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DEVELOPMENT OF TECHNOLOGY FOR THE PREPARATION OF HEAVY-DUTY CONCRETE MIXTURES BY PROCESSING WITH AN ULTRASONIC MULTI-FREQUENCY ACOUSTIC FIELD

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The article presents the results of a study of the use of ultrasonic technologies to increase the strength of cement mortar in the production of building and concrete structures, as well as to improve the rheological parameters of grouting mortar during the construction (drilling) of wells. During the experiment, the concrete mortar was treated for 3 minutes with an ultrasonic multi-frequency acoustic field (frequency 20.0 - 40.0 kHz, signal power - 200-400 W/dm^3) in devices of various geometric shape. Ordinary Portland Cement (OPC) of class G-100 was used in the composition of the solution without plasticizer additives in order to exclude their influence. The ratio of water and cement in the solution was 0.44, the density - 1.90 g/cm^3. Typical elements of flow channels were used as volumes where ultrasonic exposure is carried out. The hydrodynamic regime of the processes in the water-cement suspension was modeled at the beginning of the experiments by slow mixing with a paddle agitator (200 rev./min), and on closing stage, in order to prevent the effect of hydrodynamic cavitation failure, at a speed of 1000 rev./min. The maximum compression and bending stresses are measured after the mixture solidified in a steam bath (T =60°C, 24 h.) on a hydraulic stand. Conducted experiments have confirmed that ultrasonic exposure using resonant accumulators and flow hoses: has a positive effect on the hydration reaction and the structure of cement stone in the concrete sealing phase; accelerates the intensity of compressive strength. (from 24.3 MPa to 41.5 MPa); uniformity of structure; reduces the influence of temperature on strength gain (reduces energy consumption); increases the reliability of building structures, and in the case of well construction - provides a strong adhesion of the production column with rock. In general, the results of the study allowed: to formulate a technology for the production of heavy-duty concrete mixtures; to develop a set of equipment for the preparation of concrete (grouting mortar) with specified characteristics at production objects.

Keywords: ultrasonic multi-frequency acoustic field, high-strength concrete mix, water separation of mortar, cement stone (paste), compressive and bending strength of concrete mix

1 INTRODUCTION

Concrete mortars (products) occupy the main share in construction costs, therefore new technologies are required to improve their strength characteristics and accelerate solidification. The solution of these issues is due to the need to increase technological efficiency (reduction of shrinkage deformations, crack resistance of concrete), economic (reduction of energy consumption, cement consumption, decrease of construction time, the corrosion rate of reinforced concrete structures), as well as reduction of CO2 emissions within the framework of the UN Sustainable Development Concept. According to many researchers [1] – [14] one of the ways to achieve hydration acceleration is the treatment of a water-cement suspension with an ultrasonic multi-frequency acoustic field, which allows you to control the hardening of cement dough, its physicochemical properties, increasing the spread ability and plastic strength, contributing to the acceleration of the process of concrete structure formation.

The quality of concrete is determined, first of all, by the properties of cement dough (stone), which binds the filler grains into a monolith. Cement is the most expensive and energy-intensive component of concrete, but its potential is not used when using traditional technologies, since about 40% of clinker components do not participate in the hydration process [7]. In this regard, it becomes necessary to increase the intensity of cement hydration and concrete hardening by creating a strong cavitation mode due to an acoustic wave with an energy exceeding 7 W/cm2, and with a significant proportion of water in the structure of the solution - over 1.0-1.5 W/cm2. Ultrasound causes shock waves that accelerate the movement of particles and their collision, which in turn leads to an acceleration of water separation, a decrease in the granularity of the solution, and an increase in its uniformity. The formation of products of hardening occurs through the course of complex processes of structure formation: dissolution and hydration of cement materials with the formation of supersaturated solutions; spontaneous dispersion of minerals to colloidal particles; formation of thixotropic coagulation structures and, finally, the emergence, growth and hardening of crystallization structures [4].

As for the preliminary ultrasonic activation of water, in this case it is also worth noting an improvement in its quality, as well as the quality of the solution mixed on it [15] – [22]. The mechanism of cavitation in water is the same as in concrete mortar - due to alternating waves of high and low pressure generated by ultrasound. The difference lies in the cavitation threshold, which depends on the parameters characterizing the ultrasound and the liquid itself. So, for water, the cavitation threshold raising with an increase in the frequency of ultrasound and a decrease in the exposure time. At frequencies above 20 kHz, the threshold of unstable cavitation is in the signal intensity range from 0.3 W/cm2 to 1.4 W/cm2, as well as over 2.5 W/cm2 [15]. An increase in intensity to 1.5 W/cm2 leads to a violation of the linearity of the vibrations of the bubble walls - a stable cavitation stage begins, occurring in the region from 1.5 W/cm2 to 2.5 W/cm2. At this stage, the bubble itself becomes a source of ultrasonic vibrations, waves, microcurrents, and electrical discharges appear on its surface [20]. In aqueous solutions, intensive formation of atomic ozone occurs and, as a result, complete degassing of water, a change in the pH level [21]

The best hydration of cement particles occurs in the range of stable cavitation occurring in the low frequency region. Therefore, it is best to activate the mixing fluid of concrete mixtures with low-frequency ultrasound, which is due to the following factors: firstly, the frequency of 20 kHz is taken as the lower limit of the occurrence of ultrasonic vibrations; secondly, in the low-frequency region (20 -100 kHz), the range of ultrasound intensities to create stable cavitation lies, as indicated above, in the 1.5-2.5 W/cm2. When the signal frequency is higher than 100 kHz, the effect of a jet of activated water gushing may occur. Ultrasonic activation of the mixing water makes it possible to further reduce the consumption of expensive components (cement and additives) while improving the physical and mechanical properties of concrete [22].

Considering that currently there are no such technologies (complete technical solutions, a set of equipment), the purpose of the study was to study the effect of ultrasonic activation on the characteristics of concrete mortar (compressive strength parameter, the intensity of solidification of the solution) for the subsequent formulation of the conditions of the technological process of concrete production and the development of a set of mobile equipment for its preparation in the conditions of the construction site. For this purpose, tests of ultrasonic treatment of cement suspensions based on Ordinary Portland Cement (OPC) of class G-100 (without additives) were carried out in the frequency ranges of 20, 30, 40 kHz with the creation of a multi-frequency spectrum of exposure; processing methods were worked out (experimental program, technology for measuring and fixing the main characteristics of cement stone), energy and operational parameters of the proposed equipment; the optimal frequencies and time of ultrasonic activation are established.

During the research, an experimental ultrasonic installation created by specialists of Gubkin University and NPO Volna for the treatment of liquid media (emulsions and suspensions) in flow resonant channels was used as a multi-frequency activator, where cavitation is formed by creating converging acoustic fields from vibration planes of various geometric shapes (rectangle, square, circle, triangle), which makes it possible to obtain a high flow of acoustic energy (200 - 400 W/dm3) and a multi-frequency controlled oscillation spectrum. The operation of this installation is based on the principle of the piezoelectric effect, which occurs when the crystal faces are subjected to compression (compression, twisting or bending), and a potential difference occurs on opposite faces. The magnitude of the potential difference is proportional to the degree of deformation. This phenomenon is called the direct piezoelectric effect [23] - [28] acting in the opposite direction. When an alternating voltage is applied to a pair of crystal faces, a mechanical effect of compression and stretching occurs, as a result of which the crystal begins to oscillate. When the frequency of the supplied voltage coincides with the frequency of the natural vibrations of the crystal, the latter begins to resonate and generate ultrasonic waves [27]. The resonant system of the piezo-emitter is multi-frequency, which avoids the phenomenon of a «standing wave» [22]. The main advantages of the proposed installation are: the possibility of processing large (more than 2-3 m3/hour) volumes of high-density suspension (more than ~1.3-1.4 g/cm3) [25]; low specific energy consumption; simplicity and cheapness of the design of rod ultrasonic exciters with power generators; the possibility of creating a controlled mode of simultaneous multi-frequency processing of the suspension, which significantly increases the effectiveness of exposure cavitation on the treated medium.

Concrete samples obtained after treatment were compared with control samples (CS) in which the mixing water was not activated and the mixture was not exposed to ultrasound. Thus, the effect of ultrasonic activation on the characteristics of concrete was revealed.

2 MATERIALS AND METHODS

2.1 Materials

The physical properties of the studied water-cement mortar are presented in Table 1. Ordinary Portland Cement (OPC) of class G-100 ((without additives) was used as the binding element of the solution in the experiments, and the mixing water - tap water, pH = 7.5. This choice makes it possible to exclude the influence of additives on the measurement results, since the issue of their interaction with ultrasonic cavitation wave fields is beyond the scope of this work.

The water/cement ratio in the solution was 0.44, the density - 1900 kg/m^3, the spreading capacity of the solution - 24 cm, the temperature of the cement dough before exposure to ultrasound was 23^0C. Solidification of the solution took place within 24 hours in a steam bath at a temperature of 60^0C, then the samples hardened under normal conditions. The compressive strength of cement stone after a steam bath was 24.3 MPa, bending strength - 5.5 MPa. The solution uses a large filler - crushed gravel of a fraction of 10-20 m, which is sufficient in any construction area, In addition, it best meets the requirements for abrasion.

Table 1. The physical properties of the studied water-cement mortar

The physical properties of the elements of the solution	Meaning
Brand of cement	Ordinary Portland Cement (OPC) of class G-100 (without additives)
Water/cement ratio (W/C)	0,44
The density of the solution (kg/m^3)	1900
Solution temperature (^{0}C)	23
Spreading capacity of the solution (cm)	24
Water separation of the solution at 60°C (%)	2.5
Bending strength of cement stone at 60°C after 24 hours, (MPa)	5.55
Compressive strength of cement stone at 60°C after 24 hours (MPa)	24.3
pH level of cement dough	12.4
Water pH level	7.5

The following equipment was used for the experiments: True Water-141 lever scales, KR-1 flowability cone, Chandler 1250 atmospheric consistometer, PGM-500 press with a water bath for holding samples. The parameters of ultrasonic waves and the energy spectrum were measured using an acoustic wave sensor, which is a piezo crystal disk (diameter 5 mm, thickness -2 mm) with a natural oscillation frequency of about 400 kHz. The sensor is connected to a Velleman electronic USB-oscilloscope for monitoring and recording parameters of operating frequencies up to 60 kHz. The hydrogen factor (pH) of the cement dough was determined by the device «Testo-206».

In the first part of the study, in order to establish the influence of the technological and design parameters of the ultrasonic exciter on the effectiveness of ultrasonic activation of the mixture, the volumes of the treated mixture, the location of the emitter, the shapes of the flow channels (rectangular, triangular, square, pentagonal, round, etc.), signal power (200-400 W/dm^3), frequency (20.0-40.0 kHz) were changed and geometric shapes of containers (ultrasonic baths). In the second part, the change in the characteristics of the mixing water of the solution after acoustic activation and the corresponding changes in the cement dough were additionally studied. At the third stage, the results obtained made it possible to develop a mobile complex of construction site equipment for the preparation of heavy-duty concrete mortar using ultrasonic treatment with a multi-frequency acoustic field.

2.2 Methods

The developed ultrasonic technology for the preparation of concrete mixture includes 4 technological stages, the results of which are reflected in Table 2: ultrasonic activation of the applied water; preparation of cement dough; multi-frequency ultrasonic mixing of concrete mixture; supply of concrete mixture to the laying site.

Table 2. The main advantages of using ultrasonic technologies in the process of preparing a concrete mixture in the context of technological stages

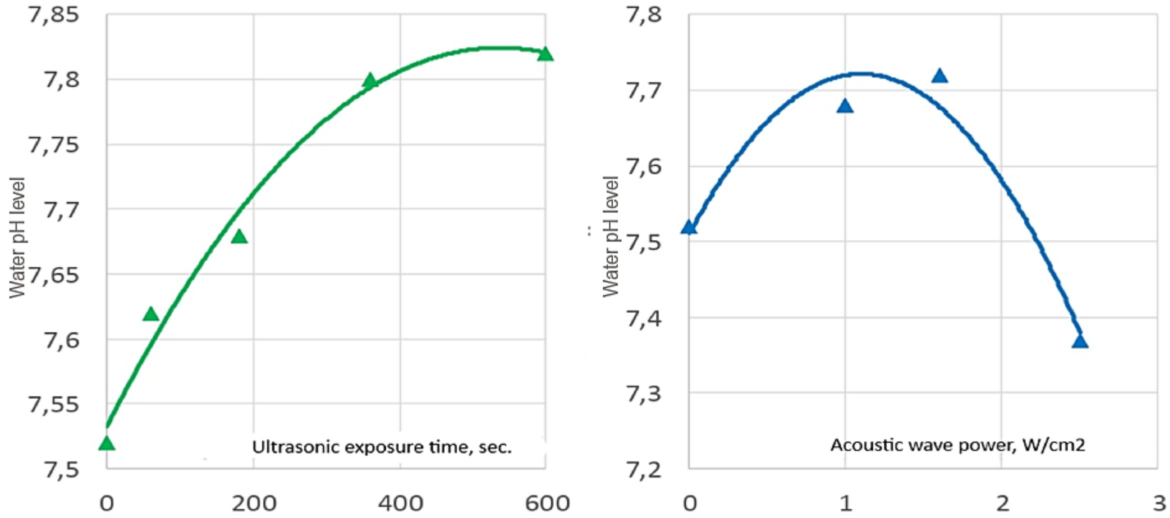
Technological stage	Achievable benefits
Ultrasonic activation of the applied water	Degassing of water Dissociation by water molecules The ability to adjust the pH level Increased electrical conductivity, which accelerates hydration
Preparation of cement dough	Multi-frequency ultrasonic sealing Destruction of cement floccules. Improving the effectiveness of the hydration reaction The ability to control the structure of cement dough. Increasing the plasticity of cement dough Regulation of setting time
Multi-frequency ultrasonic mixing of concrete mix	Improving the uniformity of concrete (reduction of water separation, reduction of intergranular voidness, degassing)
Supply of concrete mix to the installation site (when creating multi-frequency controlled acoustic fields of increased power)	Additional improvement of concrete uniformity indicators Reducing the consumption of cement dough with the same strength of concrete Increasing the strength of concrete

In general, the sequence of experiments to study the effect of ultrasound on the strength characteristics of concrete is as follows: activation of water, preparation and sealing of a water-cement mixture in a desiccator (or directly in an ultrasonic bath); ultrasonic mixing with a fixed specific energy capacity and modeling of hydrodynamic flows; measurement of parameters of ultrasonic waves and the energy spectrum; filling with a water-cement mixture of special forms for subsequent measurements of physical and mechanical parameters of concrete mix..

3 RESULTS AND DISCUSSION

3.1 Ultrasonic treatment of mixing water

The treatment of the sealing water was carried out by a multi-frequency ultrasonic generator. It was found that the primary effect of ultrasound is aimed at changing hydrogen bonds, «loosening» the structural framework of water [8, 9]. Longer activation improves the hydrogen index (pH), surface tension, electrical conductivity, redox potential, refraction index, etc., thereby having a significant effect on the cement hardening process and improving the properties of cement mortar. The frequency of exposure was brought up to 40 kHz, the time - up to 600 min, the signal power - up to 3 W/cm². The results of changes in the hydrogen index (pH) of tap water from the time and power of acoustic exposure to are shown in Fig 1 (a), (b).



(a) (b)

Fig. 1. Dynamics of the hydrogen index (pH) during acoustic activation of tap water depending on: (a) exposure time, sec.; (b) acoustic signal power, W/cm² (frequency 20 kHz)

The results of the experiment show that with an increase in the duration of exposure to 500 min, the pH level increases from 7.52 to 7.83, and then begins to decrease, which allows you to set the optimal exposure time. Studying the effect of signal power on pH, it can be noted. that an increase in the indicator was observed to 1.17 W/cm², then a sharp decline was detected. special forms for subsequent measurements of physical and mechanical parameters of concrete mix.

Water has acid-buffering properties (the constancy of the pH value when weak acids appear in the system, based on the ability of H^+ and OH^--ions to spontaneously bind to a poorly dissociated H_2O molecule, is the relaxation of water molecules). A larger amount of acid or alkali leads to a loss of buffering capacity. For water treated with ultrasound, the initial value of the hydrogen index is pH_0=8.5, which is explained by the destruction of water molecules due to the phenomenon of cavitation. The rupture of the hydrogen and chemical bonds of water molecules led to the formation of fairly stable radicals and ions, as well as to the excitation of water molecules.

After ultrasonic activation of water, the cement dough becomes more plastic, the normal density decreases to 10-12%. The intensity of the compressive strength of the cement dough (stone) changes. (Fig.2).

The greatest increase in strength is achieved on the 28th day of hardening. Moreover, on activated water, the strength increases faster, starting from the third day of hardening, almost twice, and this rate persists throughout the entire observation period. This is explained by the fact that when ultrasonic waves are applied to water, water molecules regroup and create new compounds of oxygen and hydrogen molecules and atoms, which, entering into a chemical reaction (hydration process) with clinker minerals, form a stronger structure than that of control samples.

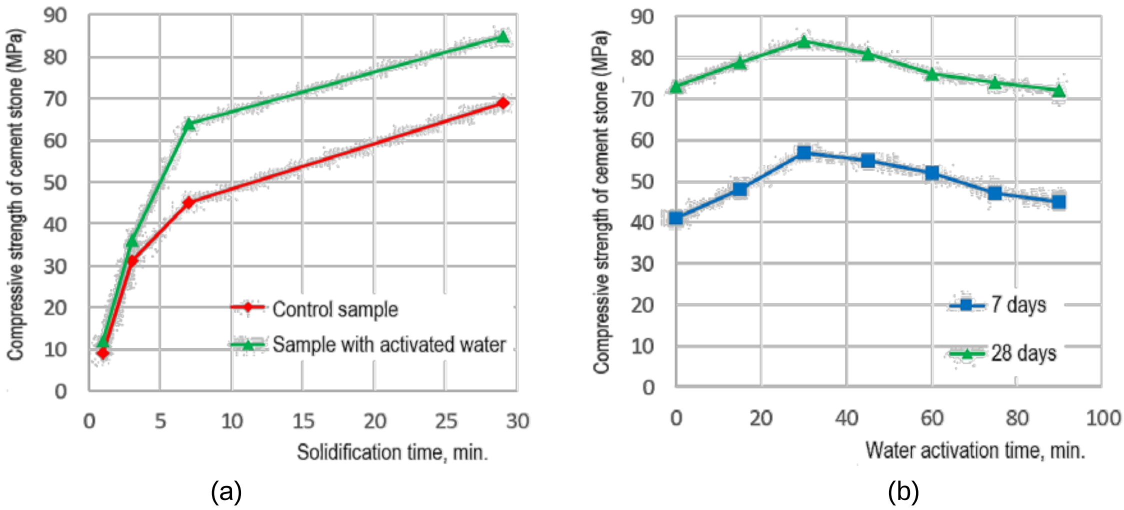


Fig. 2. ((a) Kinetics of cement stone strength set on activated and non-activated sealing water; (b) The effect of the activation time of the sealing water on the compressive strength of cement stone

The metastable state of the ultrasound-treated water is maintained for 5 minutes, then the process of restoring its acid-base equilibrium with water begins. At first, the relaxation processes of water molecules are slow, and then faster. In general, the metastable state of the water persists for 30 minutes. The water-saturated state of the surface (after 5-15 minutes of contact, up to 1.5 hours) reflects the hydration process of Portland cement, consisting of a series of complex physico-chemical processes (wetting, dissolution, hydrolysis). The rate of change of alkalinity and temperature in the suspension based on activated water is almost constant, up to 1.5 hours of contact, which indicates the uniformity of the hydration process. In suspensions based on water treated with ultrasound, the hydration processes proceed uniformly at the same speed, in the first 10 minutes of contact – 1.5-2.0 times faster than in non-activated water.

Experiments have confirmed the opinion of the scientific community [3, 7, 12, 22, 25, 29] that hydration occurs the easier where the forces of attraction between particles in a substance and in a solvent are more comparable. Since there is a large amount of OH^--ions in the activated water, the polarity difference between the activated liquid and the main character of the Portland cement surface will be smaller, therefore, wetting, dissolution, spontaneous dispersion of cement particles to colloidal sizes takes place faster and more completely (crushing goes along the most lyophilic areas of the surface), the subsequent processes of formation of hydration products take place more intensively (the processes in the solution and on the surface of cement grains run in parallel). At the same time, the rapid mixing of ions contributes to the inclusion of the mother liquor into the hydration products, a precipitate of the form $[Me(OH)_n]_m OH^-_y$. This sediment is amorphous, highly porous, loose and hydrophilic, because the ions do not have time to orient themselves, they are arranged chaotically and loosely. This precipitate is amorphous, highly porous, hydrophilic, since the ions do not have time to orient themselves and therefore are arranged chaotically and loosely. An amorphous spatial grid or a metastable gel-like mass with particles of an amorphous structure is formed. The low density of the interlayers favors the penetration of OH^--ions and water molecules through them to the cement grains, the dissolution of deeper layers of cement grains, which increases the volume of the gel-forming component in the intergranular space, reduces the number of unreacted cement grains, and ultimately increases the strength of cement stone.

Thus, ultrasonic multi-frequency treatment of mixing water helps to reduce the normal density (water demand) of cement dough by 10-12% and increase the compressive strength of hardened samples at the age of 7 days to 45%, and at the age of 28 days to 27%. These results confirmed the feasibility of the technology for the production of concrete with ultrasound-activated mixing water with increased strength and durability.

3.2 Preparation of cement dough and multi-frequency ultrasonic mixing of concrete mix

The creation of a control sample of the mixture is carried out in a standard desiccator, by mixing with a Heidolph paddle agitator with an adjustable rotation speed (200 rev/min) for 3-4 minutes until a homogeneous suspension is obtained. Similarly, the solution is sealed in ultrasonic baths of various geometric shapes. Let's consider each of them. as follows:

- 20 kHz bath (Fig. 3). A typical ultrasonic oscillator with an operating frequency of 21.7 kHz of high power is fixed on a square-section vibration plane with a special stud adhesive joint. The dimensions of the square section are calculated in such a way that the first mode of oscillation is close to the operating frequency of the exciter. Three vibration planes (respectively, three vibration exciters) form an element of the flow channel in the transverse plan in the form of an equilateral triangle, which allows converging ultrasonic waves to be received in the center of the flow channel. The working volume is 1.0 dm^3.

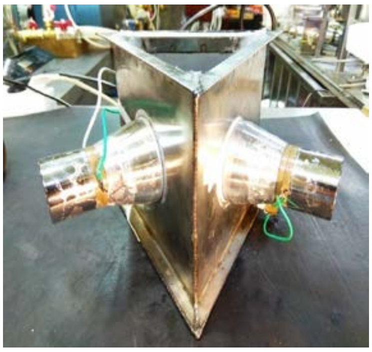


Fig. 3. 20 kHz ultrasonic bath

- 30 kHz bath (Fig. 4). A square-section vibration plane with a smooth transition between all vibration planes. There are 5 active vibration plates in total, each of which has a conventional ultrasonic medium-power exciter with an operating frequency of 30 kHz. In the center of the bath there is a summation of waves from five vibrating planes. The working volume - 1.6 m^3.

Fig. 4. 30 kHz ultrasonic bath. Vibroplane of square

- 40 kHz bath (Fig. 5). A vibrating plate of square cross-section, on each of the four planes of which an ultrasonic exciter with an operating frequency of 40 kHz of average power is installed. In this case, an element of the flow channel is formed in the cross-sectional plan in the form of a square. The working volume is 0,7 dm^3.

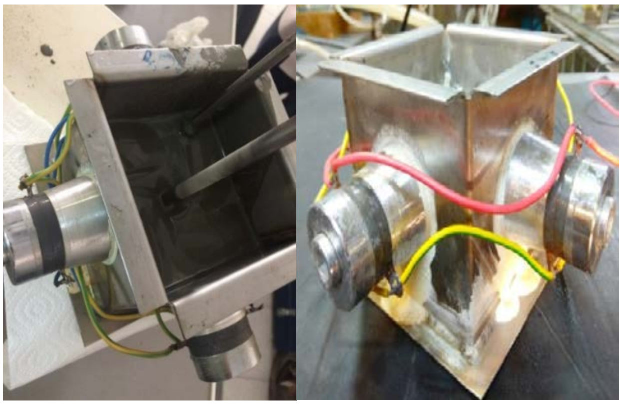


Fig. 5. 40 kHz ultrasonic bath

In the first part of the study, in order to establish the influence of the technological and design parameters of the ultrasonic exciter on the effectiveness of ultrasonic activation of the mixture, the volumes of the treated mixture, the location of the emitter, the shapes of the flow channels (rectangular, triangular, square. It is important that the vibroplane should have specified boundary conditions on pinching, providing conditions for formation of a standing wave. That is why the circular tube (no boundaries, except for the ends) is one of the most difficult in the tuning of vibration systems, because it transforms the vibration energy from ultrasonic exciters to its many frequencies and waveforms.

All 20 kHz, 30 kHz, 40 kHz baths are characterized by the creation of cavitation impact with a linear multi-frequency spectrum, typical for non-linear vibrating systems (in our case vibroplane) with distributed parameters [15], which are the sources of acoustic waves already in the treated liquid medium (water-cement mixture). Nonlinearities are formed by membrane deflections in the attachment points of the ultrasonic exciters (short-term force is up to ~10 kN, duration ~10-100 μs), when a standing wave is reflected from the vibration plane border, the ultrasonic exciter characteristic itself is nonlinear and contains 2-4 characteristic resonances. The denser and more viscous the medium is to be processed, the number of nonlinearities of higher orders decreases (harmonics degenerate) and the main harmonics remain in the wave spectrum.

Since the theoretical calculation of such strongly nonlinear systems, even with parameter modulation as in parametric resonance (PR), is currently practically impossible, the basis for the study are experimental methods, or the use of rod ultrasonic exciters of high and medium power [22]. Such systems are calculated for linear modes of operation (i.e., single or mono-frequency), have actually one advantage - creation of very intense cavitation impact field in a local zone near the transmitter end (usually disk). Creation of controllable multifrequency spectrum in such systems is difficult.

An important point to ensure the reliability of the results of the study was the modeling of the hydrodynamic flow of water-cement mortar at the stage of ultrasound treatment. To prevent the effect of hydrodynamic cavitation breakdown, after the mixing stage, the speed of the agitator was increased to 1000 rev/min It is this speed (10-20 cm/s) that corresponds to the movement of the suspension through an extended ultrasonic channel in the proposed industrial installation. The time of ultrasonic exposure - 3 minutes - is justified by laboratory experiments confirming the achievement of maximum cavitation during this period. Now about ultrasound channels. A direct-flow channel with a capacity of 1-4 dm^3/s, or 7-28 t/h of the prepared water-cement mixture was selected. The length of the through channel, based on the processing time (3 min), will be ~ 18-40 m, power consumption - up to ~ 50 kW.

It is worth noting that in the pre-cavitation mode, the acoustic exposure time reached several hours. So, during the first tests in baths of 20 kHz, 40 kHz, stagnant zones were detected in the corners (zones of coupling of vibration planes), where, due to the high density of the solution (1.90 g/cm^3) and the low speed of rotation of the agitator (~ 200 rev/min), the suspension settled without active ultrasonic treatment. Subsequently, these zones were eliminated by pouring a resistant sealant. This once again indicates the practical importance of selecting and optimizing the hydraulic mode of pumping the working suspension through a cavitation resonant ultrasonic channel. On the one hand, excessive speed (quasi-static mode) of movement and turbulence should not be allowed, on the other hand, each element of the volume should be voiced with maximum intensity.

The experimental results of measuring the amplitude of the wave are shown in Fig. 6. We see a significant effect of ultrasonic activation on the strength of the concrete mixture on bending and compression, improvement of water separation. The processing carried out in the 30 kHz and 40 kHz baths shows that these frequencies are more preferable. In a 20 kHz bath, there is no obvious dependence of the improvement of indicators on the specific processing power. This can be explained by the fact that nonlinear systems have the property of «saturation» [25]..

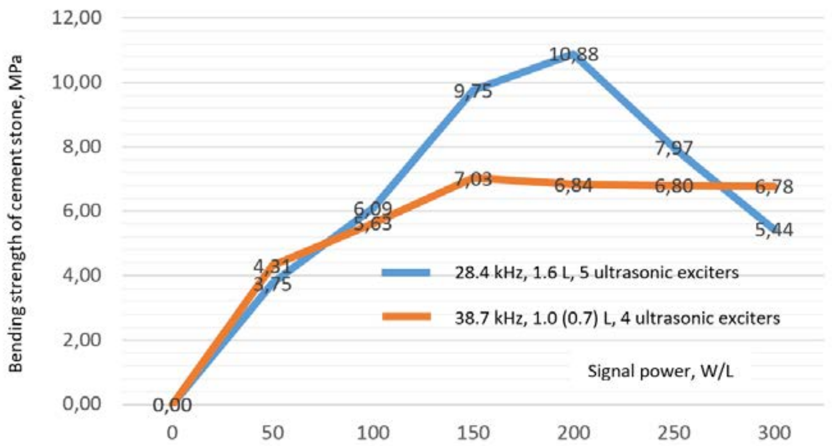


Fig. 6. Dependence of the acoustic wave amplitude on the specific power (determination of the «saturation» effect for acoustic baths 30 kHz, 40 kHz)

It can be seen that for a pure dispersion medium (water), the threshold is ~ 200 W/liter, so this value was taken as the initial value for specific power in experiments. With the addition of cement and an increase in density and acoustic stiffness (the product of density by velocity), this threshold will shift towards higher values. More efficient treatment of the water-cement solution in 30 kHz and 40 kHz baths relative to the 20 kHz bath required an analysis of the energy spectrum of the effect on the suspension. according to the acoustic wave sensor.

The spectra differ significantly from each other (Fig. 7). So, the step between harmonics in a 20 kHz bath, at the upper limit of 120 kHz, is ~10 kHz, in a 30 kHz bath is ~15 kHz (in experiments), in a 40 kHz bath is ~20 kHz..

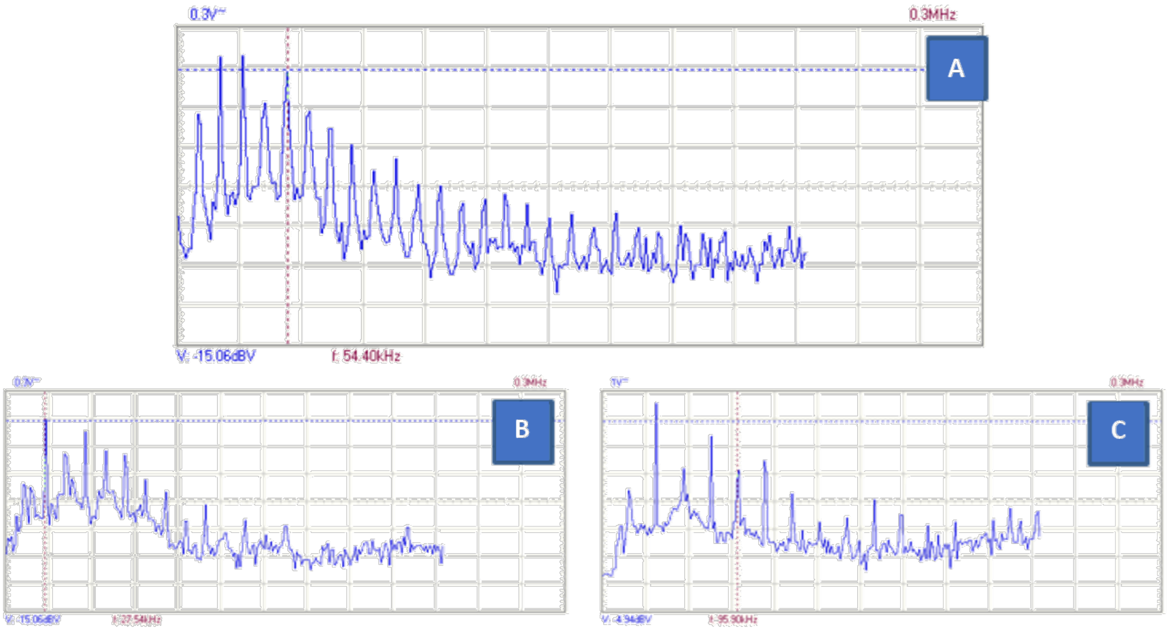


Fig. 7. Spectral characteristics for the bath 20 kHz (a), 30 kHz (b), 40 kHz (c)

This means that the energy of acoustic waves in a 20 kHz bath is «sprayed» between a set of harmonics, which, apparently, for this «heavy» medium, is not a positive factor. Concentrating energy on fewer harmonics may have a greater effect. At higher frequencies, the diffraction ability of the waves (bending around obstacles in the form of solid cement particles) will be greater, but sufficient energy is required. Thus, the frequency range is determined, where the main energy of acoustic waves involved in the process of cavitation action on the suspension is concentrated. More than 90% of the energy of acoustic waves is concentrated in the range up to 120 kHz.

The analysis of the cement stone structure carried out using a microscope confirms the results of instrumental measurements (Table 3, Fig. 8). With an increase in frequency and an increase in specific power from 200 W/liter to 300-400 W/liter, the stone structure improves, grain size decreases, uniformity increases. These indicators can be used as a basis for the design of industrial flow units for ultrasonic treatment of cement grouting mortar.

Table 3. Results of treatment of a water-cement solution with an ultrasonic multi-frequency acoustic field

Physico-mechanical characteristics of the solution	CS	Ultrasonic static bath (with a low-speed stirrer)						
		20 (21.7 kHz)		30 (28.6 kHz)			40 (38.7 kHz)	
		200 W/L	400 W/L	200 W/L	300 W/L	400 W/L	200 W/L	400 W/L
Spreading capacity of the solution (cm)	24	25	25	25	25	25	25	25
Water separation of the solution at 60°C (%)	2.5	2.85	1.6	1.65	1.7	1.7	2	1.55
Bending strength of cement stone at 60°C after 24 hours, (MPa)	5.55	7.01	6.95	7.04	6.49	7.3	5.98	8.93
Compressive strength of cement stone at 60°C after 24 hours (MPa)	24.3	36.6	38.2	38.8	41.5	37.7	35.86	38.3
Additional exposure during ultrasound treatment	-	using a propeller agitator (1000 rev/min)			frame agitator (200 rev/min)	using a propeller agitator (1000 rev/min)		

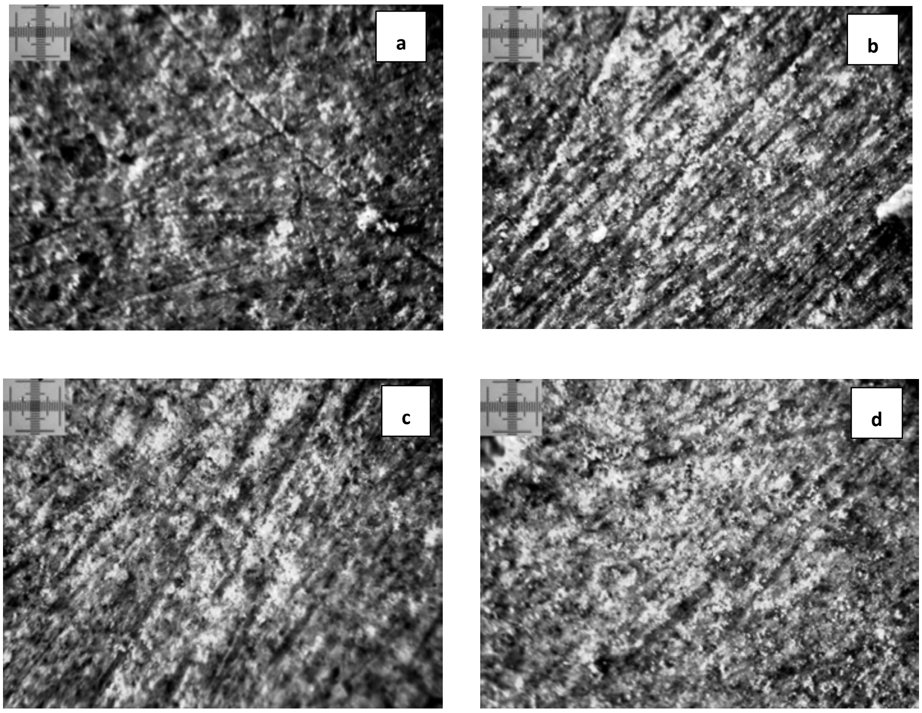


Fig. 8. Micrographs of samples: (a) control sample (without ultrasonic exposure); (b) the sample experience bath at 20 kHz, at a specific power of 400 W/L; (c) the sample by the test bath of 30 kHz, at a specific power of 300 W/L; (d) the sample experiment bath at 40 kHz, at a specific power of 400 W/L

In addition to ultrasonic baths, samples processed on rod ultrasonic systems were studied for strength in the work. However, the results were significantly less. All the results obtained formed the basis for the formulation of the technological scheme for the production of high-strength concrete on a construction site.

3.3 Technological scheme for the preparation of heavy-duty concrete mixes in the conditions of a construction site by processing with an ultrasonic multi-frequency acoustic

The technological scheme takes into account the conditions of the four stages indicated earlier, provided that the most effective method is the activation of the mixing water, subsequent treatment of the cement mixture with ultrasound without additives, then when mixing with additives and a multi-frequency acoustic field of increased power - when feeding the concrete mixture to the laying site through a sleeve [30,31]. In fact, the mixing procedure is divided into two parts, first, a mixture of cement with activated water is homogenized in the mixing chamber, then multi-frequency ultrasonic mixing occurs with the addition of small and large fillers and plasticizer additives. Each operation is tied with a pumping circuit, and the possibility of additional activation is provided in the supply sleeve. Ultrasonic exciters on the sleeve are mounted by a non-welded method (according to the «T-crest» scheme [27]) and are installed at a distance calculated depending on the speed and volume of the solution supply (sleeve diameter). It should be noted that the use of the proposed technology does not require changing the traditional scheme of preparation of concrete mortar, which saves capital costs of the construction organization. As for energy consumption, it will be 15 kW/hour, which is a fairly energy-efficient solution. The results of pilot testing of the installation showed that the unit cost of the concrete mix is reduced by 5.2%.

4 CONCLUSION

Based on the results of the experiments conducted during the study, the following conclusions can be drawn:

- It is proved that the activation of the mixing water and the treatment of concrete mortars with an ultrasonic multi-frequency acoustic field significantly improves their characteristics. The setting time of the cement dough and the period of strength gain are reduced, its plasticity increases, the structure improves (becomes more homogeneous), there is an increase in bending strength after 24 hours by almost two times (from 5.55 MPa to 8.93 MPa), compression - by 1.7 times (from 24.3 MPa to 41.5 MPa) compared to the usual solution.
- Ultrasonic treatment of a water-cement mixture is effective at frequencies of 30-40 kHz, while a specific type of a linear spectrum of energy exposure has a significant impact. With the same specific signal power, the presence of a large number of harmonics (step ~ 10 kHz or less) does not lead to an increase in processing efficiency. On the contrary, it is noted that processing on a reduced number of harmonics with increased energy is effective.
- Mixing the concrete dough with activated water provided a reduction in the normal density (water demand) of cement dough by 12%. The kinetics of heat release also confirmed the accelerated hydration of cement, which allowed to reduce energy consumption and the specific cost of the solution, to reduce the impact on the environment.

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