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Original article

PROPERTIES OF CONCRETE MODIFIED BY PRODUCTS OF A NEW TECHNOLOGY FOR TREATING WASTEWATER FROM CONCRETE PRODUCTION USING A PHASE SEPARATION PLANT FOR CONTAMINANTS

A.A. Chernilnik, A.S. Smolyanichenko, D.M. El'shaeva, E.V. Yakovleva

Abstract

Currently, the algorithm for the production of concrete mix remains almost unchanged due to the optimality and efficiency of its constituent processes. It is inextricably linked to the process of flushing equipment for the production of concrete mix, which uses large volumes of water. Polluted waters formed during flushing of equipment and concrete pipelines contain a large amount of mechanical impurities, which makes it impossible to discharge them properly, this causes the urgency of the problem and requires its immediate solution. The purpose of the study was to evaluate the effectiveness of the Pyramid N phase separator in the treatment of wastewater generated during the washing of concrete mixing equipment, as well as the possibility of reuse of purified wastewater for the manufacture of concrete mixtures and concretes. The study was carried out in two main stages: the first stage was to evaluate the effectiveness of the Pyramid N phase separator for wastewater treatment obtained after washing concrete mixing equipment and checking the quality of the treated water. The second stage is an assessment of the possibility of reuse of treated wastewater for the manufacture of concrete mixes and concretes. The research results have confirmed that the use of the Pyramid N phase separator for wastewater treatment is effective and justified. Wastewater treated with this device does not exceed the permissible standards in terms of harmful components. Concretes made with purified wastewater have strength characteristics comparable to those of concrete made with tap water. The difference between the strength characteristics ranged from 1.3% to 4.3%, and between the characteristics of fresh concrete – from 2.4% to 9.7%. The practical significance of the study was a significant reduction in water costs and a more efficient use of natural resources, which corresponds to the concept of sustainable development.

Keywords: wastewater treatment technology; installation of phase separation of phase; separation of contaminants; concrete mix; concrete

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Научная статья

СВОЙСТВА БЕТОНОВ, МОДИФИЦИРОВАННЫХ ПРОДУКТАМИ НОВОЙ ТЕХНОЛОГИИ ОЧИСТКИ СТОЧНЫХ ВОД БЕТОННЫХ ПРОИЗВОДСТВ С ИСПОЛЬЗОВАНИЕМ УСТАНОВКИ ФАЗОВОЙ СЕПАРАЦИИ ЗАГРЯЗНЕНИЙ

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Аннотация

В настоящее время практически неизменным остается алгоритм производства бетонной смеси вследствие оптимальности и эффективности составляющих его процессов. С ним неразрывно связан процесс промывки оборудования для производства бетонной смеси, который использует большие объемы воды. Загрязненные воды, образующиеся при промывке оборудования и бетонопроводов, содержат большое количество механических примесей, что делает невозможным их правомерный сброс, это обуславливает актуальность проблемы и требует неотлагательного ее решения. Целью исследования являлась оценка эффективности фазового сепаратора «Пирамида N» при очистке сточных вод, образующихся в процессе промывки бетоносмесительного оборудования, а также возможность повторного применения очищенной сточной воды для изготовления бетонных смесей и бетонов. Исследование осуществлялось в два основных этапа: первый этап – оценка эффективности фазового сепаратора «Пирамида N» для очистки сточных вод, полученных после мойки бетоносмесительного оборудования с проверкой качества очищенной воды; второй этап – оценка возможности повторного применения очищенной сточной воды для изготовления бетонных смесей и бетонов. Результаты исследований подтвердили, что применение фазового сепаратора «Пирамида N» для очистки сточных вод является эффективным и оправданным. Сточные воды, прошедшие очистку на данном аппарате, по содержанию вредных компонентов не превышают допустимых норм. Бетоны, изготовленные на очищенной сточной воде, имеют прочностные характеристики, сопоставимые с характеристиками бетона, изготовленного на водопроводной воде. Разница между прочностными характеристиками варьировалась от 1,3% до 4,3%, а между характеристиками свежего бетона – от 2,4% до 9,7%. Практическая значимость исследования заключалась в значительном сокращении затрат воды и более эффективном использовании природных ресурсов, что соответствует концепции устойчивого развития.

Ключевые слова: технология очистки сточных вод; установка фазовой сепарации загрязнений; бетонная смесь; бетон

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Introduction

The constant growth in the volume of modern construction is inevitably associated with an increase in the volume of manufacture and use of building structures, which directly leads to an increase in the volume of building materials used [1-3]. Today, it is quite popular to use various types of waste in concrete [4; 5], as well as various methods of activating the components of the concrete mixture [6-8] or the concrete mixture itself [9] to create so-called green concretes with improved characteristics. Despite the large number of new materials, the most popular solutions remain classic, proven by many years of practice. Thus, one of the main pillars of the construction industry are concrete and reinforced concrete structures, which, despite their resource intensity, are in demand due to their high performance characteristics with relative simplicity and speed of manufacture [10; 11].

The production process of a concrete or mortar mixture can be conditionally divided into the main stages: acceptance and storage of raw materials, preparation of the components of the mixture for use, precise dosing of each component in accordance with the composition of the mixture, loading of raw components into a concrete mixer, mixing, unloading of the concrete mixture, transportation of the concrete mixture to the construction site [1]. However, when mixing and unloading the concrete mixture, as well as during transportation and direct application of concrete for the manufacture of structures, all equipment in contact with the concrete mixture is covered with a layer of concrete, which must be removed after the manufacture and transportation of each batch [12]. To wash the equipment after the production and transportation of the concrete mixture, a large volume of water is used, which after use contains a significant amount of mechanical and other contaminants [13]. Thus, 0.5 – 1.0 m^3 of water is consumed for the production of 1 m^3 of concrete mortar. In addition, during the washing of concrete aggregates, water is used at the rate of 0.5 – 1.0 m^3 per 1 m^3 of crushed stone or gravel and 1.25 – 1.5 m^3 per 1 m3 of sand. 0.1 – 0.15 m^3 of water per 1 m^3 of produced concrete mix is consumed for washing the equipment. For example, up to 1.2 m^3 of water is used to clean the inner part of the drum of one concrete truck, which on average corresponds to 11.5-20.0 m^3 per day for one plant for the production of ready mixes [14].

Wastewater generated during the washing of equipment for the production of concrete mixtures can be conditionally divided into polluted, formed during the washing of raw materials and equipment, and conditionally clean. Conditionally pure water is fed into the water recycling system, and polluted, due to the high content of suspended solids (3-15 g/l), silicates, aluminates and ferrites of calcium, sodium and potassium, as well as their alkalis, heavy metals, are fed to treatment facilities [15]. Such structures, as a rule, include settling tanks, filtration and recycling plants. For example, in Turkey, 97% of plants for the production of ready-made mixtures use settling ponds for wastewater treatment [16]. In addition to standard cleaning schemes, alternative methods of cleaning the raw material component of the concrete mixture for subsequent supply to the water recycling system have been used in practice. In the materials of the article [17], the results on the use of the vortex layer apparatus for washing sand are presented, and surfactants were simultaneously supplied to the washing water. After the washing process, the water was used a second time already to seal the concrete. According to the presented results, the average compressive strength of concrete samples increased by 64%. In [18], the following technological solution is proposed: a cleaning system consisting of a concrete flush regenerator, a wedge-shaped sludge sump, a slow sand filtration unit and a neutralization unit. The results of experimental studies confirm that the purified waste of washing water with a degree of dilution up to 75% can be used for the production of ready-mixed concrete.

As a rule, phase separators of dispersions are used for simultaneous isolation of contaminants in different groups according to the phase-dispersed state. The use of separators is important not only in the field of wastewater treatment, but also for a number of industries [19; 20]. For example, in gravity-based separators (gravity separators), the separation efficiency depends on the difference in the specific weights of the phases, and the design of the gravity separator directly affects its performance [21-25]. The main component of the separator is called the segment section, which provides sufficient residence time for the less dense phase to merge and separate from the denser phase. The structure of the internal components of the gravity separator directly affects its performance by changing the residence time of the mixture [21; 22]. In [22], the influence of internal components, a system of filter materials on the separation process with an oil density from 11 to 70 API was studied. The study showed that the filter design affects the distribution of oil droplets by size, thereby affecting the separation process. The authors in [23] proposed a deposition-oriented model for better deposition of oil droplets between parallel plates, which allowed the smallest oil droplets to combine faster in a gravity separator. In [9], the separation behavior of a horizontal gravity separator with three different inner plates was investigated. Their research mainly focused on the relationship between the inflow to the plates, the plate material, the distance between the plates and the separation length. Based on the results obtained, it is proposed that a separator with internal components, such as plates, may be a suitable addition to the separator design. In [25], an inclined gravity borehole oil and water separator was investigated. This type of separator has a number of advantages, including the potential for a long service life due to the simplicity of its components and its robust construction. The productivity of the separator installation depth, installation slope, tube size and tube configuration was investigated. The simulation results showed that with a volume fraction of water from 81% to 87%, the inclined separator is able to produce oil, the efficiency of water separation reached 82%. The disadvantages of gravity separators are the large occupied areas of structures due to their horizontal location, and their design does not provide for the removal of contaminants of a dispersion degree of 10-2-10-3 microns: molecular dissolved gases and volatile impurities. However, for simultaneous purification of water pollutants in various phase-dispersed states, it is necessary to determine the maximum removal time of a particular type of contamination, which will be decisive for the whole process. With three-phase pollution systems, according to hydrodynamic parameters, the removal of gases must be carried out at the first stage of purification.

Work [26] is devoted to the issue of wastewater treatment of ferrous metallurgy using a membrane for ultrafiltration under pressure from polyvinylidene fluoride (PVDF) with a low packing density obtained by thermally induced phase separation. It has been established that the ultrafiltration membrane has a good trapping ability and high characteristics of protection against contamination. In the study [27], the authors considered the use of liquid membrane separators, namely, methods of three-phase extraction carried out in a cascade of stages of volumetric liquid membrane separation, each of which consists of two interconnected (extraction and steam) chambers, and multiphase extraction, which provides that each stage of separation includes a scrubber chamber located between the extraction and steam chambers. The prospects of using three-phase extractors for wastewater treatment from phenol are shown. An increase in the efficiency of three-phase extraction can be achieved by carrying out the process in a cascade of three-phase devices. The authors [28] investigated the issue of separation of oily wastewater. The study was devoted to the membrane-forming effect of electroforming with a different ratio of polydimethylsiloxane (PDMS) and PVDF. With the help of electric spinning technology, the authors produced membranes for oil-water separation from PDMS/PVDF with the developed microstructure. The results showed that microspheres will improve the hydrophobicity of the membrane. Microspheres allow the membrane to achieve macroscopic uniformity and microscopic phase separation, so that the membranes have both good elongation and tensile strength. The study [29] considered the issue of industrial wastewater treatment using iron oxide nanoparticles developed by the authors, which acted as an effective nanocatalyst for the adsorption of heavy metals by chemical means. The authors considered the adsorption ability of iron oxide to remove bulk metal elements taking into account cadmium (Cd), lead (Pb), zinc (Zn), chromium (Cr), copper (Cu) and nickel (Ni) present in industrial wastewater. It was found that iron oxide nanoparticles make it possible to obtain the percentage of removal of the above elements equal to Cr (61.2%), Cd (98%), Cu (66%), Ni (64%), Zn (97%) and Pb (98%). The authors [30] considered the use of a solid residue of sulfuric acid, which is a waste during repeated processing of ash from Egyptian boilers together with kaolin as a base component for obtaining cheap zeolite and industrial wastewater treatment from heavy metal ions. Using synthesized zeolite, the quality of wastewater samples obtained from the Egyptian General Petroleum Corporation (Eastern Desert, Egypt) was significantly improved, and the content of heavy metal ions was significantly reduced.

The possibility of reuse of waste water for the manufacture of concrete mixtures and concretes was investigated in [31-35]. In [31], treated wastewater was used as an alternative to tap water in the manufacture of concrete. Concretes made with purified wastewater gained 85-94% of the final strength of reference samples made with tap water. The use of washing water of a ready-mixed concrete production plant for the manufacture of self-compacting concretes is considered in [32]. It is established that the use of waste water negatively affects the workability of self-compacting concrete and its strength characteristics. In [33], concretes made with well water and purified domestic wastewater were studied. It has been established that purified household water can be used as a viable alternative to fresh water in the production of concrete. Studies [34-36] are also devoted to the use of treated wastewater in the production of concrete mixtures and concretes, and the test results showed good characteristics of the properties of concrete.

The technology of wastewater treatment in concrete production considered in this study using a phase separation of impurities differs from the known methods primarily in its compact design, ease of operation and high efficiency in removing mechanical impurities. The installation includes, in terms of functionality, three capacitive structures at the same time – a mixer, a settling tank with a dedicated thin-layer settling zone and a clarifier. The scientific novelty of the work is determined by the following main provisions:

– development of theoretical principles of preliminary separation of contaminants in various aggregate state before post-treatment plants, which formed the basis of technological solutions (phase dispersion separator);

– obtaining new computational dependencies based on a computer model of fluid flow in the Pyramid N phase separation unit with an acceptable statistical error, which describe experimental data on the disaggregation of pollutants in the practice of industrial wastewater treatment.

The main purpose of the study is to evaluate the effectiveness of the Pyramid N phase separator in the treatment of wastewater generated during the washing of concrete mixing equipment, as well as the possibility of reuse of purified wastewater for the manufacture of concrete mixtures and concretes. The objectives of the study are to assess the quality of water purified at the Pyramid N phase separator and to assess the possibility of using purified wastewater in the manufacture of concrete mixtures and concretes.

Materials and Methods

Materials

Portland cement CEM I 42.5N (CEMROSS, Stary Oskol, Russia), which does not contain additives, was used as a binder for the manufacture of prototypes. The chemical composition and composition of the clinker of Portland cement is presented in Table 1.

Table 1.

Chemical composition and composition of portland cement clinker

Characteristic	**Actual value**
Chemical composition	
Losses during calcination of the IFR (%)	1.6
Silicon Oxide SiO_2 (%)	21
Aluminum Oxide Al_2O_3 (%)	4.8
Iron Oxide Fe_2O_3 (%)	3.9
CaO Calcium Oxide (%)	62
Magnesium Oxide MgO (%)	2.8
Alkaline oxides in terms of Na_2O (%)	0.7
Insoluble residue (%)	0.4
Sulfur Oxide SO_3 (%)	2.8
Chlorine ion Cl (%)	0
Clinker composition	
Tricalcium silicate C_3S (%)	63.2
Bicalcium silicate C_2S (%)	15
Four-calcium aluminoferrite C_4AF (%)	13.5
Tricalcium aluminate C_3A (%)	5.6
Magnesium Oxide MgO (%)	2.7

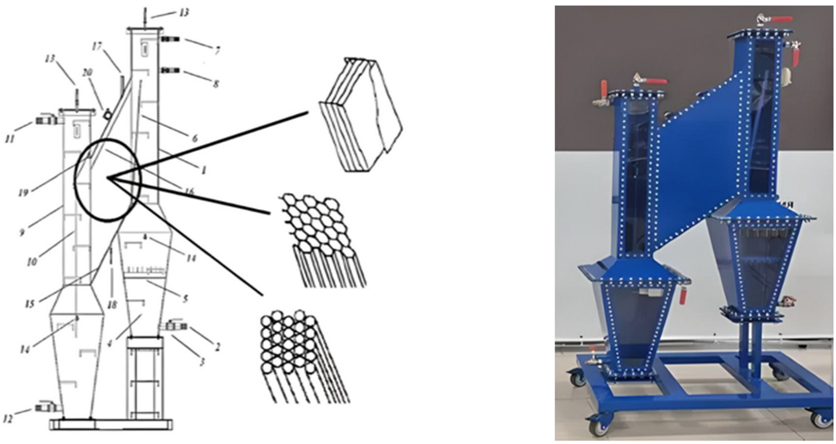
For the production of samples-beams of cement-sand mortar, polyfraction sand was used (LLC "Polikvartz", Moscow, Russia) with the following characteristics: silicon oxide content – 98%; humidity 0.1%; weight loss during calcination – 0.4%.

For the manufacture of concrete mixes and concrete, large and small aggregates were used. Sandstone crushed stone was used as a large aggregate (Granit LLC, Krasny Sulin, Russia) with the following characteristics: particle size – 5-20 mm; bulk density – 1378 kg/m^3; apparent density – 2561 kg/m^3; resistance to fragmentation – 12.7 wt%; the content of lamellar and acicular grains – 8.7 wt%; voids – 45%. Quartz sand was used as a fine filler (LLC "DON-RESOURCE", Kagalnik, Russia) with the following characteristics:

fineness modulus – 1.64; bulk density – 1455 kg/m3; the content of dust and clay particles – 0.4% content of clay in lamps – 0.13%.

Methods

Wastewater treatment was carried out in the developed phase dispersion separator in several stages: mechanical cleaning, coagulation, thin-layer sedimentation, clarification in the suspended sediment layer [37]. In addition, it provided for the removal of floating substances, settling contaminants, oil and petroleum products, as well as gas impurities in the pressure and non-pressure modes of operation of the installation. The appearance and schematic diagram of the Pyramid N phase separator are shown in Fig. 1.



(a) (b)

Fig. 1. Phase separator «Pyramid N» for wastewater treatment with a replaceable block of thin–layer modules: (a) scheme (1 – housing of the flocculation zone and flow stabilization (column 1), 2 – the feed pipeline of the source wastewater, 3 - the reagent supply point with a metering pump, 4 – the zone of the suspended filter, 5 – the directional partition, 6 – adjustable partition of clarified wastewater with inlet distribution windows, 7 – pipeline for the discharge of petroleum products in pressure mode, 8 – pipeline for the discharge of petroleum products in non-pressure mode of operation of the installation, 9 – the tank (column 2), the second in the course of the movement of the liquid to be cleaned, 10 – the guide partition of the wastewater standing in the thin–layer module, 11 – the pipeline for the discharge of treated wastewater, 12 – the sludge discharge pipeline, 13 – gas discharge pipelines, 14 – sampling control points, 15 - the thin–layer sedimentation chamber, 16 - thin-layer modules, 17 – fittings for flushing the interstitial space of thin–layer modules, 18 – a pipeline for the discharge of washing water and sludge, 19 – a pipeline for the discharge of gases and petroleum products, 20 - an interceptor device and the removal of floating substances); (b) installation photo

A distinctive feature of this installation is a replaceable block of thin-layer modules. Thin–layer modules in the block are presented in three design variants:

– tubular with thin-layer elements in the form of pipes of circular cross-section;

– tubular with thin-layer elements in the form of pipes of polygonal cross-section;

– plate (shelf), when thin-layer elements are formed by flat shelves.

Thin-layer modules in the form of flat shelves were made of rigid sheet materials (steel 20). Thin-layer tubular and polygonal modules were manufactured on a 3D printer with PICASO 3D Polygon X™ software installed from PETg Standart material. The technical characteristics of 3D printing of thin–layer modules of tubular and polygonal cross-sections are presented in Table 2, and their appearance is shown in Fig. 2.

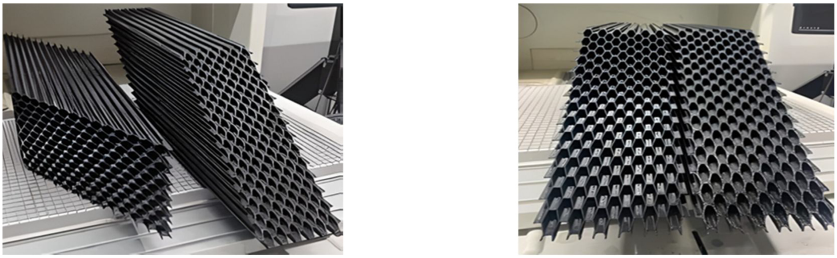
Table 2.

Technical characteristics of 3D printing of thin-layer modules of tubular and polygonal cross-section for the "Pyramid N" phase separator

The name of the indicator	Value
Heat Resistance (°C)	70
Shore hardness	76
Rockwell Hardness	R106
Elongation at break (%)	260
Tensile modulus of elasticity (MPa)	2100
Maximum tensile strength (MPa)	74
Softening temperature according to VIC (°C)	70
Density (g/cm^3)	1.29
Shrinkage in the manufacture of products (%)	0.3–0.6
Manufacturing method	3D printing, gluing – chemical bonding using dichloromethane
Extrusion temperature (°C)	215–245
Table temperature (°C)	20–80

The assessment of the quality of wastewater obtained after washing concrete mixing equipment, after cleaning on a phase–dispersed separator "Pyramid N" was carried out in accordance with the requirements of [38; 39].

Computer simulation of fluid movement was performed using the program ANSYS 2022 R1 (22.1.0.2021111419), taking into account the main technological characteristics of contaminants with a degree of dispersion of more than 10-1 microns (suspensions) - hydraulic size particles (U0) (the rate of its free deposition in water at t = 20 °C), which is the main indicator for determining the size of settling tanks.



(a) (b)

Fig. 2. Appearance of replaceable thin-layer modules of tubular and polygonal cross-section made on a 3D printer: (a) general view; (b) cross-section

The value of the hydraulic particle size was determined by the formula:

$$\sqrt{\frac{\pi}{6} d \frac{\rho-\rho_{\text{в}}}{\rho_{\text{в}}} g \frac{1}{\Psi}}, \qquad (1)$$

where d – particle diameter (m);

ρ, $\rho_{\text{в}}$ – density of the particle material and water (kg/m^3);

g – acceleration of gravity (m/s^2);

Ψ – coefficient of resistance.

The resistance coefficient generally depends on the shape of the particle and on the Reynolds number (Re). For laminar mode Ψ:

$$\Psi = \frac{3\pi}{Re}, \qquad (2)$$

where Re is the Reynolds number.

Then formula (1) was transformed into the Stokes formula:

$$U_0 = \frac{1}{18} g \frac{\rho - \rho_{\text{в}}}{\mu} d^2 \qquad (3)$$

where μ is the water viscosity coefficient (kg/(m *s)).

In the turbulent mode, the resistance coefficient does not depend much on Re. In this case, the determination of the hydraulic size is carried out as follows:

– the Archimedes number (Ar) is determined by the known values of d, p, μ and by the formula:

$$Ar = \frac{Re^2}{Fr} = \frac{d^3(\rho - \rho_{\text{в}})\rho_{\text{в}} g}{\mu^2} \qquad (4)$$

where Fr is the froude criterion;

μ is the coefficient of dynamic viscosity (Pa· s).

To assess the possibility of using purified wastewater in the production of concrete mixtures and concretes, samples of the control composition on tap water and samples on purified wastewater were made. The designs of mixtures for the production of samples are presented in Tables 3 and 4. The experimental research program is shown in Fig. 3.

Table 3.

Design of cement-sand mixture

Treated waste water (ml)	Tap water (ml)	Sand (g)	Portland cement (g)	Type of composition
–	225	1350	450	1C
225	–	1350	450	1A

Table 4.

Concrete mix design

Type of composition	The proportions of the concrete mixture on 1 m^3				
	Portland cement (kg/m^3)	Tap water (l/m^3)	Purified waste water, (l/m^3)	Crushed stone (kg/m^3)	Sand (kg/m^3)
2C	346	200	–	1078	703
1B	346	–	200	1078	703

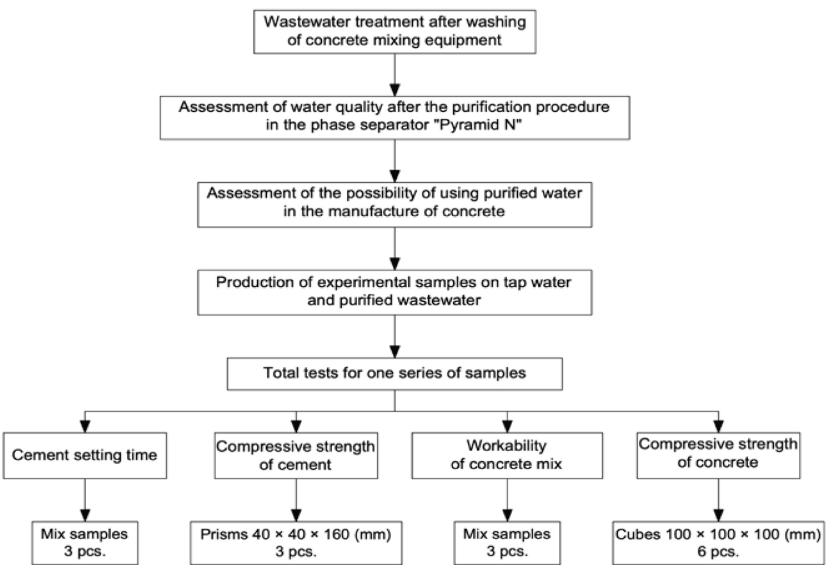


Fig. 3. Experimental research program

The beam samples were made as follows. The sand was poured into the metering device of the mixer. Water was poured into the mixer bowl previously wiped with a damp cloth and cement was added, after which the mixer was turned on and the mixing procedure was carried out. Then the resulting mixture was placed in a mold and compacted. The finished samples were stored in a wet hardening chamber for 1 day, then removed from the molds and the remaining 27 days were stored in a bath with water.

The production of concrete mix and concrete samples included the following basic technological operations: dosing of all raw components and their preliminary mixing in dry form; introduction of mixing water and mixing of the entire mixture to a homogeneous state; laying of the concrete mix into molds and compaction by vibrating for 60 seconds

The following basic testing and processing equipment was used for the production of samples, as well as their testing:

– laboratory concrete mixer BL-10 (LLC "ZZBO", Russia, Chelyabinsk region, Zlatoust);

– automatic mortar mixer (E093) (RNPO "RusPribor", St. Petersburg, Russia);

– HT-5000 laboratory scales (NPP Gosmetr, Saint Petersburg, Russia);

– Vika device (LLC "MOK", Ulyanovsk, Russia);

– cube shapes 2FK-100 and beam shapes 3FB-40 (RNPO "RusPribor", St. Petersburg, Russia);

– normal hardening chamber KNT-1 (RNPO "RusPribor", St. Petersburg, Russia);

– laboratory vibration platform (IMASH, Armavir, Russia);

– hydraulic press "P-50" ("NPK TECHMASH", Neftekamsk, Republic of Bashkortostan, Russia). The setting time of cement and its compressive strength were evaluated in accordance with the requirements of [40-42]. The workability of the concrete mix was evaluated in accordance with the requirements of [43, 44].

The compressive strength of concrete was evaluated in accordance with the requirements of [45-49].

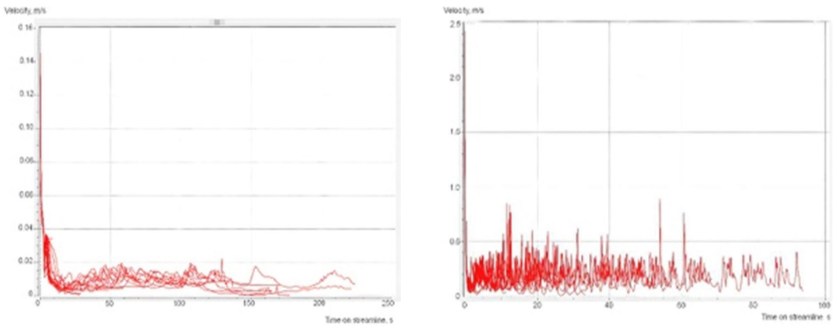
Results and discussion

The principle of operation and evaluation of the efficiency of the phase separator "Pyramid N"

Data on the residence time of the treated water in each compartment of the phase separator – chamber 1, chamber of thin-layer sedimentation, chamber 2 are shown in Fig. 4, 6, 8. In these figures, you can also observe characteristic changes in the speed mode of the water trickle during the entire period of stay in the separator compartment. The simulation results in this case are given for a thin-layer settling chamber of a plate (shelf) type.

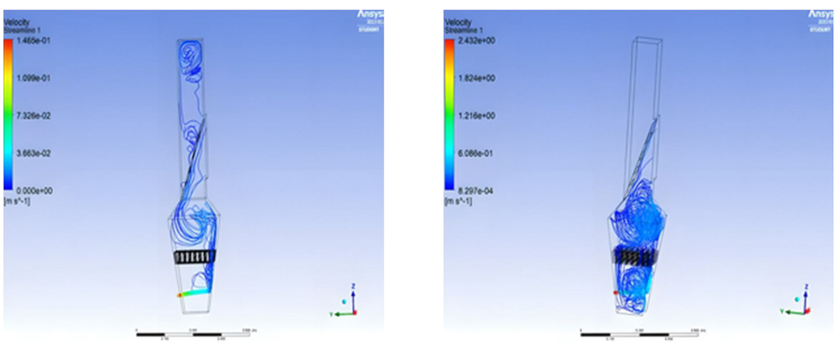
Thin-layer modules in the thin-layer settling chamber and the separating partition in the jet (Fig. 5, 7, 9) in the course of fluid movement in the column allow to achieve laminar fluid flow, that is, they serve as a flow rectifier.

The graph of the water trickle velocity fluctuations over the time spent in column 1 is shown in Figure 4, and the vector of water velocities in 3D format in column 1 is shown in Fig. 5.



(a) (b)

Fig. 4. Graph of water trickle velocity fluctuations over the time spent in column 1 at: (a) capacity Q = 0.5 m³/h; (b) capacity Q = 1.0 m³/h



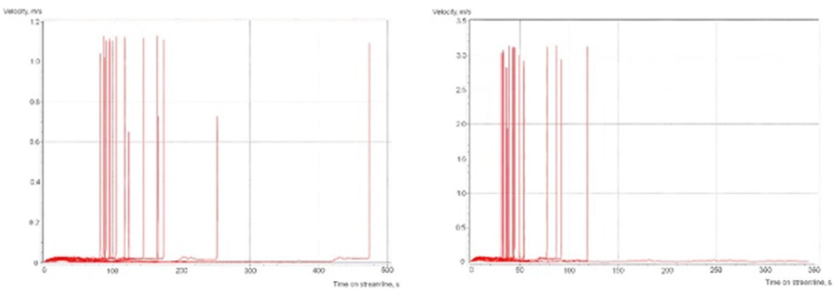
(a) (b)

Fig. 5. Vector of water velocities in 3D format in column 1 at: (a) capacity Q = 0.5m³/h; (b) capacity Q = 1.0 m³/h

A flow rectifier is a device for eliminating or reducing radial components of the flow velocity and obtaining a steady-state velocity profile. The flow rectifier is used to reduce the degree of turbulence of the flow. For shelf thin-layer elements, the flow rate is maintained 5-10 mm/s.

Analyzing the data of computer simulation of fluid motion in column 1 at capacities Q = 0.5 m3/h and Q = 1.0 m^3 / h (Fig. 4 and 5), it was found that the residence time of the trickle in the first case is t = 225 s at a velocity of υ = 0.01 m/s, and in the second case t = 94 s at a speed of υ = 0.05–0.45 m/s. It is also possible to observe, at a capacity of Q = 1.0 m^3/h, intense vortex formation throughout the entire volume of the column at pulsating speeds in the range of 0.05 -0.9 m/s, at the same time, at a capacity of Q = 0.5 m3/h, a laminar regime with insignificant vortex formation was established in the column. Based on the recommended value of the mixing time of the reagent supplied to column 1, t = 120 s, the optimal range of performce ensuring stable contact of the treated liquid and the reagent is the performance Q = 0.5–0.8 m^3/h.

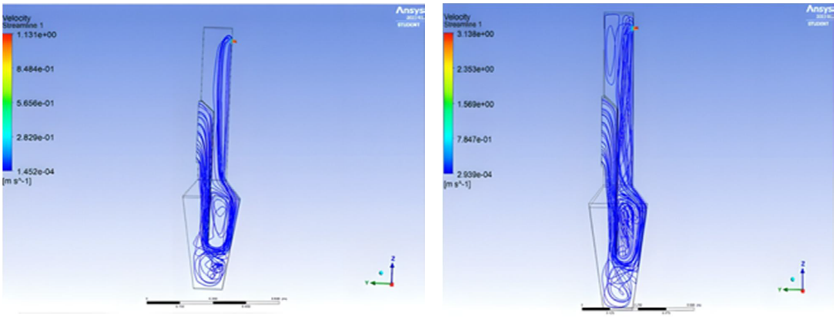
In a tubular chamber (the cross section of the tubular sections was hexagonal and round) of thin-layer sedimentation, the tiers of the thin-layer module are divided into separate channels in the form of pipes (Fig. 6 and 7). Figures 8 and 9 show a graph of fluctuations in the velocity of a trickle of water over the time spent in a thin-layer sedimentation chamber and a vector of water velocities in 3D format in a thin-layer sedimentation chamber, respectively.



(a) (b)

Fig. 6. Graph of water trickle velocity fluctuations over the time spent in column 2 at: (a) capacity Q = 0.5 m^3/h; (b) capacity Q = 1.0 m^3/h

In such a design, it is easier to achieve laminar water flow. These modules are normally operated at high flow rates, but they also have disadvantages: rapid siltation by precipitation, difficulty in cleaning, increased material consumption. The speed of fluid movement in the tubular elements of the settling chamber is up to 20 mm/s. The angle of inclination of the tubes is up to 60°. In this case, the phase separator will be periodic.



(a) (b)

Fig. 7. Vector of water velocities in 3D format in column 2 at: (a) capacity Q = 0.5 m^3/h; (b) capacity Q = 1.0 m^3/h

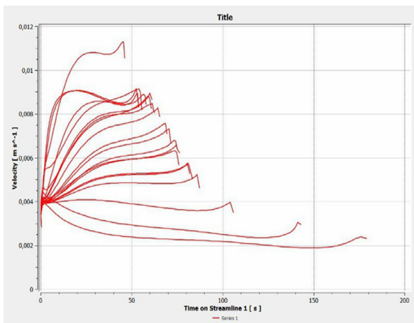


Fig. 8. Graph of fluctuations in the water trickle velocity over the time spent in the thin-layer settling chamber at a productivity Q = 0.5m^3/h

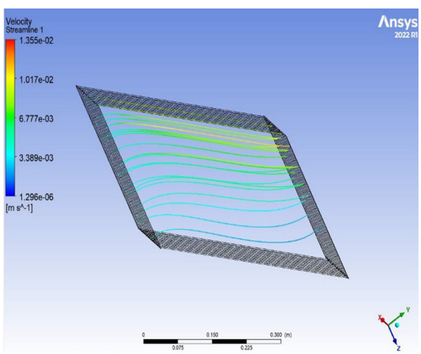


Fig. 9. Vector of water velocities in 3D format in a thin-layer settling chamber at a productivity Q = 0.5 m^3/h

The settling period alternates with the period of cleaning the tubes from sediment. For this purpose, the installation provides flushing fittings for thin-layer modules and a flushing water outlet pipeline. A phase separator equipped with tubular thin-layer modules is advisable to use for the purification of slightly polluted waters with a flow rate of source wastewater from 100 m^3/day to 10000 m^3/day. The effectiveness of thin-layer sedimentation is maintained in the range of 80-85%.

As mentioned above, the simulation of fluid flows was carried out with a thin-layer settling chamber of the plate (shelf) type installed at a capacity of Q = 0.5 m3/h as the most optimal. In Figure 8, according to the data of the graph of fluctuations in the velocity of the water trickle over the residence time, an uneven distribution of velocities can be observed along the height of the module – from v = 0.0023 m/s at t = 175 s in the lower part of the chamber, v = 0.006 m/s at t = 75 s in the middle part of the chamber and up to v = 0.015 m/s at t = 45 s in the upper part of the chamber. However, as shown in Figure 7, by means of a guide partition of wastewater standing in a thin-layer module, such a high-speed unevenness is smoothed out and the liquid flow reaches the bottom of the column 2 in laminar mode.

Regarding the data on column 2 (Figures 6 and 7), it can be concluded that the residence time in it t = 470 s with a capacity Q = 0.5 m3/ h is sufficient for precipitation. With a capacity of Q = 1.0 m3/h, the residence time is slightly lower – t = 345 s, and there is also a more uneven flow distribution in the second compartment of the column, which can negatively affect the quality of treated wastewater treatment.

The properties of the waste water obtained after washing the concrete mixing equipment, after cleaning on the phase-dispersed separator “Pyramid N” are presented in Table 5.

Table 5.

Properties of wastewater after purification on a phase dispersed separator

Name of the characteristic	Actual value	Normalized values of water after purification for mixing concrete mixture [38]
Suspended solids	189±3 mg/l	200 mg/l
Soluble salts	1.36±0.2 mg/l	2000 mg/l
Hydrogen pH	6.3-8.2	4-12
Sulfates SO_4^{2-}	547±0.02 mg/l	600 mg/l
Chlorides Cl^-	285 mg/l	300 mg/l

Based on Table 5, it can be seen that the wastewater obtained after washing the concrete mixing equipment, having passed the purification process on the phase-dispersed separator "Pyramid N" according to such basic indicators as the content of suspended particles, soluble salts, sulfates and chlorides meet the requirements [38] and can be used for the manufacture of concrete mixtures and concretes.

Investigation of the effect of purified wastewater after washing concrete mixing equipment on the properties of cement composites

The test results of cement and concretes made on wastewater purified in the Pyramid N phase-dispersed separator are shown in Figures 10 and 11 and in Table 6.

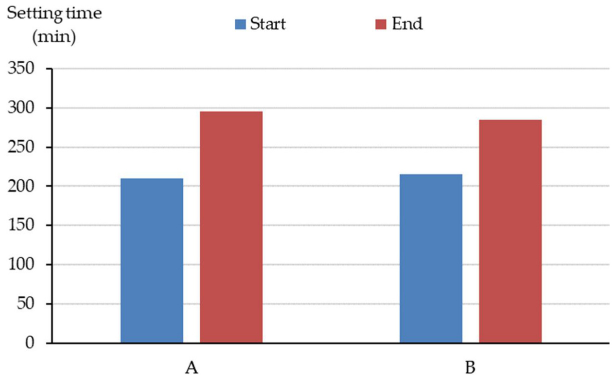


Fig. 10. Cement setting time (A – samples were made using tap water; B – samples were made using purified wastewater)

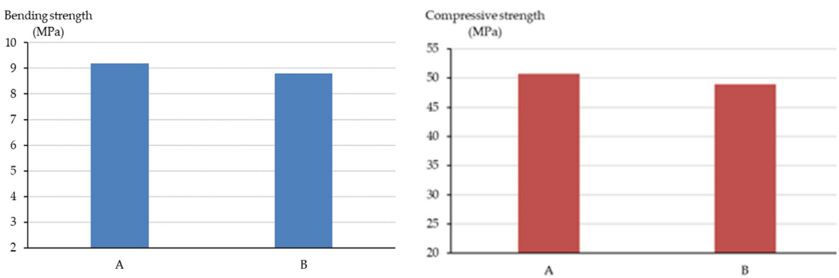


Fig. 11. Bending strength (a) and compressive strength (b) of cement-sand mortar beam samples (A – samples were made using tap water; B – samples were made using purified wastewater)

The process of determining the bending and compressive strength of the beam samples is shown in Fig. 12.

(a) (b)

Fig. 12. The process of testing beam samples: (a) flexural strength; (b) compressive strength

Table 6.

Results of determination of density, workability and compressive strength of concrete mixtures

Type of sealing water	Cone sediment [44] (cm)	Compressive strength (MPa)
Tap water	3.1±0.3	46.3±2.9
Treated wastewater	3.4±0.3	45.7±2.4

The analysis of the results showed that the difference between the setting periods ranged from 2.4% for the beginning of setting to 3.4% for the end of setting. The beginning of setting for samples on purified wastewater came a little later, and the end of setting earlier than for samples on tap water. The bending strength and compressive strength of the samples on purified wastewater after washing the concrete mixing equipment are 4.3% and 3.6% less, respectively, than the samples on tap water. From the analysis carried out, it was found that the setting time and flexural and compressive strength of samples made using tap and purified wastewater after washing concrete mixing equipment are comparable and practically do not differ from each other. Also, visually analyzing the nature of the destruction of the samples and their macrostructure (Figure 12), no significant differences were found between the samples on tap and treated wastewater.

The process of determining the compressive strength is shown in Fig. 13.

According to the test results presented in Table 6, the workability of concrete mixtures and the compressive strength of concretes made with purified wastewater are comparable to these characteristics recorded in concrete mixtures and concretes made with tap water. The draft of the cone is 9.7% more, and the compressive strength is 1.3% less for the concrete mixture on purified water in comparison with tap water. The nature of the destruction of concrete samples (Fig. 13), similar to the samples of cement-sand mortar (Fig. 12), did not reveal significant differences between the compared samples on tap and treated wastewater. Accordingly, the wastewater purified in the Pyramid N phase-dispersed separator in full can be used for the re-manufacture of concrete mixtures and concretes.

(a) (b)

Fig. 13. Press testing of concrete samples: (a) before destruction; (b) after destruction

The working hypothesis about the use of treated wastewater in concrete technology and the confirmation of this hypothesis is in good agreement with the works of other authors, namely [34; 50; 51-53]. In [34], purified wastewater was used for the manufacture of concretes, and all concretes made with such water are durable based on the results of tests for the permeability of chloride ions. Concretes with waste of blast furnace granulated slag and granite powder made on purified wastewater [50] showed strength comparable to control samples. In the works [51; 52], concretes made with the use of treated wastewater also demonstrate good physical and mechanical characteristics.

The development and introduction into the production of a concrete mixture of a process for the treatment of wastewater generated during the washing of equipment using a phase separator "Pyramid N" will not only ensure their lawful discharge, but also immediately after purification to send them to the recycling water supply system, which will lead to a significant reduction in water costs and more efficient use of natural resources, which corresponds to the concept of sustainable development [54-56]. It should also be noted that the installation of the Pyramid N phase separator can be used as an independent purification system with subsequent post-treatment to achieve optimal quality of the treated water, or integrated into an existing water purification system in order to improve it. As has been confirmed by studies [37; 57], the installation includes three stages of cleaning at once. At the same time, based on the quality of incoming waters, it is possible to intensify their treatment by selecting a thin-layer module with an appropriate cross-section shape.

The performed research is consistent with the research conducted earlier by other authors, but at the same time has scientific novelty, as well as engineering practical novelty. The scientific value and scientific novelty of the research lies in obtaining fundamentally new dependencies, models and data that form the basis of theoretical research on further improvement of wastewater treatment technology, as well as on the use of various kinds of waste and recycling in concrete technology [51, 58-60]. The significance of engineering or practical lies in the fact that the information obtained is transformed into an applied development that already has patent protection and at the same time is a proven engineering task in practice [61]. Thus, the prospects for the development of the study lie in the direction of further study of wastewater treatment technology, as well as the use of waste water treatment, including water after the implementation of such technologies when reused in concrete mixtures. Such recycling will significantly reduce the cost of production of concrete mixes, increase the environmental friendliness of construction and production, as well as engineering solutions for water treatment. This can be useful for the construction industry in terms of a cheaper version of concrete, for greening the environment in terms of reuse and establishing waste-free production, as well as for the manufacturing industry in terms of establishing more economical and environmentally friendly technologies, which will have a positive impact on all aspects and stages of the life cycle of the production and construction industries [55; 62].

Conclusions

Based on the results of the study, the efficiency of the Pyramid N phase separator was evaluated for the treatment of wastewater generated during the washing of concrete mixing equipment, as well as the possibility of reuse of purified wastewater for the manufacture of concrete mixtures and concretes. For this purpose, an assessment of the quality of water purified at the Pyramid N phase separator and the possibility of using purified wastewater in the manufacture of concrete mixtures and concretes have been implemented. At the same time, the theoretical principles of preliminary separation of contaminants in various aggregate states before post-treatment plants have been developed, which formed the basis of the phase dispersion separator, and new calculated dependences based on the model of fluid flow in the Pyramid N phase separation plant with an acceptable statistical error have been obtained, which describe experimental data on the disaggregation of pollutants in the practice of cleaning industrial waste water.

The conclusions of the study are as follows.

(1) The installation of the Pyramid N phase separator for wastewater treatment with a replaceable block of thin-layer modules has been upgraded.

(2) Several types of replaceable thin-layer modules have been developed: flat shelves, tubular section, polygonal section. The methods of their manufacture are described and their effectiveness is evaluated. Thin-layer modules of tubular and polygonal cross-section are more effective in comparison with modules in the form of flat shelves. The fluid velocity in the tubular elements of the settling chamber can reach up to 20 mm / s, and in the shelf thin-layer elements up to 10 mm/s.

(3) The quality of wastewater after purification in the Pyramid N phase separator according to the main indicators, namely the content of suspended particles, soluble salts, sulfates and chlorides meets the requirements of regulatory documentation.

(4) The possibility of using purified wastewater for the manufacture of concrete mixtures and concretes has been experimentally evaluated and proven. The timing of cement setting and its flexural and compressive strength, the workability of concrete mixtures and the compressive strength of concretes made using tap water and purified wastewater showed equivalent results. The difference between the strength characteristics ranged from 1.3% to 4.3%, and between the characteristics of fresh concrete – from 2.4% to 9.7%.

The practical significance of the study lies in a significant reduction in water costs and more efficient use of natural resources, which corresponds to the concept of sustainable development. The prospects for the development of the study lie in the direction of assessing the durability properties of concretes in which purified wastewater is used in comparison with tap water concretes, as well as in the direction of using purified water for the manufacture of other types of building composites.

Conflict of interest information. The authors of this work declare that they have no conflicts of interest.

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