5 MPa and for kaolin and materials mixed with kaolin it is below 0.1 MPa (Figure 2c). Under same conditions, the material made of Kantatsk polymineral clay (KK) will have a slightly lower swelling pressure than the one of bentonite materials ~0.4 MPa, and in case of its mixture with bentonite (B30KK70) it will amount to 0.8 MPa at a matrix density of 1.55 g/cm³.

At an equal matrix density, capillary pressure (suction) is higher for bentonite materials than the one for kaolin materials and mixtures (Figure 2d). However, taking into account the differences in the material deformation under equal loads resulting in different matrix densities, the ratio of capillary pressure in materials of different compositions can be different: equal or even higher for kaolin materials. It is important that for all types of materials the capillary pressure exceeds the deformation pressure at the same matrix density levels. Therefore, gas filtration through water-saturated clay materials is impossible: under no circumstances, gas can squeeze out the pore water. Since in this case the capillary pressure level should be exceeded, which is excluded as the material deformation always occurs when the pressure acting on a water-saturated material is lower than the capillary pressure.

Figure 3 presents the filtration coefficients and dependences of the matrix density on the effective pressure for the studied materials based on the filtration tests, whereas, Table 3 shows the equations for the curves approximating these data. The dependences of the filtration coefficients are approximated by exponential functions, the deformation curves are approximated by the power ones. Experimental points obtained from the filtration experiments are more scattered compared to those obtained from the compression experiments since in the latter case the data were obtained from a series of tests involving only one sample, and in the former case - from several series involving different
Deformation and Filtration In Clay Materials
Constituting to the Safety Barriers of Radiation Hazardous Facilities

samples. Thus, both sample inhomogeneity and experimental reproducibility affect the results.

Filtration coefficients for all studied materials show dependence on the mineral composition, and for mixtures — additivity with respect to the clays being mixed. The greater is the ratio of montmorillonite and kaolinite contents in the material, the lower are the filtration coefficients. For bentonite materials with a matrix density of 1.3 g/cm³, which is attainable in case of minimum compaction when the barrier is backfilled at the post-saturation phase, \( K_f \) is below 5·10⁻¹² m/s, for mixtures involving B30KK70, B30T70 and material from Kantatsk clay KK, at a matrix density of 1.7 g/cm³, Kf does not exceed 10⁻¹¹ m/s, and for a mixture of B30KK70 and kaolin materials with similar matrix density levels, \( K_f \) falls within the range of (2—6)·10⁻¹¹ m/s (Figure 3a).

All these values fit within the limits specified in the requirements on barrier materials established for the FSUE NO RAO’s disposal facility in Novouralsk intended for RW Class 3 and 4 (10⁻¹² m/s) and isolation facilities for decommissioned production uranium-graphite reactors (PUGR) at FSUE MCC site in Zheleznogorsk (5·10⁻¹¹ m/s) [14]. With regard to deep disposal facilities designed for RW Class 1 and 2 to be sited at a depth of 500 m in a mountain range near the Zheleznogorsk city, the requirements for barrier materials have not been specified yet. According to experimental data, pore permeability of gneisses and amphibolites similar to the host rocks of the above facility is at least 10⁻¹⁸ m² [15]. Under deep disposal conditions, this corresponds to a filtration coefficient for water of 10⁻¹¹ m/s. Obviously, it makes no sense to install any barriers for which this indicator would be lower than the one of the host rocks themselves, especially since groundwater in the massif circulates not through the pore space of the rocks, but through open cracks and the filtration coefficient tends to be in the range of 10⁻⁴—10⁻² m/day [16], i.e., at least 10⁻⁹ m/s. A safety margin of two decimal orders seems quite sufficient to provide the safety of the facility. Thus, in terms of \( K_f \), given adequate compaction both bentonite and B30KK70, B30T70 mixed materials and even the material from the Kantatsk polyminal clay KK appear to be suitable for the construction of safety barriers at deep disposal facilities designed for RW Class 1 and 2 disposal.

Based on the filtration tests, the deformation curves (Figure 3b) for different materials correspond to the data obtained by direct compression method (Figure 2b). According to the nature of deformation, the studied materials can be divided into three groups: the densest are kaolin materials

Table 3. Dependences between the filtration coefficients and the matrix densities \((r, g/cm³)\); the matrix densities and the effective pressures \((P, MPa)\) for the studied materials according to the filtration tests

<table>
<thead>
<tr>
<th>Material</th>
<th>(K_f, \text{m/s} )</th>
<th>(r, \text{g/cm}³ )</th>
<th>(P, \text{MPa} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>KGPO-23</td>
<td>2.34·10⁻¹⁵</td>
<td>1.81·10⁻⁹</td>
<td>0.09</td>
</tr>
<tr>
<td>T-2</td>
<td>1.71·10⁻⁴</td>
<td>1.79·10⁻⁷</td>
<td>0.10</td>
</tr>
<tr>
<td>KK</td>
<td>2.25·10⁻⁴</td>
<td>1.49·10⁻⁸</td>
<td>0.21</td>
</tr>
<tr>
<td>VB</td>
<td>7.38·10⁻⁴</td>
<td>1.31·10⁻⁸</td>
<td>0.09</td>
</tr>
<tr>
<td>KhBGP</td>
<td>6.08·10⁻⁴</td>
<td>1.28·10⁻⁸</td>
<td>0.15</td>
</tr>
<tr>
<td>B30K70</td>
<td>5.6·10⁻⁵</td>
<td>1.79·10⁻⁸</td>
<td>0.10</td>
</tr>
<tr>
<td>B30T70</td>
<td>9.21·10⁻⁵</td>
<td>1.68·10⁻⁸</td>
<td>0.11</td>
</tr>
<tr>
<td>B30KK70</td>
<td>1.3·10⁻⁴</td>
<td>1.48·10⁻⁸</td>
<td>0.26</td>
</tr>
</tbody>
</table>

Figure 3. Dependences of filtration coefficients on the matrix densities (a) and the matrix densities on the effective pressures (b) for clay materials in a water-saturated state according to the filtration tests: symbols — experimental data, curves — approximation by functions from Table 3.

Radioactive Waste № 4 (17), 2021

61
and mixtures with these materials; the least dense are bentonite materials; materials from polymineral clay and its mixture with bentonite are characterized by intermediate matrix density. However, according to the filtration tests, all deformation curves are shifted towards higher matrix densities, i.e., towards increasing deformation, and have a less steep slope relative to the density axis. The latter effect is especially pronounced for materials from polymineral clay KK: at low loads, their matrix density is similar to the one of bentonite materials, and at a high pressure acting on the matrix, their deformation level approaches the one considered characteristic for kaolin materials.

Compression curve shifting and flattening under filtration tests was associated with a significantly longer duration of these experiments compared to the compression tests, i.e., with increased relaxation time after the load has been applied. As a result, the system tends to be closer to the equilibrium state. This effect, caused by insufficient stress relaxation time during compression tests, manifests itself when other compression characteristics are identified: swelling pressure from the decompression curve and capillary pressure from the difference between deformation and swelling. The higher the load is, the longer relaxation time is required. Therefore, the stopping criterion for the deformation, which was mentioned in the description of the test procedure, is essential for correct results especially in case of water-saturated samples. However, it should be understood that we can only talk about minimized systematic error during compression tests. Under real experimental conditions, it seems infeasible if the time spent on each loading step is comparable to the filtration test duration. For dry samples, the described effect is most likely insignificant, since relaxation is achieved fairly quickly.

In conclusion, it should be noted that compression and filtration characteristics approximated by power and exponential equations from Tables 2 and 3 have no physical meaning, but facilitate the calculations associated with these characteristics given the experimentally studied values, that is, their interpolation. Extrapolation of characteristics beyond these limits is possible for a very limited range of variation in the values both as regards arguments and functions. Attempts at long-range extrapolation may turn out to be completely incorrect.

Conclusions

Skeleton densities for bentonite and kaolin materials differ both in the dry state and even more so in the water-saturated state. The maximum compression shock occurs at water saturation due to water interaction with the clay mineral surfaces. Compression characteristics of bentonite and kaolin material (B30K70, B30T70) mixtures do not show additivity, but shift towards a denser kaolin component. However, additivity of compression properties is manifested in case of mixed material B30KK70 from Khakass bentonite and Kantatsk polymineral clay, the mineral composition of which appears to be similar to the one of bentonite-kaolin materials. This evidences that the compression properties depend not only on the ratio of kaolinite, montmorillonite and detrital minerals in the material, but also on the structural features (shape, size, etc.) of the clay and non-clay minerals that make up the material, i.e., on the genesis (origin) of clay mineral raw materials and the method used to fabricate the barrier material.

Swelling pressure appears to be quite high in case of bentonite materials, materials from Kantatsk polymineral clay and its mixture with Khakass bentonite. For Kampanovsk kaolin materials and their mixtures with 30 wt% Khakass bentonites, the swelling pressure does not manifest itself at actually achievable matrix densities. For the studied clay materials, the capillary pressure exceeds the deformation pressure at equal matrix density levels. Therefore, gas filtration through water-saturated clay materials is impossible.

Given minimum compaction at the backfilling stage, for all studied materials, filtration coefficients satisfy the requirements established for near-surface disposal facilities designed for RW Class 3 and 4 and isolation facilities for PUGR (no more than $5\times10^{-11}$ m/s); for materials made of bentonite, polymineral clays and mixtures of Khakass bentonite with B30KK70 and B30T70 kaolins, these coefficients do not exceed $10^{-11}$ m/s, which should be sufficient for deep disposal facilities intended for RW Class 1 and 2 disposal.

According to the filtration experiments, the deformation curves for clay materials are closer to the equilibrium state than those resulted from the compression tests of water-saturated materials. The difference increases along with an increasing load acting on the sample matrix. To minimize the systematic error of the applied compression method, it is important to choose correct strain stabilization criterion, especially in case of water-saturated materials.

Acknowledgements

The study was performed with the financial support provided by the Ministry of Science and Higher Education of the Russian Federation.
References


Disposal of Radioactive Waste


Information about the authors

Martynov Konstantin Valentinovich, Ph.D., leading researcher, A. N. Frumkin Institute of Physical Chemistry and Electrochemistry, Russian Academy of Sciences (31, Leninsky prosp., Moscow, 119071, Russia), e-mail: mark0s@mail.ru.

Zharkova Victoria Olegovna, researcher, A. N. Frumkin Institute of Physical Chemistry and Electrochemistry, Russian Academy of Sciences (31, Leninsky prosp., Moscow, 119071, Russia), e-mail: v.zarkova11@gmail.com.

Zakharova Elena Vasilievna, Ph.D., head of laboratory, A. N. Frumkin Institute of Physical Chemistry and Electrochemistry, Russian Academy of Sciences (31, Leninsky prosp., Moscow, 119071, Russia), e-mail: zakharova@ipc.rssi.ru.

Bibliographic description