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IMPREGNATION OF POROUS CONSTRUCTIONS AND NATURAL MATERIALS USING ULTRASOUND

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ABSTRACT: The results of the experimental and theoretical studies of the acoustical flows in the porous or microcrumbling building and natural materials are presented. Building constructions, walls or foundations of concrete, brick or natural facing stone material being porous media absorb water due to the natural capillary effect. This happens mostly in countries with humid climates and if the faces of building structures are not protected by a waterproof layer. The damp penetrates into the foundation if the waterproofing layer between the foundation and the wall is damaged, the damp comes up the wall due to the natural capillary effect. Just the same, if the protective covering of the concrete or brick wall is damaged, they begin to absorb the damp from the air, growing damp by and by and worsening their protective properties. There exist different ways to restore damaged waterproofing layers. One possible way is to impregnate walls or/and foundations by some special hydrophobic liquid using the ultrasound. Being then dried out, the elements of constructions become water-repellent, do not absorb damp more and remain dry. The usage of the ultrasound makes the impregnation much more effective and fast, being at the same time the nondestructive method. The speed of the penetration depends on the porosity or microcrack or porosity factor. The paper presents the results of the study of the dependence of the velocity of the hydrophobic liquid movement from the average diameter of the capillaries and from the acoustical intensity.

Keywords: Ultrasonic impregnation, Porosity, Building materials, Capillary effect, Nondestructive protection

1. INTRODUCTION

It is possible to accelerate the impregnation and to increase its efficiency using ultrasound. The effect of saturation of porous media by the liquid in the ultrasonic field is based on the fact, that the acoustic pressure causes acoustic flow in the liquid. That is why the ultrasonic oscillations essentially help the liquid to move into the pores or capillaries of the material. The effect is strong within the wide range of frequencies and intensities of sound. The effect is well known. It is a so-called “ultrasonic capillary effect”. This effect was first opened in the USSR, described by Konovalov and Germanovitch [1] and was also studied by Prokhorenko and Dezhkunov [2,3], etc. Later this effect was studied and described thoroughly by Dukhin and Goetz [4]

The effect essentially increases after the arrival of cavitation. The essence of this effect is that the depth and the velocity of movement of the liquid into the capillaries increase significantly under the influence of cavitation in comparison with the influence of the acoustic radiation field.

2. FLOWS IN WALLS AND BRICKS

The impregnation in the presence of ultrasonic oscillations is widely used in the electronic and chemical-engineering industry. As a rule, it is used in plants, where it is possible to submerge the detail fully into the impregnating bath filled with the liquid and having the high power ultrasonic transducer inside the bath.

The main goal of our investigation was to study the process of liquid penetration in real, not in laboratory conditions. It is quite clear, that the concrete foundation or the brick wall cannot be submerged into the bath. Obviously, we had to look for some other engineering solution.

The main goal of our investigation was to study the process of liquid penetration in real, not in laboratory conditions. It is quite clear, that the concrete foundation or the brick wall cannot be submerged into the bath. Obviously, we had to look for some other engineering solution.

Figure 1 shows our design [5]. The ultrasonic vibrator 1 is mounted upright near the wall 2, subject to impregnation. The liquid 3 (special silicone hydrophobic liquid) forms an intermediate layer between the emitting surface of the vibrator and the wall. A special elastic rubber U-tank 4 prevents liquid leakage from the layer. This U-tank forms a kind of a small caisson. The tank is fed by the liquid from a special feeding service tank (not shown in the figure). The vibrator is firmly attached to the wall (the attaching construction is not shown in the figure), but it is necessary to control the layer thickness. This thickness must be quite definite – it is very important. The vibrator is excited by means of the power ultrasonic generator 5, which has the self-tuning circuit. The depth L of liquid penetration into the porous material (brick) was measured by pulse ultrasonic method.

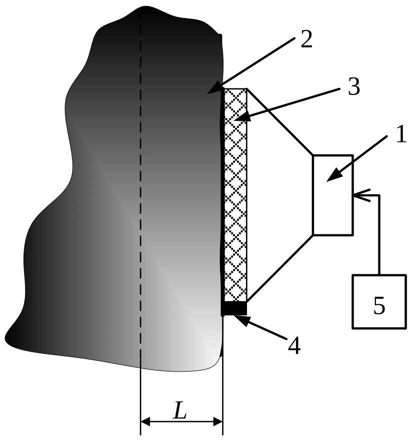


Fig. 1. Experimental setup

The main goal of this work is to compare this depth of the liquid penetration into different types of bricks under the influence of ultrasound of different power and different frequency.

3. EXPERIMENTAL RESULTS

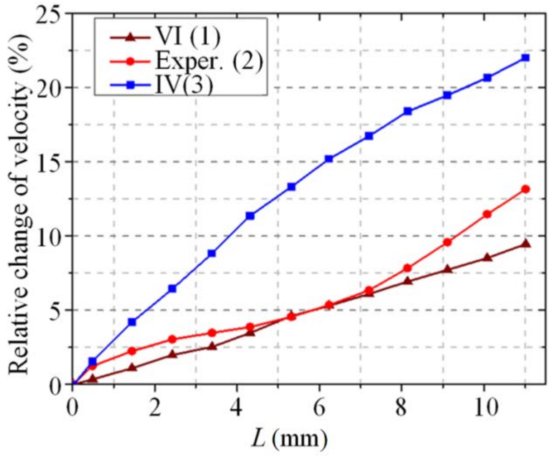
Three types of porous material were used for the experiment. These were bricks, and their properties one can see in the following table.

Table 1 Specimen properties

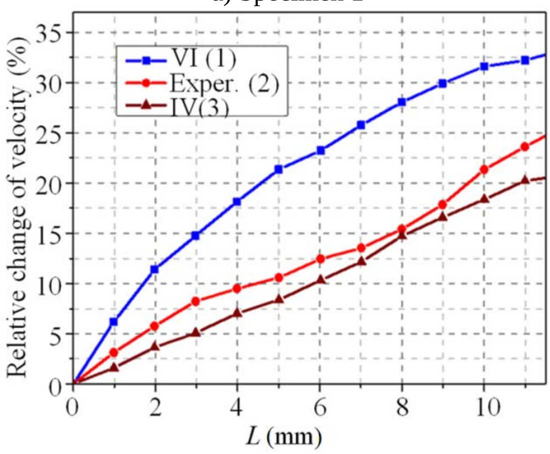
№	Density ($\times 10^3$ kg/m^3)	Aver. grain diam. (mm)	Mean capillary diameter (mm)	Density %
1	3.4	0.35	0.02	8
2	2.9	0.5	0.05	17
3	1.8	1.0	0.17	38

The filling liquid was a special organic-silicon hydrophobic solution "Gifob" (density ρ=1.07·10^3 kg/m^3, viscosity η=0.19·10^{-3} Ps), the temperature t=+20±2 C°).

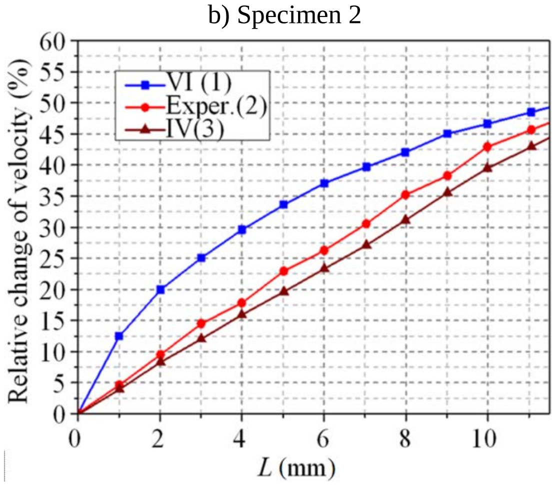
First, it was necessary to compare the theoretical velocity of ultrasound in the porous partially filled material with experimental. The review of acoustic wave propagation in fluid-saturated porous materials was given in [6]. Different authors proposed various theoretical models for the velocity of the elastic wave. Methods of measurements of ultrasound velocity in numerical anisotropic porous media are described in [7]. The best approaches were earlier obtained by Sato [8] and Gilberstein [9].



a) Specimen 1



b) Specimen 2



c) Specimen 3

Fig. 2. Calculated and experimental changes of ultrasound velocity from the depth of filling (L). IV and VI correspond to [8] and [9] respectively

Approximation by Sato [5] is the following:

$$C_x = C_0\{1 - z \cdot \frac{\varphi}{2}[\frac{(1-k)(1+\sigma_1)}{2(1-2\sigma_1)+k(1+\sigma_1)} + , \quad (1)$$

$$+10\frac{1-2\sigma_1}{7-5\sigma_1} - (1-D)]\}$$

where: $k = \frac{\rho_2 C_{2l}^2}{\rho_1 C_0^2}$;

C_0 – the longitudinal velocity of elastic wave in porous media;

σ_1 – Poisson's ratio for 3*D* infinity media;

φ – porosity;

k – bulk elastic modulus of the liquid, filling capillaries, to that of continuous media;

D – density of the liquid to that of continuous media ratio;

z - depth of penetration factor.

P.G.Gilberstein [9] proposed the following approximation:

$$C_x = \frac{C_0}{\sqrt{\frac{1-zQ}{1-1{,}08zQ}(1+1{,}08zQS)}}, \quad (2)$$

$$S = \frac{1+2\sigma_1(1-\sigma_1)}{1-\sigma_1},$$

where C_0 – longitudinal velocity of elastic wave in porous media;

σ_1 – Poisson's ratio for 3*D* infinity media;

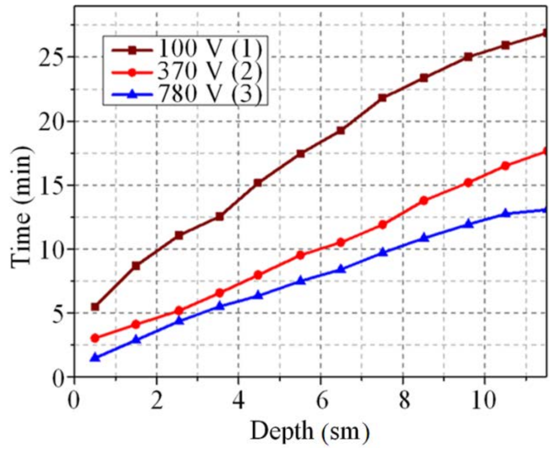
Q – total volumes of holes to that of material;

z – depth of penetration factor.

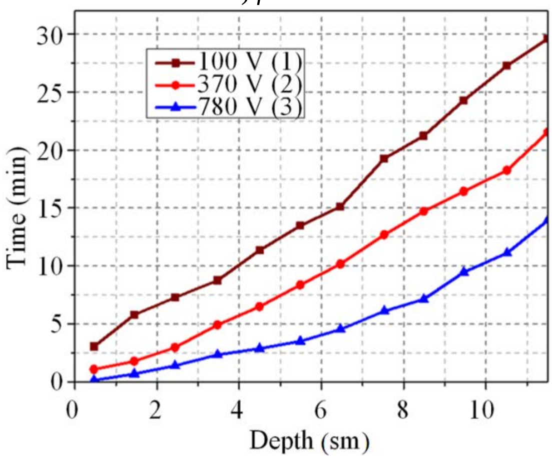
One can see from figure 2, that the model, proposed by Gilberstein fits very good with experiment.

The experiment showed, that the intensity of filling the specimen by liquid increases with increasing of the ultrasonic field power. This effect can be seen in figures 3, 4 and 5. Figure 3 shows the dependences of time of filling from the depth of penetration for different frequencies – 20 kHz, 60 kHz, and 100 kHz and different values of power for the specimen № 1. Different values of electric amplitude on transducer – 100 V, 370 V, and 780 V correspond to different values of sound-energy-flux density. These values are $2 \cdot 10^4$ Wt/m^2, $4 \cdot 10^4$ Wt/m^2, and $8 \cdot 10^4$ Wt/m^2, correspondingly. All The measurements were carried out below the threshold of cavitation. This level for this type of the hydrophobic liquid was about $8.4 \cdot 10^4$ Wt/m^2. The increase of the sound intensity causes the increase of the impregnation velocity, but it is quite necessary to avoid cavitation because cavitation demolishes the water-repellent properties of the liquid.

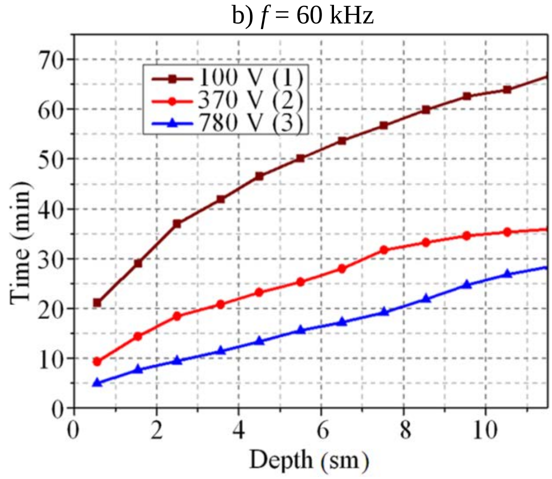
The increase of the impregnation time is caused by the growth of the ultrasound frequency, which leads to the wave decrement. This causes the reduction of the ultrasonic power as the depth of filling increases. As a result, the time of impregnation increases.



a) f = 20 kHz



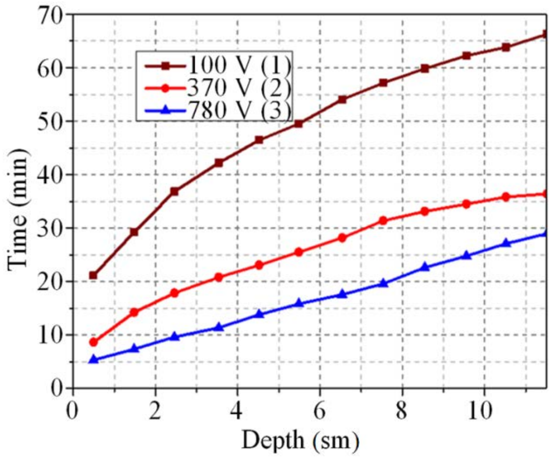
b) f = 60 kHz



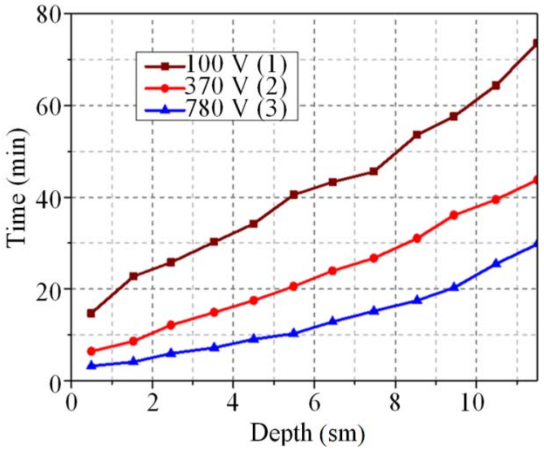
c) f = 100 kHz

Fig. 3. Times (t) of filling specimen № 1, L=12 sm

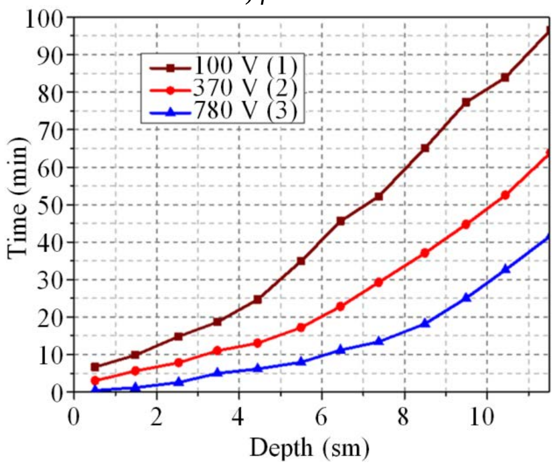
The interpretation of the fill-up time of the porous material from the frequency shows, that the time grows as the frequency increases. That is illustrated by figures 5,6 and 7. At the beginning of the process the velocity of flow is proportional to the ultrasonic frequency, but then the time of filling up slows down due to the reduction of power.



a) f = 20 kHz



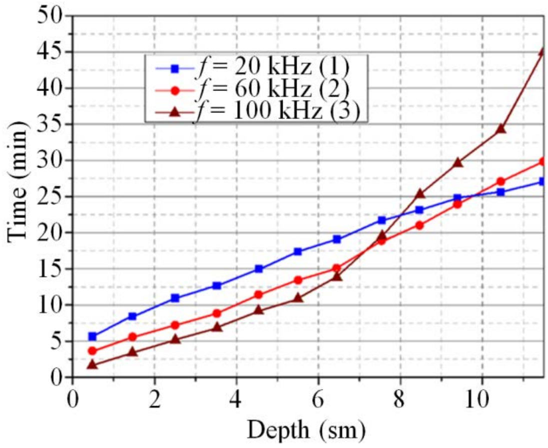
b) f = 60 kHz



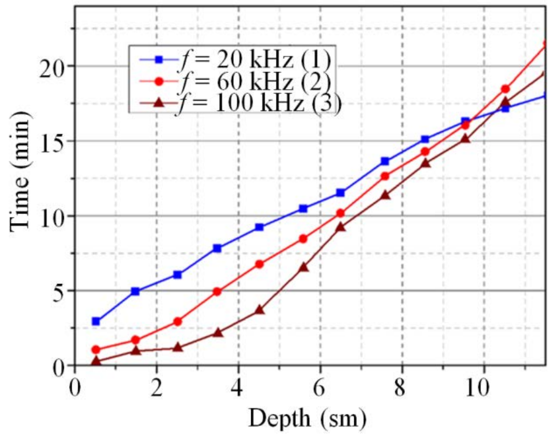
c) f = 100 kHz

Fig. 4. Mean times (t) of filling specimen № 3, L=12 sm for different frequencies and different signal amplitudes

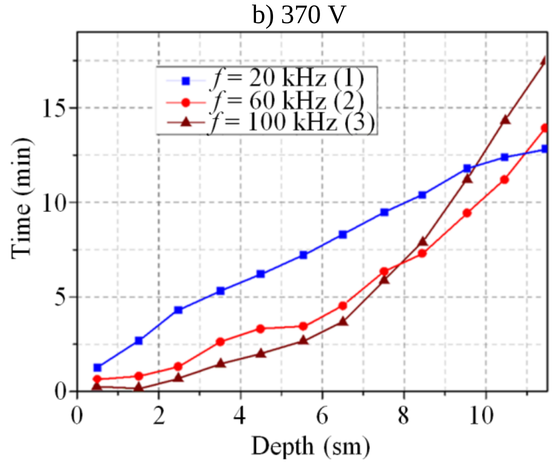
Figure 5 shows the dependence of the average filling-up time from the depth of penetration at different frequencies (20 kHz, 60 kHz, and 100 kHz) and different signal amplitudes (100 V, 370 V and 780 V, that correspond to values of sound-energy-flux density of $2 \cdot 10^4$ Wt/m^2, $4 \cdot 10^4$ Wt/m^2 and $8 \cdot 10^4$ Wt/m^2.



a) 100 V



b) 370 V

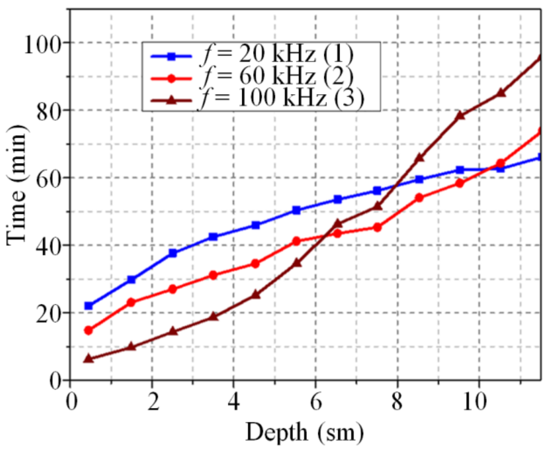


c) 780 V

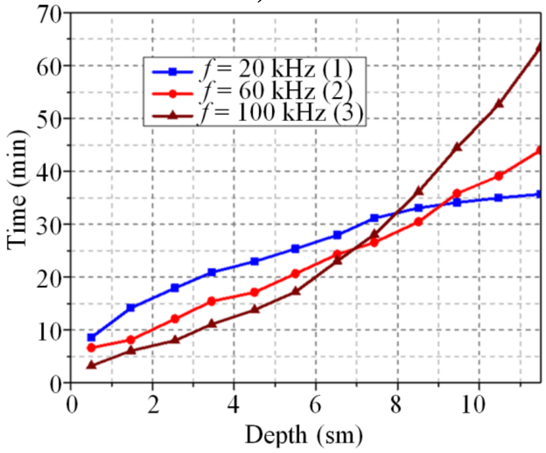
Fig. 5.Times (t) of filling specimen №2, L=12 sm for different frequencies and different signal amplitudes

Figure 5 is for specimen №1, L=12 sm, figure 6 is for specimen №2, L=12 sm and figure 7 shows these dependences obtained for specimen №3, also for L=12 sm.

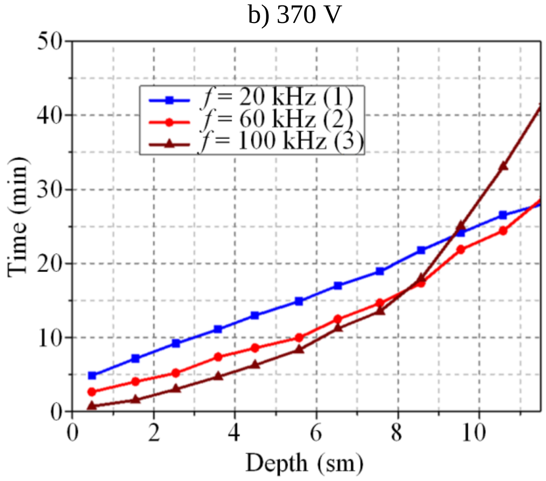
All dependencies are in good accordance with those of figures 2, 3 and 4.



a) 100 V



b) 370 V



c) 780 V

Fig. 6. Mean times (t) of filling specimen № 3, L=12 sm for different frequencies and different signal amplitudes

4. CONTROL OF DEPTH OF FILLING

The depth of liquid penetration into the porous medium (brick) was controlled by an ultrasonic pulse method using a specially designed ultrasonic measuring unit [10]. The quality control of impregnation is based on the change of the velocity of C_f longitudinal ultrasonic wave propagation in the material depending on the depth of its filling with the solution.

The measurement scheme is shown in Fig.7. The radiating ultrasonic transducer 1 emits pulses with a carrier frequency of 1 MHz into a porous medium partially filled with a solution. The velocity of ultrasound C_f in a filled medium is different from the velocity of ultrasound C_u in a medium already filled with liquid. The distance that an ultrasonic pulse travels in a fluid-filled medium is L_f and the total length of the material is L_t. The ultrasonic pulse, which has passed both parts of the sample, is received by the transducer 2.

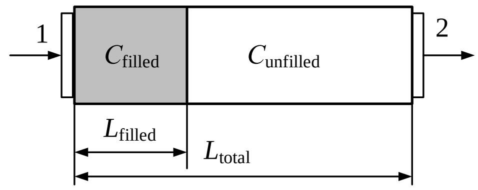


Fig. 7. Measurement of depth of impregnation

As a first approximation, the material can be considered homogeneous, and the speed of sound in it does not depend on the particle size of the material, which is an acceptable assumption [11, 12]. Then the time of propagation of ultrasonic vibrations in the material can be determined using the following expression:

$$t = \frac{L_f}{C_f} + \frac{L_t - L_f}{C_u} \tag{3}$$

For experimental studies of the control of the depth and time of filling the porous material with a solution, a specialized setup was developed (Fig.8).

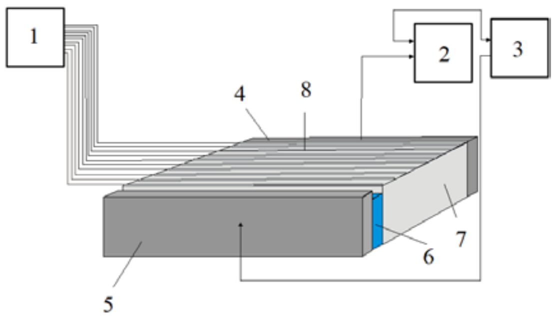


Fig. 8. Experimental setup for determination of depth and time of filling of porous material

Ultrasonic radiating transducer 5 by means of mechanical fastening is pressed against the surface of the porous material 7 (Fig. 8). Between the transducer and the material is a U-shaped rubber gasket, fixing the gap between them. The gap between the surface of the material and the piezoelectric transducer was chosen to be approximately 1/4 wavelength of the ultrasound wave in the liquid, which is the optimal value for matching the emitter and the material. The gap is filled with a solution to overlap the radiated surface of the transducer. The receiving piezoelectric transducer 4 is installed on the opposite side. Piezoelectric transducers are structurally made in the form of a set of piezo plates with dimensions 20×20 mm. The resonant frequency of the transducers can be changed by connecting or disconnecting a number of plates, which allowed: for the radiating transducer to fill the entire volume of the brick with a solution, and for the receiving transducer to control the entire spectrum of ultrasonic pressure.

5. DISCUSSION OF RESULTS

Our theoretical and experimental studies have found that in most solution-saturated samples the velocity of elastic longitudinal waves is higher than in dry ones. The total increase of the sound velocity in filled bricks reaches 13-50%. relatively dry bricks, depending on the brand of material.

From the theoretical and experimental results obtained, one can see that the best match of the measured values of the longitudinal wave velocities with the theoretical ones for various brick samples is obtained by the Hilberstein formula.

In bricks, there is usually a more or less natural increase in speed with saturation.

One can also notice that with a small filling of capillaries (up to 10-20 mm), the change in speed is more abrupt than with further saturation.

With an average pore filling (up to 30-70 mm), the velocity usually increases smoothly, but when saturation reaches the values over 80 mm, the sound velocity increases sharply. It should be noted that in samples with higher porosity the velocity changes more smoothly, while in samples with lower porosity more sharp and significant changes are observed.

With the gradual saturation of the bricks with liquid, an uneven increase of the velocity is usually observed. At the stage of ultimate saturation, associated with a sharp transition of the system to a new physical state, usually there comes an abrupt change in speed.

In general, the nature of the change in the saturation velocity can be explained from the point of view of the contact model, i.e. is associated with a change in the contact area.

However, a significant role is also played by the nature of the links, their rigidity, so the reasons for the change in speed are often more complex than in the simplified model.

The velocities of longitudinal elastic waves in water-saturated materials are determined by the elasticity of the skeleton and fluid, as well as porosity, and by the lithological features of rocks affecting the state of elastic bonds (mainly composition and type of cement).

While the first factor is quantifiable, the second is much more difficult to account for. Note that in natural conditions the velocity of longitudinal elastic waves is affected by a number of other factors (pressure, temperature, etc.).

Measurements of the velocity of ultrasonic oscillations in various depths of fill brick mortar showed the impermanence of the velocity of propagation of the oscillations. This is due to the heterogeneity of the brick material.

The statistical analysis of the results showed that the confidence interval of the measured values varies depending on the frequency of ultrasonic vibrations. As the frequency increases, the confidence interval of the measured velocity values decreases.

For combining on the same physical principle of impregnating the material hydrophobic solution and simultaneously to control the depth of penetration of this impregnation was carried out by additional experimental research of ultrasonic impregnation of porous material by hydrophobic solution. During the experiments, it was found that the filling of the brick increases with the increasing power of the ultrasonic field. However, the increase in power at certain values can cause cavitation of the hydrophobic solution.

The obtained results show that the time of filling the brick increases with increasing frequency: the increase in impregnation time is associated with an increase in the frequency of the acoustic signal, which leads to the weakening of the signal. This, in turn, leads to a decrease of the acoustic power along with an increase in the depth of the brick filling respectively, a decrease in the rate of impregnation.

The time of filling the porous material is also related to the adsorption forces in the capillaries of the brick. This is due to the change in the capillary volume, which affects the mechanism of rigid friction of the wall surface. When the diameter of the capillary decreases, the number of rubbing areas of the surface of the capillaries increases, which leads to an increase in the slowing down of the velocity of the liquid along the capillary of the porous material.

6. CONCLUSION

In conclusion, we can say, that the results of this investigation provide new possibilities for the water-repellent treatment of brick walls and concrete foundations. The time of hydrophobic liquid fill-up under the influence of ultrasound is about 8-10 times less than without the ultrasound, in the course of natural capillary seepage. Generally speaking, the ultrasonic effect on fluid flow is complex. The acceleration of the rate of impregnation can be explained by different effects. Among these effects the most important ones seem to be the capillary wall vibrations, the influence of ultrasound on the meniscus in the capillary channel, changes in physic-chemical properties of the fluid, acoustical pressure and cavitation.

Similar results were obtained for other porous materials, including concrete, ceramics, and some natural porous materials, such as marble and polycrystalline rocks, some natural facing materials.

The majority of theoretical works in both seismic and acoustic literature are devoted to the study of the propagation velocities of longitudinal and only in some cases transverse waves, and usually idealized media were considered.

Therefore, it became necessary to analyze the basic theoretical expressions derived for different types of aggregates, in terms of their applicability to the characteristics of porous materials, and to find out to what extent the available theoretical provisions are linked to the experimental data.

The usage of ultrasonic technologies is not limited to hydrophobic water-repellent impregnation of building structures. For the operation of stationary mining, fixed with concrete, it is often necessary forced repair of concrete support, caused by the destruction of its individual sections. That is why it seems possible to prevent impregnation of the concrete lining workings by hydrophobic liquid using ultrasonic technologies. High efficiency and manufacturability, small consumption, low cost and, environmental solutions and liquids allow us to hope for their use in the extraction of minerals both open and underground methods [13]. Solutions of the corresponding consistencies and liquids in combination with acoustic technologies can be used for fixing the walls of mine workings, or strengthening of the massif of rocks, including water-saturated (siltstone, mudstone, sand, and others).

7. ACKNOWLEDGMENTS

The authors would like to thank the faculty of the Department of Electroacoustics and Ultrasonic Engineering of the Saint Petersburg Electrotechnical University “LETI” for useful discussions.

It is also possible to use the technology described above for the restoration of architectural monuments, sculptures, and historical buildings

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