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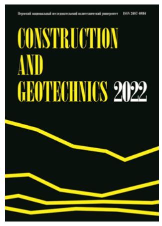

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WATER PERMEABILITY OF SAND AND FINE CLAY SUSPENSION MIXTURES – WASTE PRODUCT OF DIAMOND ORE CONCENTRATION

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ABSTRACT

For the insulation of underground structures, the creation of protective screens in hydraulic structures and on waste storage tanks sand-bentonite mixtures are successfully used. Unlike natural clay soils they are characterized by homogeneity of composition, workability, high deformation and strength characteristics, lack of shrinkage, etc. As a rule, mixtures are prepared from dry ingredients.

The purpose of this present research was to study the possibility of preparing and determining the properties of mixtures of sands with a saponite-containing suspension – a waste product of concentration of the diamond-bearing ore from the settling pond of the tailings of one of the enterprises in Arkhangelsk region. Saponite is a clay mineral belonging to the same group as montmorillonite, which predominates in the composition of bentonite.

For the preparation of mixtures four types of sands of different composition and genesis were used. The studied mixtures in terms of water permeability turned out to be almost identical to sand-bentonite mixtures, for example, the introduction of 16 % saponite-containing waste ensured a decrease in the filtration coefficient of sands to (1.2…15.3) · 10^{-5}, and 24 % – to (0.4…2.0) · 10^{-5} m/day.

There were obtained experimental dependencies of the filtration coefficient k from effective or free porosity n_e and degree of pore blocking in the sand matrix δ. The first value is found by excluding from the pore volume the volume of water sorbed by highly dispersed clay and dusty-clayey particles contained in the sand, and the second value is found as the ratio of the volume of clay, dusty particles and moisture sorbed by them to the volume of pores between sand particles.

The use of the studied mixtures, for example, for the installation of screens on industrial and domestic waste storage tanks, will significantly reduce costs due to the use of industrial waste and sands from local quarries, as well as the absence of the need for preliminary drying of materials.

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ВОДОПРОНИЦАЕМОСТЬ СМЕСЕЙ ПЕСКА С СУСПЕНЗИЕЙ ВЫСОКОДИСПЕРСНОЙ ГЛИНЫ – ОТХОДОМ ОБОГАЩЕНИЯ АЛМАЗОНОСНОЙ РУДЫ

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АННОТАЦИЯ

Для изоляции подземных сооружений, создания защитных экранов в гидротехнических сооружениях и на накопителях отходов с успехом применяются песчано-бентонитовые смеси, которым в отличие от природных глинистых грунтов присущи однородность состава, удобоукладываемость, высокие деформационно-прочностные характеристики, отсутствие усадки и др. Смеси готовят, как правило, из сухих ингредиентов.

Целью настоящих исследований было изучение возможности приготовления и определение свойств смесей песков с сапонитсодержащей суспензией – отходом обогащения алмазоносной руды из пруда – отстойника хвостохранилища одного из предприятий Архангельской области. Сапонит – глинистый минерал, относящийся к той же группе, что и монтмориллонит, преобладающий в составе бентонита.

Для приготовления смесей были использованы четыре типа песков различного состава и генезиса. Исследованные смеси по водопроницаемости оказались практически идентичными песчано-бентонитовым смесям, так, например, внесение 16 % сапонитсодержащих отходов обеспечило снижение коэффициента фильтрации песков до (1,2…15,3) $\cdot 10^{-5}$, а 24 % – до (0,4…2,0) $\cdot 10^{-5}$ м/сут.

Получены экспериментальные зависимости коэффициента фильтрации k от эффективной или свободной пористости n_e и степени блокировки пор в песчаной матрице δ. Первую величину находят, исключив из объёма пор объём воды, сорбированной высокодисперсной глиной и содержащимися в песке пылевато-глинистыми частицами, а вторую – как отношение объёма глинистых, пылеватых частиц и сорбированной ими влаги к объёму пор между частицами песка.

Применение исследованных смесей, например, для устройства экранов на накопителях промышленных и бытовых отходов позволит существенно сократить затраты за счет использования промышленных отходов и песков из местных карьеров, а также отсутствия необходимости предварительной сушки материалов.

Introduction

Colmatation of permeable soils with particles of highly dispersed clays, which recently are often called nanoglines, has long been used to reduce water losses from channels and reservoirs [1]. The depth and degree of colmatation, in addition to soil porosity, are determined by many factors – the granulometric and mineralogical composition of soil and clay, pressure gradient, the presence of certain salts in water, etc. To achieve the desired effect careful selection of the colmatation mode is required, which eliminates the accumulation of clay particles on the surface and their removal from the pores by water flow [1–6].

Heterogeneity of the natural clays composition causes the problem of their use [7, 8]. Therefore, since 1980s sands with the addition of highly dispersed clay introduced by mixing have been used for isolation of underground structures, creation of protective screens in hydraulic structures and on waste storages. The most widespread are sand-bentonite mixtures (SBM) [9–11]. In addition to the homogeneity of the composition these mixtures are characterized by workability, high deformation and strength characteristics, lack of shrinkage, etc. [12–15]. In waste handling a very useful property of SBM is the ability to sorb a certain amount of pollutants contained in the filtered water [16, 17].

The most common are SBM with bentonite content of 5 to 20 %, rarely – up to 30 % [13, 18]. The optimal moisture content of mixtures of this composition usually varies in a narrow range of 12–16 % [13, 14]. The experiments by R.P. Chapuis have shown that if the mixture contains less than 5 % of bentonite, its particles can be removed by the flow of filtered water, although according to C.R. Ryan such a threshold value is the content of bentonite equal to 15–20 % [9, 11].

Analysis of experimental data from various authors who conducted research on SBM showed variations in the filtration coefficient over a very wide range, which is caused by the differences in the properties of starting materials, methods of sample preparation, etc. [9, 13, 16, 19, 20, 22–26]. However, calculation using average values of filter coefficients *k* allowed us to obtain a trend line (Fig. 1).

A detailed review of the research on the properties and special aspects of SBM use is given in our previous publication [4].

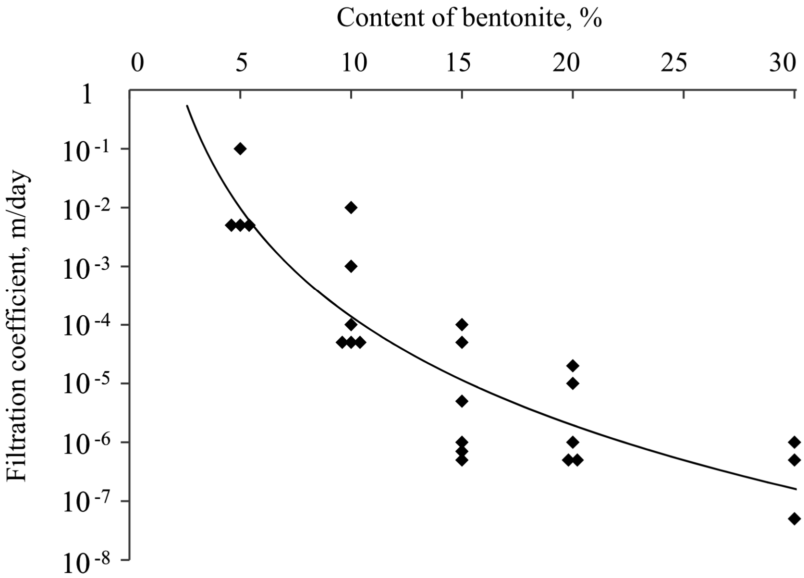

Fig. 1. Water permeability of sand-bentonite mixtures
Рис. 1. Водопроницаемость песчано-бентонитовых смесей

Mixtures are usually made from dry ingredients – sand and crushed bentonite. Even small water content in the sand causes the formation of lumps of clay and an increase in water permeability due to the heterogeneity of the mixture [16, 20, 27]. In our country, for example, the production of dry mixtures intended for the installation of anti-filtration and waterproofing structural elements has been established [27].

At the same time, waste from the enrichment of diamond-bearing ore from one of the enterprises in the Arkhangelsk region, containing saponite, a clay mineral of the subclass of layered silicates belonging to the same group as montmorillonite, which predominates in the composition of bentonite clays, is not used. The content of saponite in the solid phase of the suspension from the pond zone of the tailings can reach 87 % [28]. A distinctive feature of the suspension is the extremely slow sedimentation of clay particles, which complicates the normal functioning of the circulating water supply system. The concentration of the solid phase in the water increases with depth and varies depending on the time of year usually from 0.5 g/l near the surface up to 350 g/l in the bottom layers, where the content of rapidly settling sand particles can reach 30–40 %.

The purpose of the present research was to study the possibility of preparation and determine the properties of sand mixtures with a saponite-containing suspension. The absence of necessity for pre-drying of materials and the use of sands from local quarries would significantly reduce the cost of screens installation, for example, on industrial and domestic waste storage tanks.

Several publications of foreign authors contain information about experiments with mixtures of sand and bentonite suspension of various concentrations. In particular, S. Yeo et al. used a suspension of 2–5 %, and D. Castelbaum and C.D. Shackelford 5–7 % [21, 29]. S.Q. Shen and M.L. Wei worked with a suspension containing 8 % of bentonite; in the process of its preparation clay and water were not only thoroughly mixed, but also kept for at least a day to swell the particles [22]. It should be noted that due to the use of a low-concentration suspension SBM is formed with moisture content significantly higher than optimal for compaction. In experiments aimed at the increase of sand strength characteristics, where the possibility of compaction of the resulting composition was crucial, M.B. Baker and his co-authors used a suspension of bentonite with a concentration of 38 % [30].

Materials and Methods

Four types of sands of different composition and genesis from quarries located in the Arkhangelsk region were used for the preparation of mixtures. The total weight of the tested samples of all sands was 35–40 kg. Results of the analysis of their particle size distribution, including the degree of heterogeneity $c_u = d_{60}/d_{10}$, as well as the particle density values ρ_s, are given in Table 1.

Table 1

Granulometric composition of studied sands

Таблица 1

Гранулометрический состав исследованных песков

Sands	Fraction content, %, with size of the particles, mm					d_{60}, mm	d_{10}, mm	c_u	ρ_s, g/cm^3
	more than 0.50	0.50–0.25	0.25–0.10	0.10–0.05	less than 0.05				
1. Fine (*a*)	0.20	31.70	61.36	5.44	1.30	0.23	0.11	2.2	2.65
2. Fine (*am*)	0.49	13.68	64.59	12.10	9.14	0.19	0.05	3.5	2.66
3. Medium size (*f*)	18.82	33.36	34.04	5.85	7.93	0.34	0.07	5.0	2.66
4. Fine (*lg*)	0.07	0.32	82.57	12.32	4.72	0.18	0.07	2.5	2.65

The content of chemical elements in the sands obtained by analyzing the characteristic spectrum of fluorescence radiation of the sample excited by X-rays and registered by a semiconductor silicon pin detector included in the MetExpert small-size X-ray apparatus is presented in Table 2.

A saponite-containing suspension with a total volume of about 600 liters was taken from floating vessels in the pond area of the tailings dump of a mining processing plant from a depth where the content of dust and sand particles was minimal. The concentration of solid phase in the samples was 7.9–10.3 %, the content of particles smaller than 0.001 mm varied within 91.5–94.2 %, particles from 0.001 to 0.002 mm – 0.5–2.5 %. Mineralogical composition was studied by comparing the intensity of characteristic spectral lines under the action of high-energy radiation of X-ray tube with a certain wavelength with previously obtained calibration data on the workstation ARL9900. Tests showed that saponite (62.8 %) prevails in the solid phase of the suspension, quartz (7.6 %), montmorillonite (7.3 %), palygorskite (6.8 %) and other minerals are also present. The maximum hygroscopic humidity of the solid phase is 26 %, the swelling humidity is 89 %.

Table 2

Elemental Composition of Sands

Таблица 2

Элементный состав песков

Sands	Composition of elements, %					
	Si	K	Ca	Fe	Al	Others
1. Fine (*a*)	77.59	9.03	4.04	8.34	–	1.00
2. Fine (*am*)	75.07	9.60	7.01	6.93	–	1.39
3. Medium size (*f*)	54.79	9.61	9.08	16.67	6.65	3.20
4. Fine (*lg*)	65.35	8.66	7.96	14.22	–	3.81

As noted above, the problem in preparing mixtures using a suspension is an excess of moisture, namely the moisture content substantially exceeding the optimum and preventing compaction of the samples. Increase in solids concentration as a result of particle sedimentation proved unacceptable due to the duration of the process. Drying the suspension or its mixture with sand was not considered as an acceptable way to achieve optimal humidity, since heating, which is usually uneven, leads to an irreversible change in the structural bonds between clay particles, and its use in industrial conditions requires significant energy consumption. In their experiments the authors used centrifugation as the main way to increase the concentration of suspension, especially since the mining and processing plant is currently conducting pilot tests of decanter centrifuges for clarifying recycled water.

Experimentally it was found that centrifugation for 30 minutes at a speed of 2000 rpm did not give a significant effect. In the same centrifugation mode, but with the addition of a coagulant $FeCl_3$ In the amount of 2 % of the weight of the suspension, the concentration increased by 3.8–4.6 times – up to 350–420 g/l, and the clarified water was about 2/3 of the initial volume. Repeated centrifugation for 30 minutes made it possible to bring the concentration of the solid phase to 550–610 g/l, while the clarified water occupied about 1/3 of the volume of sediment obtained at the first stage of thickening. Experiments have shown that by selecting the centrifugation mode it is possible to obtain a suspension of the required concentration.

Mixtures of four types of sands with sгызутышщт were prepared based on the content of the solid phase of suspension amounted to 4, 8, 16 and 24 % of the mass of the sand solid phase. The concentration of suspension was selected in such a way that the moisture content of the mixture was close to the optimum for compaction. To obtain a homogeneous mixture manual stirring for 20 minutes was sufficient.

The maximum density and optimal humidity of sands and mixtures were determined according to the standard method regulated by GOST 22733-2016, using a semi-automatic device of the standard compaction manufactured by “Geotech” SPP.

Water permeability studies were performed in three-axis compression chambers manufactured by GeoComp on the samples with a diameter of 73 mm and a height of 145 mm. Preliminary compaction of samples up to compaction factor of 0.95–0.98 was performed layer-by-layer in a forming ring.

For samples of sand and mixtures with a highly dispersed clay content of up to 16 % inclusive the pressure in the instrument chambers and the vertical load on the samples were set to 100 kPa. For mixtures of 24 %, due to higher head gradients, the compression pressure was increased to 200 kPa to eliminate filtration along the walls of the samples in contact with the latex shells. Distilled water was used in the experiments. A pump with a microstepper motor was used to supply it. It maintained a pressure from 5 to 180 kPa depending on the filtration rate. It should be noted that the pressure values were set in multiples of 5 kPa, for example, 5, 15 and 25 kPa, so the head gradient at the height of the samples of 145 mm took on somewhat unusual values for such experiments – 3.4; 10,3; 17.2, etc. The devices used made it possible to measure the volume of filtered water even with a slightly excessive accuracy of 0.001 cm^3. Water flow rates at each gradient were determined with at least a double repeat.

Results

Table 3 gives the values of maximum density ρ_d^{max} and optimal humidity W_{opt} of sands and their mixtures with highly disperded clay from saponite-containing waste. As we can see, with the increase of the introduced clay particles mass the maximum density of the mixtures increased by 0,11–0,20 g/cm^3, while the optimal humidity changed slightly and remained in a very narrow range – from 12 to 16 %. Note that the maximum density increased linearly with the increase in the coefficient of heterogeneity c_u of the studied snds and mixtures.

Table 3

Results of experiments on mixtures compaction

Таблица 3

Результаты опытов по уплотнению смесей

Sands	ρ_d^{max}, g/cm^3, with clay content, %					W_{opt}, %
	0	4	8	16	24	
1. Fine (*a*)	1.63	1.69	1.73	1.80	1.81	15–16
2. Fine (*am*)	1.72	1.77	1.81	1.86	1.87	14–15
3. Medium-sized (*f*)	1.84	1.89	1.91	1.95	1.95	12–14
4. Fine (*lg*)	1.63	1.69	1.75	1.82	1.83	15–16

Graphs of filtration rate versus head gradient are given in Fig. 2, and filtration coefficient values are given in Table 4. Note that due to the low water permeability of mixtures with a clay content of 24 %, samples for increasing water consumption were tested only at high head gradients. For to the lack of correlation between the initial head gradient and the composition of the mixtures, as well as to exclude the two-factor experiment, the initial gradient was assumed to be zero. Experiments have shown that the addition of 4 % of highly dispersed clay had practically no effect on the water permeability of the sands. The application of 8 % clay led to a decrease in the filtration coefficient by 100–467 times, with the exception of fine lake-glacial sand (*lg*), for which the effect appeared to be not so significant. The application of 16 % and 24 % clay reduced the filtration coefficient by four and five orders of magnitude, respectively. Thus, the use of diamond mining waste instead of bentonite makes it possible to obtain mixtures with approximately the same water permeability characteristics.

Discussion

Analyzing the results of SBM tests for water permeability many authors used a model in Fig. 3 which the solid phase is represented by two components – sand and bentonite (diagram *b*) instead of the generally accepted two-phase soil model (diagram *a* in Fig. 3). The simplest approach based on this model is to obtain a dependence of the filtration coefficient *k* on the content in the bentonite mixture. Fig. 1 shows such a dependence for SBM according to the literature data. Due to the variety of sand grain size distribution, differences in bentonite properties, methods of mixing and compaction of samples the correlation was very weak.

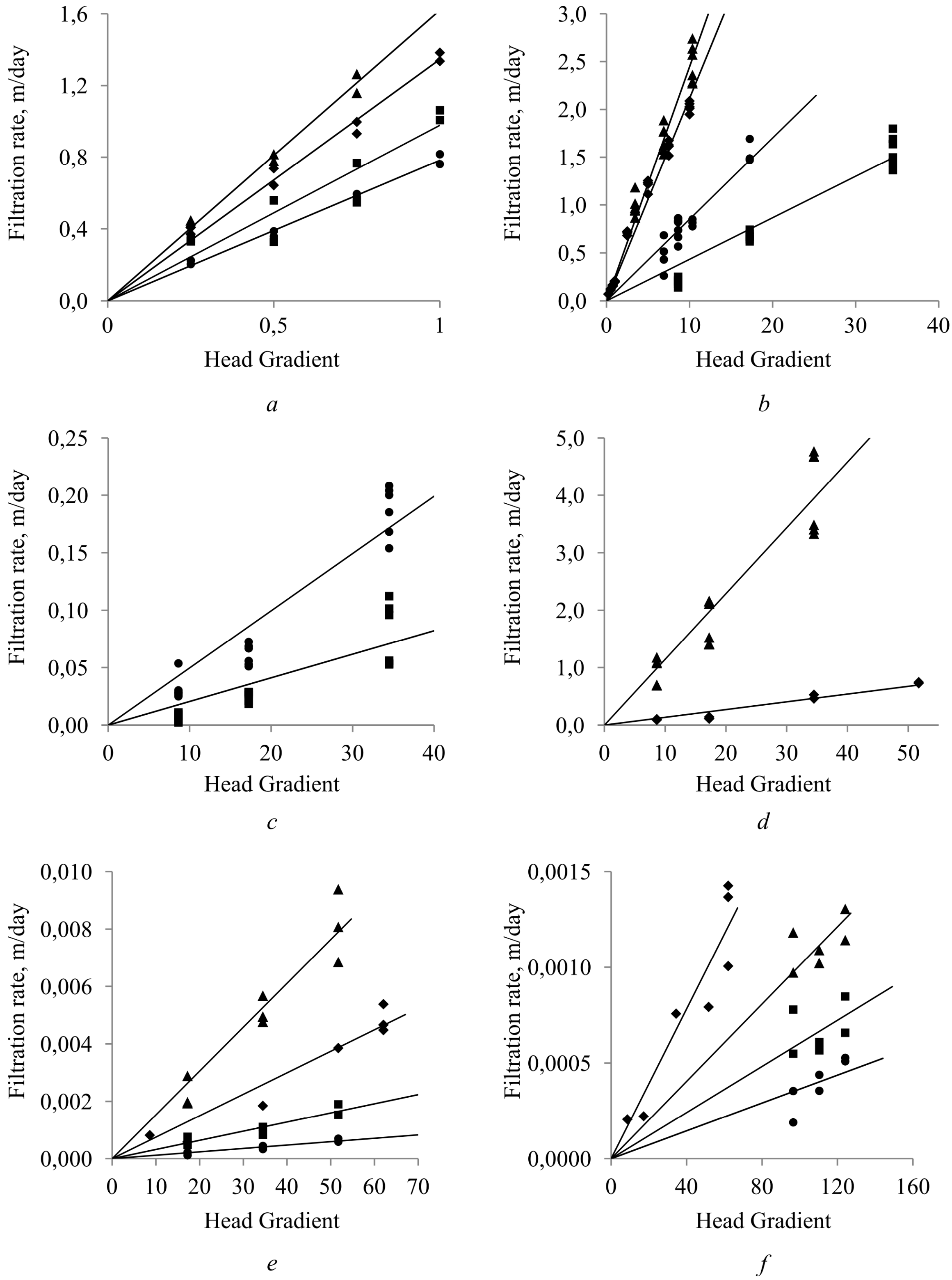

Fig. 2. Dependencies $v = f(I)$ for the mixtures of various composition.
The content of highly-dispersed clay, %: *a* – 0; *b* – 4; *c*, *d* – 8; *e* – 16, *f* – 24.

Numbers of sands according to the Table 1: ♦ – 1; ● – 2; ■ – 3; ▲ – 4

Рис. 2. Зависимости $v = f(I)$ для смесей различного состава.
Содержание высокодисперсной глины, %: *a* – 0; *b* – 4; *c*, *d* – 8; *e* – 16, *f* – 24.

Номера песков по табл. 1: ♦ – 1; ● – 2; ■ – 3; ▲ – 4

Table 4

Coefficients of Mixtures Filtration

Таблица 4

Коэффициент фильтрации смесей

Sands	k, m/day, with the clay content in the mixture, %				
	0	4	8	16	24
1. Fine (*a*)	1.35	0.21	$13.5 \cdot 10^{-3}$	$7.5 \cdot 10^{-5}$	$2.0 \cdot 10^{-5}$
2. Fine (*am*)	0.78	0.09	$5.0 \cdot 10^{-3}$	$1.2 \cdot 10^{-5}$	$0.4 \cdot 10^{-5}$
3. Medium-sized (*f*)	0.98	0.04	$2.1 \cdot 10^{-3}$	$3.2 \cdot 10^{-5}$	$0.6 \cdot 10^{-5}$
4. Fine (*lg*)	1.62	0.24	$115 \cdot 10^{-3}$	$15.3 \cdot 10^{-5}$	$1.0 \cdot 10^{-5}$

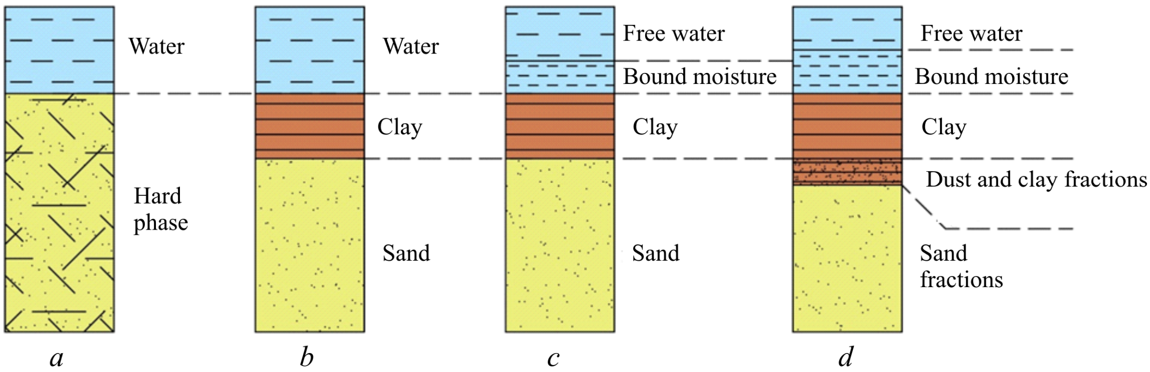

Fig. 3. Design schemes of sand mixtures with highly dispersed clay
Рис. 3. Расчетные схемы смесей песка с высокодисперсной глиной

In our experiments with mixtures of sands with saponite-containing waste, in which the preparation of mixtures and compaction of samples were carried out according to the same method, a closer correlation relationship was obtained (Fig. 4):

$$k = 477\, C^{-5{,}6}, \text{ with } R^2 = 0.57, \quad (1)$$

where C – the content of highly dispersed clay in the mixture, i.e. the ratio of the mass of clay to the mass of sand $m_{гл}/m_{п}$, expressed as a percentage.

T. Sakita et al., using the same model in the analysis of water permeability of the mixture, obtained the dependence of filtration coefficient on the so-called effective density of bentonite, i.e. the average density of bentonite distributed in the pores of the sand matrix [16]:

$$\rho_e = \frac{m_{гл}}{V_{в} + V_{гл}}, \quad (2)$$

where $m_{гл}$ – clay mass, $V_{в}$ – volume of water (volume of pores in the mixture), $V_{гл}$ – clay volume.

Subsequently, the model was changed by dividing the water in the pores into bound, that is, sorbed by clay particles, and free or gravitational water, the movement of which mainly causes water permeability of soils (scheme *c* in Fig. 3). In particular, it was introduced the concept of free or effective porosity of the mixture, while calculating of which the volume occupied by bound water was excluded from the pore volume $V_{св}$ [9, 18]:

$$n_e = \frac{V_в - V_{св}}{V}, \tag{3}$$

where V – volume of mixture.

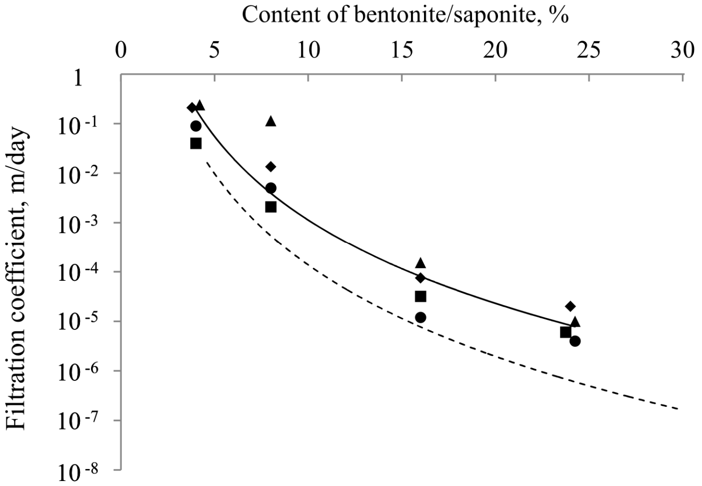

Fig. 4. Dependence of filtration coefficient on the content of highly dispersed clay.
The dotted line shows the dependency for SBM from Fig. 1.

Numbers of sands according to the Table 1: ♦ – 1; ● – 2; ■ – 3; ▲ – 4

Рис. 4. Зависимость коэффициента фильтрации от содержания высокодисперсной глины.
Пунктиром показана зависимость для песчано-бентонитовой смеси из рис. 1.

Номера песков по табл. 1: ♦ – 1; ● – 2; ■ – 3; ▲ – 4

In the models given above and their dependencies it is not taken into account the composition of the sand used, although this factor can have a significant effect on water permeability. For example, in experiments by R.P. Chapuis, D. Castelbaum and C.D. Shackelford, D'Appolonia with the same composition of mixtures prepared by using sands of different grain size distribution the filtration coefficient differed by one to two orders of magnitude [9, 29, 31].

We propose to isolate fractions of dusty and clay particles as part of sand, which not only fill the pores between larger particles, but also sorb pore water on their surface (scheme *d* in Fig. 3).

Taking into account the difference in the density of solid particles and water, formula (2) was transformed and instead of the effective density of clay the degree of blocking of pores in the sand matrix bound by moisture, clay and dust particles was found:

$$\delta = \frac{V_{св} + V_{гл} + V_{пыл\text{-}гл}}{V_в + V_{гл} + V_{пыл\text{-}гл}}, \tag{4}$$

where $V_{пыл\text{-}гл}$ – the volume of dusty-clayey particles in the composition of sand.

The dependence of filtration coefficient of the mixture on the value under consideration can be expressed by an exponent with a very high coefficient of determination – $R^2 = 0.68$ (Fig. 5):

$$k = 8.3\, e^{-16.4\delta}. \tag{5}$$

In calculating the volume of moisture associated with highly dispersed clay swelling humidity of 0.89 was used, and dust and clay particles – ten times less than 0.09 according to the ratio of swelling deformations of highly dispersed clay and local clay soils, in the composition of the clay fraction of which hydromica prevail [32].

The dependence of the filtration coefficient on the effective porosity, which was found by excluding from the pore volume the volume of water sorbed by highly dispersed clay and dusty-clayey particles contained in the sand according to formula (3), is also exponential with the coefficient of determination $R^2 = 0.75$ (Fig. 6):

$$k = 2.9 \cdot 10^{-7}\, e^{40.6 n_e}. \qquad (6)$$

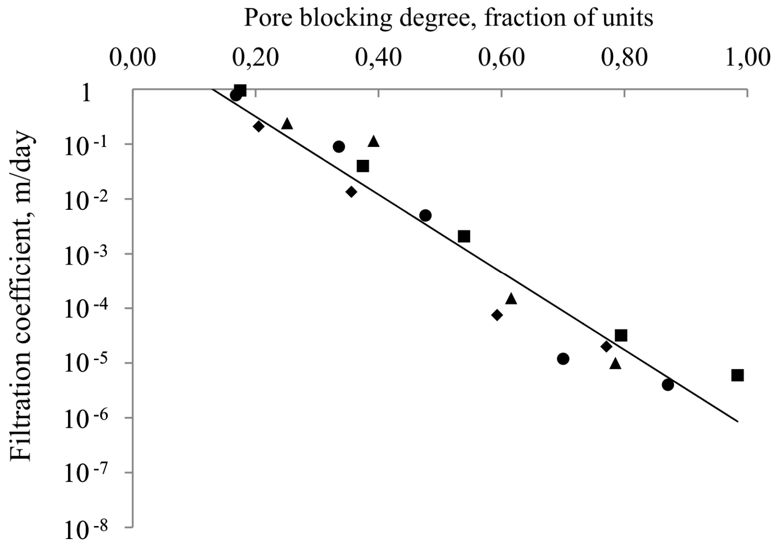

Fig. 5. Dependence of the filtration coefficient on the degree of pore blocking in the sand matrix.
Numbers of sands accorsding to the Table 1: ♦ – 1; ● – 2; ■ – 3; ▲ – 4
Рис. 5. Зависимость коэффициента фильтрации от степени блокировки пор в песчаной матрице.
Номера песков по табл. 1: ♦ – 1; ● – 2; ■ – 3; ▲ – 4

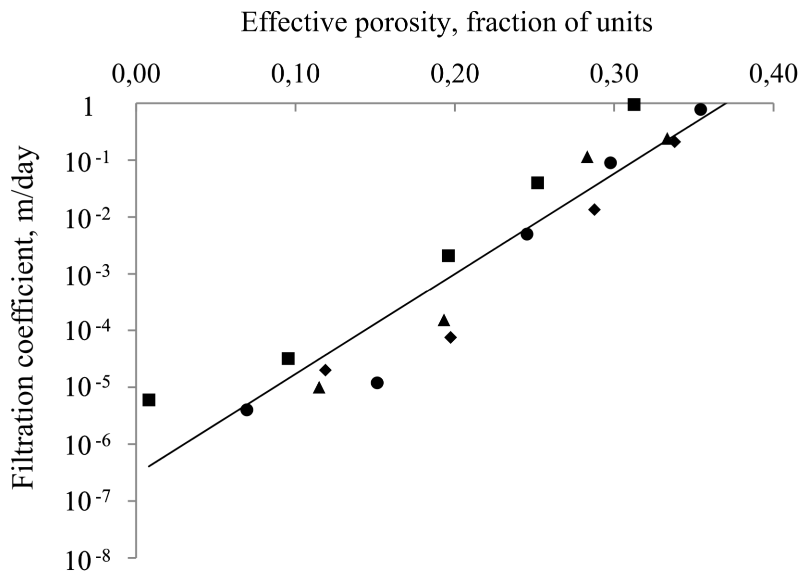

Fig. 6. Dependence of filtration coefficient on effective porosity.
Numbers of sands according to the Table 1: ♦ – 1; ● – 2; ■ – 3; ▲ – 4
Рис. 6. Зависимость коэффициента фильтрации от эффективной пористости.
Номера песков по табл. 1: ♦ – 1; ● – 2; ■ – 3; ▲ – 4

It should be noted that an attempt to apply power dependencies, usually used in predicting the water permeability of soils (formulas by I. Sauerbray, D. Kozeni, M. Kazenov, etc.), gave a somewhat worse result. Exponential functions of various types, as in our studies, were used less frequently in hydrogeology [33, 34].

The results obtained open the prospect of a new direction for the disposal of saponite-containing waste associated with the protection of the geological environment during the construction of industrial and domestic waste storage facilities. Standards for the design, operation and reclamation of landfills for the disposal of municipal solid waste establish a requirement for soils of a geological barrier at their base $k \leq 10^{-5}$ cm/s or $0.9 \cdot 10^{-2}$ m/day (SR 320.1325800.2017, alteration 1). Approximately the same requirements for water permeability contain standards for the design of industrial waste landfills of hazard class IV, where the criterion for the applicability of soil as an insulating material laid on the bottom and slopes of the waste storage area is indicated by the value $k \leq 10^{-7}$ m/s or $0.9 \cdot 10^{-2}$ m/day (SR 127.13330.2017). When disposing of waste of hazard classes II and III, the filtration coefficient should be 100 times less ($0.9 \cdot 10^{-4}$ m/day), and I class – even an order of magnitude less ($0.9 \cdot 10^{-5}$ m/day).

Conclusion

1. Mixtures of highly dispersed saponite-containing clay, which is a waste product of diamond-bearing ore benefitiation, with sands can be used in the installation of waterproof screens on industrial and domestic waste storage tanks and anti-filtration elements of hydraulic structures. By adding 16 % clay to the sand the filtration coefficient is reduced to $(1.2\ldots15.3) \cdot 10^{-5}$, and 24 % – up to $(0.4\ldots2.0) \cdot 10^{-5}$ m/day. In terms of water permeability the studied compositions are almost identical to the widely used sand-bentonite mixtures.

2. It has been obtained experimental dependencies of the filtration coefficient k on effective ot free porosity n_e and the degree of pore blocking in the sand matrix δ. The first value n_e is found by excluding from the pore volume the volume of water sorbed by highly dispersed clay and dusty-clayey particles contained in the sand, and the second δ – as the ratio of the volume of clay, dusty particles and moisture absorbed by them to the volume of pores in the sand matrix.

3. The preparation of mixtures is possible without preliminary drying of ingredients, namely with the use of a suspension of highly dispersed waste taken from the sedimentation pond of the tailings dump. To achieve optimal moisture content of the mixture the suspension can be thickened in a centrifuge with the addition of a coagulant $FeCl_3$ in the amount of 2 % from the mass of suspension.

4. The optimal moisture content of the mixtures varies within a very narrow range of 13 to 16 %, and the maximum density – from 1.69 to 1.95 g/cm^3 and it becomes higher with the increase of the mass of applied clay particles and the coefficient of sand heterogeneity.

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