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Intensification of Sand Dehydration in Warehouses Using Vacuum Installations

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Abstract. The issue of dewatering sand, which is used in construction as an aggregate for heavy, simple, fine-grained, large-cell and silicate concrete, concrete mixtures, in the manufacture of reinforced concrete structures, in the production of asphalt and road surfaces, roofing construction materials, in the manufacture of glass, is considered. The results of experimental studies of the operation modes of the process of dewatering construction sand at drainage warehouses with the use of vacuum units are presented, depending on the time of its dewatering, the granulometric composition of the sand, and the placement scheme of special needle filter elements of the suction system.

Introduction

Sand is a natural non-mineral bulk material that consists of granules of various sizes, mostly quartz (a mineral of the class of simple oxides and hydroxides, the main mineral of the silica group SiO_2 or silicon dioxide) and impurities and is one of the most accessible and important raw building materials [1].

The main characteristics of sand as a construction fine aggregate are: sand grain size module, grain composition, grain surface type, mineralogical composition, intergranular voids, presence of various impurities [2]. Sand grain size module is an important parameter, which determines water consumption during the production of construction mixtures and, accordingly, affects the amount of binding material [3]. Coarse sand has a granulometric composition greater than 2.5, medium – from 2.0 to 2.5, fine – from 1.5 to 2.0, and very fine from 1.0 to 1.5. Sand belonging to the fine group is used in the manufacture of roofing roll materials, silicate building materials and cement mortars, in the manufacture of ceramics. Very fine sand (powdery) is used for the preparation of construction fine-dispersed mixtures, it is the main raw material for the production of glass: its share among all ingredients is 75 %. Sand of medium and large groups is usually used in construction as an aggregate for heavy, simple, fine-grained, coarse-grained and silicate concrete, concrete mixtures, in the manufacture of reinforced concrete structures, used in the production of asphalt and road surfaces (the proportion of sand in road asphalt reaches 90 %). It was determined that the higher the brand of loose sand, the better the quality of the building material.

Each type of sand is used in a certain area, in which it will be able to show its properties to the maximum: buoyancy, flowability, porosity and moisture capacity. In addition, it should be noted that sand is a non-combustible, ecological [4, 5] and fire-resistant building material [6, 7]. After the necessary preparation, quartz and perlite sand can be used as a light filler in special fire-retardant coatings due to their layered structure [8].

There are four types of sand depending on the place of its extraction: sea, river, mountain and quarry [9, 10]. It is river sand that is considered the most sought-after construction material, because it has the necessary particle size composition and does not contain unnecessary impurities, it is the cleanest and most homogeneous [11, 12], does not require additional cleaning, and is immediately ready for use after dehydration [13].

Sands are also classified depending on the coefficients of porosity, filtration and water flow, which are given in the tables 1–3.

Tab.1 Classification of sands according to the porosity coefficient.

A type of sand	Porosity coefficient *e*		
	Gravelly sands, coarse and medium-sized	Fine sands	Dusty sands
Dense	< 0.55	< 0.60	< 0.60
Medium density	0.55–0.70	0.60–0.75	0.60–0.80
Loose	> 0.70	> 0.75	> 0.80

Tab.2 Classification of sands according to the filtration coefficient.

A type of sand	Approximate filtration coefficient *K*, [m/day]
Gravelly sands	50–100
Coarse sand	25–75
Medium grain sand	10–25
Fine sand	210
Dusty sand	0.1–2

Tab.3 Classification of sand according to the average value of the water yield coefficient.

A type of sand	Water yield coefficient μ
Coarse-grained, gravelly sands	0.25–0.35
Medium-grained sands	0.2–0.25
Fine-grained sands	0.15–0.20
Dusty sands	0.10–0.15

According to [14], there are industrial methods of dewatering sand, which, according to the nature of the physical process of removing moisture from the material, are divided into mechanical methods and thermal drying. In the sand dewatering industry, various mechanical methods and means of sand dewatering have become exceptionally widespread, the use of which is simultaneously considered an integral part of the complex solution to the problem of preventing materials from freezing and preserving their free-flowing properties. The application of the thermal method of dewatering sand as a cardinal solution is allowed only in individual cases due to the high energy intensity of the process. The simplest and most widely used methods among them are solutions that provide gravity dewatering of washed sand stacks [15]. However, this solution has a number of serious drawbacks, namely the decrease in the quality of mined sand due to the uncontrolled fluctuation of its moisture level, which often leads to the negative consequences of disrupting the technological process of manufacturing concrete, construction mortars and mixtures, and ultimately to a decrease in the quality of products. It was established that an unaccounted change in the humidity of building sand by only 1 % can lead to a change in the mobility of the concrete mixture by 4 cm or lower the strength limit of concrete by 2 MPa, and in some cases even more.

In work [16], it was determined that mechanical methods and means for the boundary degree of moisture removal from sand can be divided into two groups: methods and equipment for preliminary and partial dehydration of sand, using which gravitational moisture is partially removed, implemented using mechanical classifiers, hydrocycles, vibrating dehydrators (humidity varies between 10–25 %); methods of equipment for deep dehydration, using which gravity moisture is almost completely removed and moisture is stabilized, the indicator of which does not exceed the value of the smallest moisture capacity, is implemented by means of centrifugation, vacuuming and combined methods (humidity ranges from 0.5 to 3 %). All these technical means, equipment and its components [17, 18] work in a corrosive-active environment [19, 20] and are subject to special protection [21, 22] and their locations [23].

To reduce the humidity of sand, a study was conducted using a thermal method of dehydration in combination with mechanical methods of sand dehydration [24, 25]. These studies were conducted to explore the possibility of borrowing similar methods used for dewatering sand in the mining, coal and chemical industries (drying drums, drying tubes, etc.). The results of the study showed that despite significant fluctuations in the humidity of the sand in the source material, from 26–56 %, the humidity at the exit from the machine did not exceed 3 %, the heat consumption per 1 kg of evaporated substance was 3680–3980 kJ. It was established that the use of the specified method for dewatering sand on an industrial scale is impractical due to high energy consumption.

Studies show [26] that, regardless of design features, the process of sand dehydration in vibrating devices occurs during the movement of sand particles with a fraction of 0.15–5 mm by shaking, when the forces of inertia tear off drops of gravitational and capillary moisture from the particles of sand grains. As a result of vibration, there is a sharp decrease in the friction of sand particles on the walls of the device, which will ensure vibrational transportation of dehydrated sand. The time of dehydration in vibrating devices is insignificant, the energy consumption of the process is 2–4 times less than in spinal classifiers, the amount of residual moisture of sand is on average 12–16 %. Further reduction of sand humidity in vibrating devices is limited due to significant increase in dehydration time and deterioration of economic indicators.

In work [27], the analysis of the technological scheme of the hydromechanized method of mining and dewatering of sand was established that in all cases of the use of dewatering means, it is necessary to provide for measures aimed at the maximum removal of gravitational moisture from the sand, to stabilize the residual moisture content at the level of 18–22 %.

In the article, an analysis of the operation of the hydroclassifier and hydrocyclones used in the dewatering and cleaning of sand was carried out [28]. It was determined that when using these devices, the value of the centrifugal force is relatively small during the insignificant time of its impact on the sand during dehydration, and the increase in centrifugal force in these devices is limited by energy and technological factors, which in turn determines the relatively high content of residual moisture in the sand at the level of 18–25 %. According to the results of the study, it was established that the value of sand moisture thresholds, which is achieved by using the above-described means for dewatering sand, should be considered marginal; the sand that arrives at the warehouse after this equipment, in the future, in most cases, is subjected to additional dehydration, which is carried out by the method of sedimentation.

In [29], an experimental laboratory installation (centrifuge) was proposed, with the use of which deep dehydration of sand is achieved. Dewatering in this device is based on the filtration of liquid through a porous surface under the action of centrifugal forces, which made it possible to reduce the moisture content of sand from 40 % to 3–6 %. In the simplest case, the filter unit is a perforated rotor, which is open on one or both sides and rotates around its axis. As a result of the study, it was established that the moisture content of coarse-grained sands can be obtained within 2.5–4 % and 7 % for fine sands. The paper also notes that the residual moisture content in sand after the end of the dehydration process, in addition to the design and technological parameters of the centrifuge itself, is influenced by the initial moisture content of the sand, its classification by grain size composition and water saturation coefficient, and the performance of the device. According to the results of the research, the disadvantages of the centrifuge were determined, which are relatively low productivity, periodicity of work, high energy consumption and rapid wear of filtering organs, which limits the use of similar structures for dewatering sand on an industrial scale.

In many studies [30, 31] it was established that the removal of moisture from sand by drainage has become the most widespread and is used in open or closed warehouses, wash basins, which are located on a drainage soil base or equipped with a drainage removal system. Moisture is removed by natural filtration under the influence of gravity. The results of the study showed that the dehydration of sand of different density and granulometric composition (0–0.8; 0.1–0.25; 0.5–2.0) at the initial moisture content of the sand for all fractions with 28 % within 6 hours moisture content in sand decreased for small fractions to 23.5 % and for large fractions to 11.5 %. It was determined [32, 33] that the main disadvantage of the sump is the low technical level of implementation, which is caused by the excessive duration of the sand dehydration process.

This work proposes an experimental study of regularities and the development of a mathematical model of the process of dehydration of construction sand samples by size in drainage warehouses during the movement of water in a porous medium under the action of vacuum units to the dehydration elements, which will be used in the future in construction as a component of construction mixtures, aggregate in concrete and asphalt pavement manufacture, etc.

The purpose of the work is to determine the dependence of the sand dewatering time on the proposed equipment, to develop rational parameters and to compile a methodology for calculating this equipment based on experimental and theoretical studies of the operation modes of the construction sand dewatering process by size in drainage warehouses using a vacuum installation through special needle filter elements of the suction system.

Materials and Research Methods

In order to solve the considered problem, it is necessary to reveal the regularities inherent in the research object, to build a mathematical model of the process of dewatering building sand samples by size, under the conditions of using vacuum installations with a system of horizontally located needle filter elements of the suction system, which are located at the base of the composition that has a prismatic shape and is symmetrical figure according to the circular and linear scheme of placement.

In the solution of the problem related to the category of evaluation tasks, the greatest practical interest is the determination of the time of decrease in the depth of the water flow that saturates the composition of the sand to a given height, as well as the change in the amount of water flow sucked by each needle filter element from dehydrated sand, as a function of time.

To conduct research and develop a mathematical model for sand dehydration, we use an experimental setup that required simplification by crushing the research object using the fragmentation method presented in fig.1.

For a mathematical description of the processes that take place during sand dehydration, the movement of the water flow for the considered case of filtration, which has not been established, is written in the form of the Boussinesq equation in the form:

$$\frac{k}{m^I}\frac{\partial}{\partial x}\left(H\frac{\partial H}{\partial x}\right)=\frac{\partial H}{\partial t}, \tag{1}$$

after linearization of which we obtain

$$\alpha^2\frac{\partial^2 U}{\partial x}=\frac{\partial U}{\partial t}, \tag{2}$$

where, $U=\frac{H^2}{2}$ – a new function is introduced; $\alpha^2=\frac{k\cdot H_0}{2\cdot m^I}$ – conductivity level coefficient; H_0 – initial flow depth; k – sand filtration coefficient; m^I – water yield coefficient.

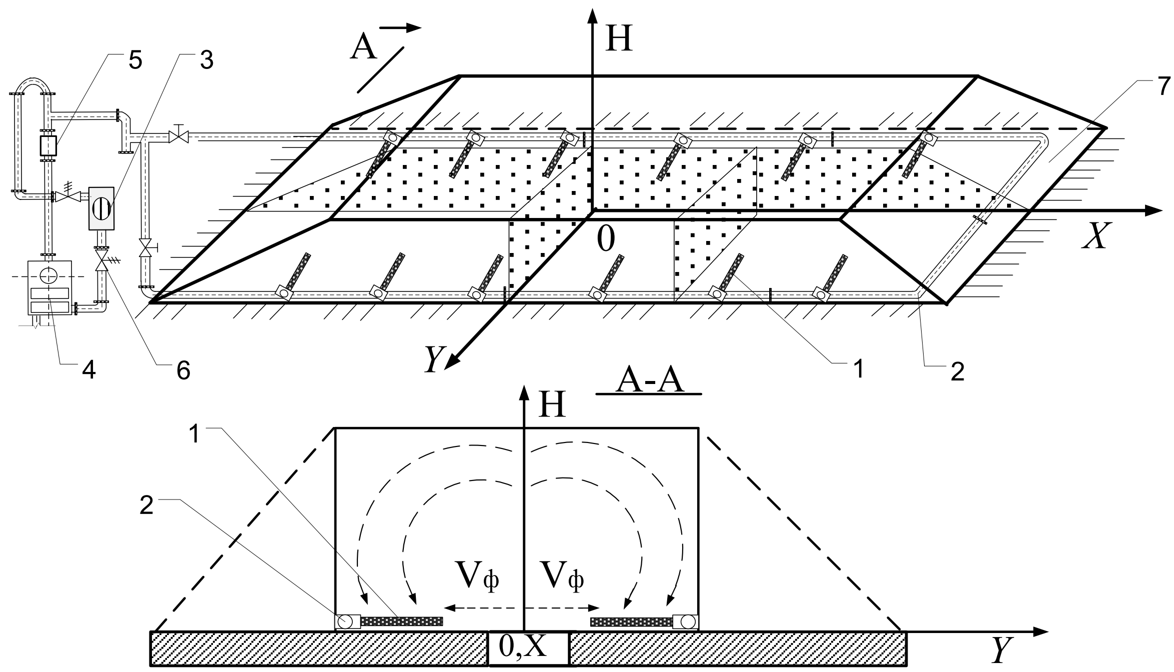


Fig. 1. Experimental installation: 1 – needle filter element; 2 – catchment collector; 3 – centrifugal pump unit; 4 – circular tank; 5 – water jet pump; 6 – valves of the suction and pressure mains; 7 – composition of sand

We will form the boundary conditions as follows:

$$\frac{\partial U(0,t)}{\partial x} = 0 \text{; where } U(l,t) = 0 . \tag{3}$$

The shape of the depressed surface of the water flow, which has not settled, can be described by the function of the kind $F(x/l)$. Then, according to the previously accepted assumptions, we will write down the initial conditions in the form:

$$U(x,0) = U_0(x,0) = \frac{H_0^2}{2} \cdot \left(1 - \frac{x^2}{l^2}\right). \tag{4}$$

General solution for the function $U(x,t)$ we are looking for in the form:

$$U(x,t) = \sum_{i=1}^{\infty} C_i \cdot \exp\left(-\alpha^2 \cdot \lambda_i^2 \cdot t\right) \cdot \cos \lambda_i x , \tag{5}$$

where, $\lambda_i = \dfrac{(2n+1)\cdot \Pi}{2l}$ – eigenvalues of the differential equation (2) with multiple conditions (4) and (5); l – half the distance between the needle filter element of the suction system.

After determining the coefficients and transformations finally for $U(x,t)$ looks like:

$$U(x,t) = \frac{16 H_0^2}{\Pi^3} \sum_{i=1}^{\infty} \frac{(-1)^i}{(2i+1)^3} \cdot \cos \frac{(2i+1)\Pi \cdot x}{2l} \cdot \exp\left(-\alpha^2 \cdot \lambda_i^2 \cdot t\right). \tag{6}$$

The obtained solution allows us to proceed to the solution of the spatial problem using a similar approach. Let's select a certain volume from the array of the composition, which is a rectangular prism with a height equal to the height of the composition and sides equal, respectively, to the width of the composition 2*a* and the laying step 2*b* of the needle filter elements of the suction system.

We reduce the solution for the spatial problem to the determination of water inflow to one of the four-point drains located at the corners at the base of the selected volume.

The Boussinesq equation for the unsteady motion of planar and plane pressure less flow has the form:

$$\frac{k}{m^{l}}\cdot\left[\frac{\partial}{\partial x}\left(H\frac{\partial H}{\partial x}\right)+\frac{\partial}{\partial y}\left(H\frac{\partial H}{\partial y}\right)\right]=\frac{\partial H}{\partial t}, \tag{7}$$

and after linearization

$$\frac{\partial^2 U}{\partial x^2}+\frac{\partial^2 U}{\partial y^2}=\frac{1}{\alpha^2}\cdot\frac{\partial U}{\partial t}. \tag{8}$$

The boundary and initial conditions of the considered problem are taken as:

$$\left.\begin{aligned}&\left.\frac{\partial U}{\partial x}\right|_{x=0}=0; \qquad &\left.\frac{\partial U}{\partial y}\right|_{y=0}=0\\ &U\big|_{x=a}=f(y)\cdot\psi(t); \qquad &U\big|_{y=b}=\varphi(x)\cdot\mu(t)\end{aligned}\right\}, \tag{9}$$

where, *f(y)* – a function describing the nature of the depression curve in the cross section of the stream with coordinates $y=b$, $0\le x\le a$;

$\psi(t)$ – a time function describing the nature of the unsteady movement of the depression curve in the same cross-section (with filtering established $\psi(t)=1$);

$\varphi(x)$ – a function describing the nature of the depression curve in the cross section of the stream with coordinates $x=a$, $0\le y\le b$;

$\mu(t)$ – a function of time that describes the nature of the unsteady movement of the depression curve in the same cross-section (with filtering established $\mu(t)=1$).

Function value $U(x,y,t)$ in the form of a product is allowed by a linearized equation (8). Initial conditions for $U(x,y,t)$ is written as:

$$U(x,y,0)=U_0(x,y), \tag{10}$$

moreover:

$$\Delta U=0. \tag{11}$$

Solving a stationary problem with the same boundary conditions. We are looking for a solution to equation (8) in the form of a sum of two functions:

$$U(x,y,t)=V(x,y,t)+W(x,y,t), \tag{12}$$

where, $V(x,y,t)$ – function that will satisfy the boundary conditions (9).

For the function $W(x,y,t)$ we have the equation:

$$\Delta W+\Phi=\frac{1}{\alpha^2}\cdot\frac{\partial W}{\partial t}, \tag{13}$$

where, Φ is expressed through *V* as follows:

$$\Phi=\Delta V-\frac{1}{\alpha^2}\cdot\frac{\partial V}{\partial t}. \tag{14}$$

In this case, we have homogeneous final and initial conditions:

$$\left.\begin{aligned}&\left.\frac{\partial W}{\partial t}\right|_{x=0} = \left.W\right|_{x=0} = \left.\frac{\partial W}{\partial t}\right|_{y=0} = \left.W\right|_{x=0} = 0\\&W\big|_{t=o} = U_0(x,y) - V(x,y,0) = 0\end{aligned}\right\} \tag{15}$$

The procedure for calculating the above assessment tasks using a mathematical model may be different, depending on the available initial data, but the general principle of building the calculation method remains unchanged.

Discussions of Results

In the work, a study of changes in the moisture content of different samples of building sand by grain size was carried out directly at the sink warehouses, which showed that the developed method eliminates the main drawback of natural drainage (settling) – the duration of the sand dehydration process. Based on the results of the study, it was established that after the end of the washing of the sand map, i.e., in the final composition, the corresponding sand samples were completely saturated with moisture and intense seepage of water was observed on the slopes. The elevation line was located on average at a height of 1.4–1.6 m from the base of the warehouse.

During this period, vacuum installations with horizontally located needle filter elements of the suction system, which were placed at the base of the warehouse according to a ring scheme, were turned on. The determined indicators of water consumption by the installation that dewatered during the specified period changed from 26 m^3/h to 1.1 m^3/h, and the rarefaction in the mixing chamber of the water jet pump from 0.0618 MPa to 0.008 MPa.

Measurements of the moisture content of sand samples in the warehouse were carried out the first time 30 minutes after the end of washing, and the second time after the end of the operation of the vacuum unit, the time of continuous operation of which was 50 hours. The initial moisture content of the sand samples was 28–32 %, after dehydration the sand moisture content did not exceed 6-7 %. Sand samples were taken at different points of the warehouse and at different levels in specially opened trenches. The final moisture content of construction sand samples within the height of the warehouse changed from 4.5 % to 9.5 %. Before the use of vacuum installations, the composition of similar sizes settled for 6–7 days, and as a result of dehydration due to natural drainage, the moisture content of the sand decreased to an average of 12.9–15.5 % in the upper layers about 1.5–2 m thick. Moisture content of the main mass construction sand - the bottom layer about 1.5 m thick, this period was 21–23 %.

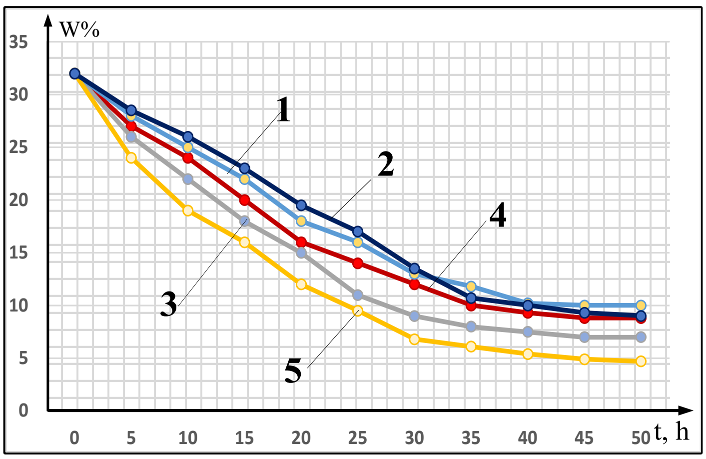
It should be noted that when dewatering construction sand samples from the warehouse using a vacuum unit with a linear arrangement of needle filter elements of the suction system, the dehydration time increases, compared to a ring arrangement of needle filter elements. According to the research results, it was established that a vacuum of about 0.064 MPa was created in the water collection collector and needle filter elements, the dehydration process continued continuously for 50 hours. Water consumption during sand dewatering varied from 22 m^3/g to 0.8 m^3/g, while the degree of rarefaction in the mixing chamber of the water jet pump was from 0.64 MPa to 0.18 MPa. The moisture content of the sand samples after the specified time in the area of operation of the vacuum installation decreased on average from 28–32 % to 7–10 %. Construction sand samples were taken at a distance of 4–5 m from the line of laying needle filter elements at a depth of about 3.5–4 m from the top of the warehouse. In the rest of the warehouse during this period, the moisture content of the sand decreased to 11–13 % in general. It should be noted that when using vacuum installations, the time of dehydration of sand samples in drainage warehouses is reduced by approximately 2–3 times compared to the duration of this process during natural settling of the same warehouse.

The obtained results of the study on the change in the moisture content of construction sand samples by size in the conditions of dehydration of this material by a system of horizontally located needle filter elements of the suction system according to the ring and linear placement scheme, which are located at the base of the drainage composition before and after the tests, are shown in Table 4.

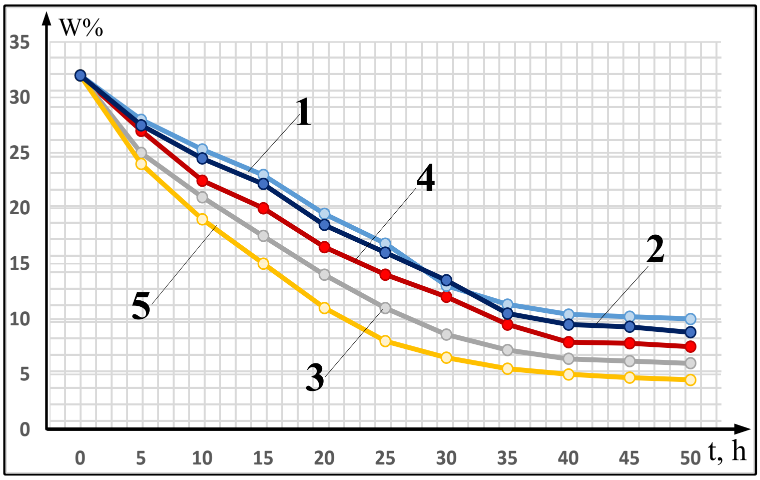
Tab. 4 The results of the study of the dehydration of construction sand samples in drainage warehouses

Size class d, [mm]	Samples of construction sand according to different granulometric composition [%]				
	1	2	3	4	5
+3.0	–	–	1.96	–	–
2.5–3.0	–	1.26	10.13	1.22	10.20
2.0–2.4	6.26	14.07	29.07	7.48	10.32
1.6–2.0	16.0	14.09	14.59	7.55	11.6
1.0–1.6	18.52	17.05	13.07	11.93	29.75
0.63–1.0	13.19	8.56	14.19	10.67	27.5
0.315–0.63	23.58	22.15	8.32	19.25	6.5
0.2–0.315	6.12	7.63	2.29	19.92	1.07
0.1–0.2	3.99	4.21	2.11	4.63	1.03
0.05–0.1	3.02	2.96	1.38	5.19	0.42
0–0.05	9.32	8.02	2.9	13.18	1.61
Total	100.0	100.0	100.0	100.0	100.0
initial humidity, [%]					
Placement of needle filter elements	28–32	28–32	28–32	28–32	28–32
	final humidity, [%]				
circular	8–10	8–9.5	5–7	7.5–9	4–6
linear	9–11	9–12	7–10	8–10	7–9

Taking into account the results obtained from Tab. 4 and the proposed system of equations (1–14), we will plot graphical dependences of the process of dehydration of construction sand samples by size. The resulting graphical dependencies are presented in Fig. 4.



a)



b)

Fig. 4. Dependence of changes in the moisture content of building sand samples on the time of dehydration using a vacuum installation in the drainage warehouse: a) – ring arrangement of needle filter elements according to the results of experimental studies; b) ring placement of needle filters of elements according to the results of the calculations

The analysis of the research results allows the following conclusions to be drawn:

– in building sand with a granulometric composition, the size of which is smaller (from 0.05–0.5 mm) as a percentage of the total volume (samples 1, 2, 4), the time required to reach the final indicators of dehydration is greater because the intensity of its dehydration determined by cohesive and capillary moisture, the value of which depends mainly on the coarseness of the sand composition and the way its particles are arranged in the mass;

– in those samples of construction sand that contained clay impurities and their varieties, during dehydration the sand became denser and the intensity of its dehydration decreased due to the sticking of its particles, the time during which the final indicators of dehydration were reached increased;

– it was established that after 35 hours of dehydration, the moisture content of building sand practically stabilizes when gravitational water is removed. The water-holding capacity of sand in this case is equal to the smallest moisture capacity;

– the greater the coarseness of construction sand according to its granulometric composition in percentage ratio (samples 3 and 5), the greater the intensity of its dehydration and the shorter the time for which the final indicators of dehydration of sand samples are reached;

– the use of a vacuum installation with the placement of needle filter elements of the suction system according to a linear or ring scheme during the period of washing the construction sand warehouse provided a reduction of the significant filtration load on the warehouse, which made it possible to exclude long temporary stops of this process, in order to avoid erosion of the warehouse, and to reduce the time of washing from 13–17 days on average up to 7 days;

– the effective use of a vacuum installation with the placement of needle filter elements of the suction system according to a linear or ring scheme made it possible to significantly reduce the moisture content of construction sand samples in the upper and lower layers of the main mass of the composition from 32 % to 6–12 %.

The results obtained in the course of the study confirmed the conclusions about the high efficiency of using a vacuum unit with needle filter elements of the suction system in dewatering construction sand samples by size, which covers almost all classes of mined non-mineral sand.

Summary

Experimental studies were conducted to determine the time of change in the moisture content of construction sand samples with different granulometric composition at the beginning and after the tests, which is used in construction as an aggregate for heavy, simple, fine-grained, large-cell and silicate concrete, concrete mixtures, in the manufacture of reinforced concrete structures, in the production of asphalt and road surfaces, roofing roll construction materials, in the production of ceramics and various types of glass. The dependence of the time of dehydration of building sand samples of different sizes on the proposed technological equipment (vacuum installations) was determined, with the use of special needle filter elements of the suction system according to the linear or ring placement scheme.

It was established that in samples of construction sand with a granulometric composition, the size of which is higher, the intensity of its dehydration occurs faster and in a shorter time, the final indicators of dehydration of sand samples are reached in the range of 4–7 % for the ring scheme and 7–10 % for the linear scheme of placement of needle filters of the suction system elements. It should be noted that when using vacuum installations with the use of special needle filter elements of the suction system, the time of dehydration of sand samples in drainage warehouses is reduced by approximately 2–3 times compared to the duration of this process during natural settling of the same warehouse.

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