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Acoustic Methods for the Nondestructive Testing of Concrete: A Review of Foreign Publications in this Experimental Field

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Abstract—Acoustic methods for experimental studies of the problems of nondestructive testing that are used in the analysis of the strength and other physical properties of concrete are reviewed on the basis of an analysis of foreign publications. The classical transmission, pulse-echo, and impact-echo methods, changes in the internal structure of concrete under loading, and factors that influence the correlation between the strength and acoustic-wave velocity are considered.

Keywords: nondestructive testing, acoustic methods, concretes, experimental studies

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1. INTRODUCTION

The presented review of acoustic nondestructive testing (NDT) methods is devoted to the state-of-the-art situation in the field of experimental studies of the physical properties of concrete. The evaluation of these properties (predominantly strength) is a long-standing urgent problem in the mechanics of structures and its importance is constantly increasing with the advent of novel types of concrete materials.

The generally recognized opinion of practicing engineers is that concrete strength can be evaluated with a sufficient accuracy only upon its partial or complete destruction. However, such methods are not always applicable and, in addition, they are very laborious. As compared to destructive methods, NDT methods are advantageous due to the possibility of detecting cracks and pores in concrete; in addition, they show good results in the testing of such materials as metals and composites.

Among the conventional NDT methods (X-ray, electromagnetic, acoustic (ultrasonic), and impact-echo) that are described in this study, only the acoustic (mainly ultrasonic) and impact-echo methods are considered. Their advantages are as follows: an acceptable accuracy, safety in experiments, low cost, and the easy transportability of equipment to the place where actual engineering measurements are performed.

However, the application of NDT to concretes has certain difficulties that are associated with their complex internal structure. Concrete can be considered as a composite of composites, it is inhomogeneous at the micro- and macrolevels, and is simultaneously characterized by such opposite properties as brittleness and softness, elasticity and inelasticity, properties that are characteristic of a liquid (fluidity) and a solid (shear strength), the presence of cracks, cavities, and pores that are filled with air or a liquid (or with both air and a liquid). Exactly for this reason, it seems to be useful to apply the methods that were developed for composite materials [5, 11, 12] to concrete mechanics. Unfortunately, researchers have paid virtually no attention to this idea.

It should be noted that the properties of concrete also change with time (strength) and under the influence of ambient conditions [44, 41]. The structural inhomogeneity in concretes is determined by their constituting components: cement, sand, solid aggregates, water, etc. Solid aggregate components are preserved in solidified concrete together solidified mortar, when pores remain filled with air and water. In this sense, concrete can be regarded as a four-component composite material (cement, water, air, and a solid filler), but the internal structure of concrete is more complex. The solidified-cement component is actually a multiphase medium. Mineral additives are also composite materials, which substantially differ from mortar, and the boundary between the filler and mortar has its own specific physical properties.

These properties of concrete make the propagation of elastic waves irregular and complicate the NDT problem. The attenuation of ultrasound in concrete is rather high, and is much higher than in other elastic materials. The attenuation coefficient is 0.7 dB/mm at a frequency of 200 kHz and 2.7 dB/mm for $f = 800$ kHz [10]. The maximum attenuation is caused by sand and mortar [17]. The signal-to-noise ratio (SNR) is very low; therefore, the informative signal is very noisy. In many cases, this SNR cannot be improved via operation with time-averaged quantities; i.e., the main noise component is coherent and does not resemble “white noise.” Note that, as a rule, the existing methods for NDT of concrete require direct contact between the concrete surface and a transducer. This contact is usually nonideal because of the rough concrete surface. For the reasons that were mentioned above, the experimental methods that are efficient for more homogeneous materials are difficult to apply to the study of the mechanical properties of concrete.

One of the basic problems in NDT of concrete is the question of its strength, especially under actual external conditions [22, 25, 65]. Among other acoustic NDT methods, exactly the measurement of elastic waves in concrete is usually associated with the evaluation of strength. Unfortunately, because of the absence of any theoretical regularities, the correlation between the strength and velocity is established empirically. The existing standards that establish such correlations yield an accuracy of ~20% under laboratory conditions, but under industrial conditions (influence of the environment, concrete age, humidity, temperature, etc.), the measurement accuracy decreases and many authors report an accuracy of 80%.

Despite the criticism [53], the pulse-velocity measurement method still predominates in ultrasonic testing of concretes. Such methods, which are used to localize pores and cracks, determine the thicknesses of objects, etc., do not give precise data on the strength of concretes. Nevertheless, some of these methods determine the measured parameters with good accuracy. Note that the behavior of concretes that are prone to damage was studied in [62].

Several reviews that are devoted to ultrasonic-testing methods [7, 8, 23, 39, 40, 51, 54, 67] can be found in the literature, but many important problems in the field still remain open, thus making our review quite urgent. Here, we give references to the most significant papers that were published abroad and papers where additional useful references can be found.

2. A BRIEF REVIEW OF THE EXISTING EXPERIMENTAL METHODS

Nondestructive-testing methods for studying concretes can be classified according to the type of waves that are generated: X-ray methods, electromagnetic methods, sonic and ultrasonic methods, impact-echo methods, and combined methods.

Acoustic methods, which are the subject of this review, can in turn be classified as follows: resonance methods, ultrasonic-pulse methods (echo and transmission methods), the surface-wave method, and the acoustic-emission method.

The latter method is not widespread for NDT of concrete; therefore, it is not specially considered here, although useful references on this subject can be found in [19].

The resonance method is based on small vibrations (longitudinal, bending, or torsional) of an entire specimen or a structure as a whole. Depending on the geometry and physical properties of a structure, the resonance method is commonly used at frequencies that range from several hertz to several kilohertz. The use of relatively simple instruments allows one to determine the natural (i.e., resonance) frequencies and the damping decrement for several types of oscillations. After this, the elastic modulus E, the shear modulus G and the Poisson ratio ν can be calculated. For example, for a beam with a length l, the spectrum of natural-flexural frequencies ($\omega_n = 2\pi f_n$) has the form

$$\omega_n = \left(\frac{\pi n}{l}\right)^2 \sqrt{\frac{EJ}{\rho F}}, \quad n = 1, 2, \ldots, \tag{1}$$

@.

$$\omega_n = \pi n \sqrt{\frac{E}{\rho}}, \quad n = 1, 2, \ldots, \tag{2}$$

The spectrum of transverse vibrations of an elastic plate of thickness n is determined by the formulas

$$\omega_n = \frac{2\pi n c_p}{h}, \quad n = 1, 2, \ldots \text{ (asymmetric vibrations)}, \tag{3a}$$

$$\omega_n = \frac{(2n-1)\pi c_p}{h}, \quad n = 1, 2, \ldots \text{ (symmetric vibrations)}, \tag{3b}$$

where c_p is the velocity of a longitudinal wave, which is expressed via formula (4) (see below). Analogous formulas can be derived for elastic bodies with more complex shapes. At least the first several eigenfrequencies can be extracted from experiments; therefore, the determination of three unknown elastic parameters is real. This method has been used multiple times in laboratory conditions, because similar experiments must be performed for specimens with very stringent geometries. However, this method was recently extended to actual engineering constructions. Here, the resonance method is mentioned because it can be used in combination with the pulse-ultrasonic method.

As mentioned above, special attention in this paper is drawn to acoustic methods, which can be classified depending on the mutual arrangement of the transmitting and receiving transducers of acoustic waves, viz., the transmission method or the echo method. Their application under different conditions is determined by the possibility of accessing the surface of an article only from one or two sides and testing the necessary material properties (strength, thickness, presence or absence of defects, etc.). The physical characteristics that must be measured in acoustic methods are as follows: the wave-propagation velocity, attenuation, and the composition of the frequency spectrum. In this case, a direct change in the wave that travels from the source to the receiver is the most sensitive factor.

Pulse methods are widely used and allow the following operations:

(i) The determination of elastic parameters (Young modulus E and Poisson ratio ν);

(ii) Testing of concrete for the presence of flaws;

(iii) The determination of the degree of chemical and physical influence of various factors;

(iv) Evaluation of concrete strength and homogeneity;

(v) Evaluation of concrete solidification dynamics for determining the moment when the desired strength is achieved, thus providing the choice of optimal solidification conditions;

(vi) Evaluation of structural strength under the influence of external stresses.

Using a pulse-ultrasonic method, the velocity of sound can be determined during the transmission of an acoustic pulse, thus yielding information on the dynamic elastic moduli (E and ν), if two independent velocities of sound, viz., longitudinal and transverse (for an isotropic material), and the material mass density are known. In fact, the longitudinal velocity is determined by the expression

$$c_L^2 = \frac{\lambda + 2\mu}{\rho} = \frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}, \tag{4}$$

where λ and μ are the Lame constants, and the transverse velocity of sound is

$$c_T^2 = \frac{\mu}{\rho} = \frac{G}{\rho}. \tag{5}$$

The surface (Rayleigh) velocity of sound c_R can be found from the Rayleigh equation

$$\left(2 - \frac{c_R^2}{c_T^2}\right)^2 = 4\left(1 - \frac{c_R^2}{c_L^2}\right)^{1/2}\left(1 - \frac{c_R^2}{c_T^2}\right)^{1/2} \tag{6}$$

thus proving that $c_R/c_T < 1$ for actual elastic materials. The attenuation and composition of the frequency spectrum characterize the inelastic (viscoelastic) material properties.

The attractiveness of using acoustic methods during the testing of the technological processes in the formation of the internal structure upon a change from fresh mortar to solidified concrete is based on the high sensitivity of ultrasound to changes in internal structure, especially at the initial solidification stage [14]. This important feature of acoustic methods becomes more obvious when considering the correlation between the strength and velocity of ultrasound, which is often represented in a dimensionless form (empirical expression) as a relationship that contains the solidification time:

$$\frac{R_c}{R_0} = \left(\frac{c_L}{c_0}\right)^n, \tag{7}$$

where R_c and R_0 are the strengths for the compression in a current state and at the initial moment, and c_L and c_0 are the velocities of sound at the corresponding moments. As a rule, the values of $n = 5$ and 4 are used for a mortar and concrete, respectively.

Approximate formula (7) is based on numerous experimental data. These data show that the first 10% in the concrete-strength increase correspond to a velocity increase of 60%, but an increase in the strength

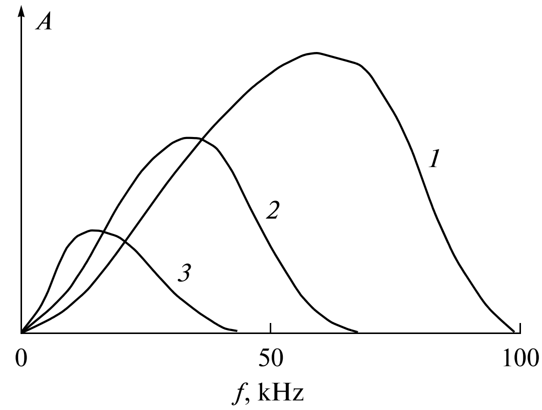

Fig. 1. (*1*) The amplitude characteristics of the transducer in the “transducer–specimen–receiver” system for cases of (*2*) weak and (*3*) intense attenuation of sound in concrete.

from 90% to the maximum value increases the velocity of sound by only 2–3%. Thus, the sensitivity of the method during the solidification from the initial to the final state decreases by a factor of 20–30.

The concept that is based on the pulse-propagation velocity was deservedly criticized [53]. However, as often occurs in the cases where, instead of an unsatisfactory method, no technique that would provide a substantial progress is proposed, this method still remains the main one for the ultrasonic NDT of concretes. Therefore, it is included in certain world standards and is properly documented. On the one hand, the efficiency of ultrasonic testing of processes in the technology of structures is also confirmed by the good correlation between the velocity and attenuation and, on the other hand, by such properties, as the strength, porosity, water–cement proportion, mass density, and thermal conductivity. The coefficients of such a correlation are rather high, ~0.6–0.7 [15].

Cylindrical or cubic specimens with dimensions of 10 × 10 cm (diameter and height) and 10 × 10 × 10 cm, respectively, are commonly used for NDT of concrete. National standards exist that are used in measurements of the velocity of ultrasonic pulses during NDT of concrete. Some of them utilize the velocity of sound for evaluating both the degree of homogeneity of the internal concrete structure and the thickness or evaluate the time-dependent changes in the properties of concrete, the presence of flaws, or anisotropy [52]. The evaluation of the elastic moduli is used only in some standards [27].

Methods for determining the velocity of ultrasonic pulses are similar in all standards; they are based on the generation of short-duration oscillations by an electroacoustic transducer, which is in direct contact with the concrete surface. The oscillation frequency must be, on the one hand, sufficiently high to provide a short pulse and, consequently, a high accuracy in measuring the transmission time and, on the other hand, rather low to provide a long pulse propagation path in a material. A frequency that is too high may cause too much attenuation as a result of diffuse reflections, which occur when the wavelength is of the same order of amplitude as the size of aggregates D: $\lambda = c/f \sim D$, where c is the velocity of sound, f is the frequency, and λ is the wavelength. As a result, the reasonable range for the practically applied ultrasonic frequencies is 20–200 kHz.

3. THE FEATURES OF TRANSMISSION METHODS

In the transmission method that is commonly used in the testing of concretes, the pulse velocity is determined by the leading edge of the arriving pulse. One specific feature of many actual materials, including concrete, is that when an ultrasonic pulse is transmitted, they operate as frequency filters [16]. This leads to a situation where the transducer-resonance frequency f_r, which determines the frequency of its operation, does not coincide with the dominant transmission frequency, f^*, in the medium (Fig. 1).

Figure 1 shows that for media with high damping (fresh mortar), high frequencies are fully damped and the spectrum of the transmitted signal is substantially shifted to the low-frequency region. Regardless of the value of the eigenfrequency of transducer vibrations, the dominant frequency in this case lies within a range of 1–10 kHz. In addition, the spectrum and dominant frequency depend on the size of the transducer base in an obvious manner. The wider the probe base is, the larger the frequency shift to the low-frequency region is and the lower the received-signal amplitude is.

As concrete solidifies, its internal structure changes substantially. In this case, the dominant frequency and the spectrum of the transmitted pulse shift to the region of higher frequencies. For solidified concrete, the main portion of the ultrasonic-pulse energy lies in a frequency region that is close to the transducer eigenfrequency. This fact is very important for the correct determination of the wavelength $\lambda = c/f$. Thus, it is desirable to use the dominant frequency, f^*, of the received signal instead of the eigenfrequency.

It can be concluded from the above consideration that at the initial stage of concrete formation low frequencies (20–40 kHz) should used. In this case, transducers with low eigenfrequencies can provide a sufficient detected amplitude. To investigate later solidification states, high-frequency (60–150 kHz) transducers are more suitable. Frequencies of up to 800 kHz are often used for very strong concretes.

After passing through concrete, the amplitude of a received pulse is transformed into an electric energy by the second transducer. The pulse velocity is calculated as $c = d/t$, where d is the distance between the transducers and t is the measured flight time. This determines the standard requirements for the equipment. The pulse generator must have a time accuracy of $\pm 1\%$ and a short peak must have a repetition rate of 100–150 pulses per second. The instruments for measuring the pulse velocity must be sensitive enough to record low-amplitude pulses. The distance between the transducers must be measured with an accuracy that is no worse than 1%.

In order to transmit the acoustic energy from an ultrasonic transducer to an article produced from concrete, a reliable acoustic contact between them must be provided. The materials that are used for this purpose must have high acoustic impedances and be sufficiently tough (in order to avoid spreading); the air between the probe base and concrete must be also removed. When measuring the velocity of an ultrasonic pulse, if its passage through the contact liquid is taken into account, the latter must have the maximum possible velocity of sound. Vaseline, plasticine, gypsum, silicon, and other materials are standard media. The possibility of testing through an air layer is under investigation [74].

The application of the technique of ultrasonic pulses to testing of concretes in the solidification stage has some specific features. Several methods for applying ultrasound in solidification processes exist. The acoustic impedance is determined by a material's structure. One of the possible approaches is to measure the wave energy that is reflected from the surfaces of certain classical materials (such as steel) and then from the surface of a concrete specimen. A greater part of the acoustic energy is reflected from the metal–concrete interface surface if concrete has not yet congealed. However, an ever-increasing portion of energy passes through concrete during solidification and the portion that is reflected from the interface surface decreases correspondingly.

Note that the nonlinear effects in the ultrasonic NDT method were considered in [63].

4. THE SPECIFIC FEATURES OF THE PULSE-ECHO (PE) METHOD

The pulse-echo method is typically used when only one side of an article is accessible. Special types of ultrasonic transducers exist that provide the transmission and reception of echo signals. In particular, this allows efficient thickness measurements of objects. However, as a rule, it is impossible to detect even rather large flaws because of both the low signal-to-noise ratio (SNR) and the too wide directivity characteristic of a transducer. The greatest positive experience in this field was received during the detection of surface cracks [64, 71].

In ultrasonic NDT of highly inhomogeneous materials, the level of a detected echo pulse depends on the reverberation noise level. Reverberation that is caused by a complex internal structure results from multiple repeated reflections of ultrasonic waves. This is accompanied by mutual transformations of longitudinal waves into transverse ones and back again. As a rule, the size of aggregates in the microstructure and the distance between them are of the same order of magnitude as the ultrasonic wavelength; therefore, the energy of a pulse that enters concrete is dissipated mainly by inhomogeneities that are close to the transducer and weakly propagates to far-field zones in the material. As a rule, acoustic noise that is received by an ultrasonic transducer decays with time much more slowly than is predicted by the known theories, which disregard high-order scattering [35]. For example, when combined transducers are used at frequencies of $f = 60$–100 kHz, the structural-reverberation noise after 40–60 μs becomes higher than the intrinsic noise of both the transducer and the receiving amplifier. When separate transducers (a transmitter and a receiver that are placed close to each other) are used, structural noise prevails after 50–70 μs. To guarantee accuracy when detecting flaws by the echo method, an echo signal must be appreciably stronger than the reverberation noise level. In this case, this method must provide the spatial resolution of the reflectors.

Improving the spatial resolution is not equivalent to mere narrowing of the central lobe of the radiation pattern in the far-field zone. For example, if the wavelength is several centimeters (e.g., for $c = 4000$ m/s and $f = 100$ kHz, $\lambda = 4$ cm), it is then impossible to create a transducer with a narrow directivity characteristic at a depth of 100–700 mm, because for this effect, the probe base must be 5–7 times larger than λ. In this case, the length of the near-field zone $z_n = D^2/4\lambda - \lambda/4$ is 6–12 times larger than the wavelength λ and usually covers more than half the article's thickness.

In the pulse-echo method, *A*-scanning yields bad visualization of the internal structure of a concrete structure because of its inhomogeneity. The main problem of *A*-scanning is a body of information that is too large because of a directivity diagram that is too wide. At the same time, much useful information is hidden behind structural noise, multiple reflections, and stochastic noise from electronics. Therefore, A-scanning is seldom used for concretes because it is actually applicable only to concrete with fine-dispersed additives (smaller than 8 mm) [7]. However, in combination with *B*-scanning and a movable transducer, flaws can be detected quite rapidly. Low-frequency filtering is often used in *B*-scanning [20].

A considerable improvement of spatial resolution accompanied by successful testing of flaws with the size λ (along the wave front and in the longitudinal direction) is attained via the use of radiation that is focused to a chosen point of a medium. Under the conditions when the depth, the transducer size, and the wavelength λ are of the same order of magnitude, this can be fulfilled using the synthetic-aperture focusing technique (SAFT) with a sufficiently large base. This is commonly used to improve the resolution and quality of a flaw image (the essence of the SAFT method was described in detail in [29, 42, 66]). In brief, the idea of this method is as follows. Sound is transmitted from the surface to a chosen spatial point at different angles and echo pulses are recorded for all these directions. All the recorded signals are then summed with their corresponding phase-time delays, which are equal to the time of flight between the source and the chosen observation point. In order to create a 2D image of a chosen cross section (a tomographic image), this process is repeated for all points in the selected region. In order to reduce structural noise and record reliable information for each chosen point, information on all possible source–receiver combinations should be collected.

In the SAFT method, each part of the measured data is focused to the image of a chosen part of the volume [13, 30]. In this case, the wide radiation pattern of the transducer provides a good sounding of an object from all sides. Stochastic noise decreases owing to multiple measurements at the same point. Scattering at aggregates is taken into account during data processing and is usually added to noise. Waves with different velocities are usually defocused and are absent in the image.

The aperture is usually created by a set of normal contact ultrasonic transducers, each of which has a base that is of the order of the wavelength. These are combined in a block (antenna array), which is consecutively placed on the surface of a tested article, and echo pulses from all transducers of the array are recorded. The coherent processing of the obtained data array from several neighboring positions of the set forms a very wide aperture [61].

One advantage of the SAFT method is that it is based on a graphical method. The SAFT method is a mathematical program that can be also used for ultrasonic and impact-echo methods. In this case, this method is subdivided into linear, 2D, and 3D methods. This technique can be improved by preliminary measurements without a flaw for the further correction of the later oscillations of a tail-type transducer. The SAFT method requires high-quality equipment for measurements, especially in a frequency range of 50–100 kHz, for testing concretes with sizes of aggregate particles of up to 32 mm. The resolution depth can be increased, if not the amplitude, but the energy (i.e., the area under the pulse-enveloping curve) is measured (integration method) [31–33].

It should also be noted that the fruitful ideas of the SAFT method appear to be very close to the acoustic-tomography method, which is based on the pulse time of flight [3, 4].

5. SPECIFIC FEATURES OF THE IMPACT-ECHO (IE) METHOD

Conventional piezoelectric transducers generate too little energy in a frequency range of up to 60 kHz. The IE method, which is based on the generation and propagation of stress waves during testing of materials of other types, plays the role of an alternative method. Data for concretes were presented in [9, 38, 56–59]. The spectral analysis of surface waves was applied to testing the elastic properties of concrete surfaces [43, 48, 49, 60].

A transient voltage pulse is generated by a mechanical impact on a surface. This method provides a high energy in a generated wave. Theoretically, the frequency component of a pulse is determined by the source size and height of fall [37, 55]. The frequency distribution is wide, and the frequency spectrum usually lies entirely below 30 kHz. In this case, it is rather difficult to control the wave field, because all the three types of waves are generated: longitudinal, transverse, and surface (with a spherical front) waves. This method demonstrates its efficiency in localizing cavities, delaminations, and the depths of surface cracks [1] and

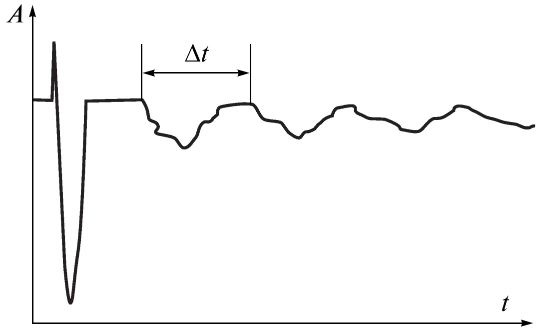

Fig. 2. A time delay between neighboring peaks yields useful information on the wave velocity.

in measuring the thicknesses of articles. Both longitudinal and transverse waves are reflected from the internal and external boundaries. If the receiver is placed near the point of impact, an L wave dominates. By analogy to the ultrasonic-pulse method, the arrival of the first L wave determines the time of arrival and if this time and the distance are known, the velocity of the L wave can be determined.

The contact time can be approximated by a half-sinusoid. By reducing the contact time, testing of smaller flaws can be attained, but an increase in this time makes it possible to achieve wave propagation to longer distances. The source of impact must be chosen especially carefully. As a rule, testing is performed with steel balls with different diameters. A ball is either guided to the upper end of the rod that performs an impact or the rod itself is on the ball, which lies on the specimen surface. To improve the accuracy in the detection of the initial impact moment, some authors propose to build a sensor into the device that performs an impact [70]. In order to evaluate the elastic properties and geometry of concrete constructions and laminated structures, the method of the frequency analysis of surface waves (SASW method) is used, which correlates with the phase delay between the velocities of surface waves that are received in a pair of receivers, which are placed at a fixed distance from each other. The obtained data on the phase delay of surface waves is used to construct a dispersion curve, from which the values of the elastic constants can be subsequently obtained [2, 24]. Some authors propose to place a lead plate between the transducer and the concrete, while others use two receivers on one direct line with the impact point. A received signal is interpreted either in the time or frequency domain. The impact moment and the time of flight of the first reflected L wave are evaluated in the time domain, where the moment of signal arrival is determined as the voltage that exceeds a certain threshold level. This methods allows determination of the velocity with an accuracy of 85–93%. Here, the error is due to the pulse dispersion (note that the time-of-flight concept disregards the dispersion). An alternative approach that is based on frequency analysis correlates with a signal that is multiply reflected from external surfaces and based on measuring the time between two peaks in the signals (Fig. 2). The plate thickness is then determined. In these measurements, one must take a correction factor that depends on the specimen's geometry into account.

The ASTM C1383 standard determines the velocity of an L wave through a measurement of the time of flight between a pair of surface receivers and the thickness through the frequency filling in the IE method. This method is applicable to structures of slab geometry, where the thickness is 6 times smaller than the transverse dimensions. This standard evaluates the inherent error in thickness measurements and recommends the use of a factor of 0.96.

Multiple repeated reflections have a periodic nature at any point that is close to the contact region. It is very difficult to evaluate the wave-front profile because of reflections between the free surface and crack boundaries. If a signal is converted to the frequency domain, each boundary has its peak and the interpretation then becomes clearer. This method has disadvantages, such as an unsatisfactory frequency spectrum, improper signal control, and difficulty in evaluating the directivity characteristic [52]. Some authors propose improvements that are associated with frequency and amplitude modulations [50].

In contrast to ordinary generation using a piezoelectric (PE) source, the characteristics of a signal that is produced by an electric drive determine a voltage wave but not the resonance of the PE crystal [26, 72]. The advantages of such generation involve the possibility of better control of the voltage-wave characteristics (in terms of its center frequency) and its frequency composition, as well as the higher mobility of transmission in the required frequency region.

Some authors [68–70] propose to use the cross-correlation technique in the IE method for determining the Rayleigh-wave velocity. The cross correlation between signals that were obtained with different

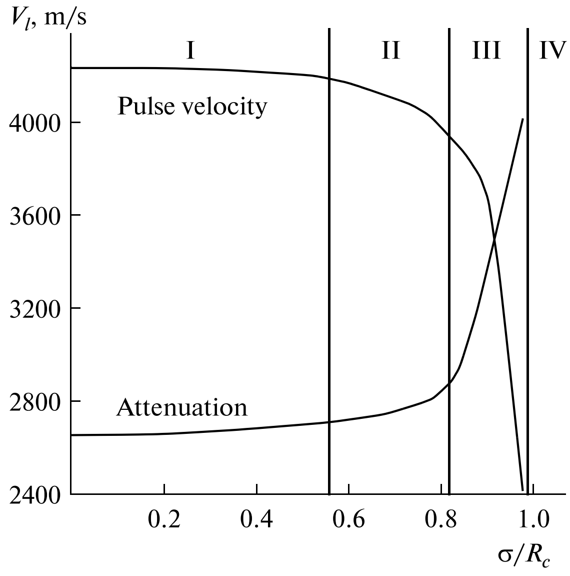

Fig. 3. The correlation between the velocity of an ultrasonic pulse and ultrasound attenuation under loading.

receivers allow attainment of a higher accuracy in determining the Rayleigh velocity. This method is based on the assumption that signals that were obtained with different receivers have the same shape only at a certain delay. Other authors [47] declare that this technique is inefficient for concretes because the signal shape appreciably changes, when signals from different sources traverse different distances.

A standard pulse-echo flaw detector with a combined receiving and transmitting probe at frequencies of up to 150–200 kHz (this is the frequency range in testing concretes) has not found actual application because of the bad directivity characteristic of the ultrasonic transducer and, as a result, low resolution. From the technological standpoint, it is also very difficult to create a transducer base with a size of several wavelengths, a short pulse, and low-level intrinsic reverberation noise [18]. It should be also noted that the use of the pulse-echo method with a liquid acoustic contact still remains only an instrument for laboratory investigations [34].

Studying the internal structure of the ultrasonic-wave reverberation in concrete shows that during NDT of concrete, it is better to use transverse waves instead of longitudinal ones; a number of developed instruments prove this statement [28, 36].

Finally, it should be noted that useful correlations between the resonance and impact acoustic methods were established in [21], where the authors also performed a comparison with the results that were obtained using MKE.

6. CHANGES IN INTERNAL CONCRETE STRUCTURE DURING LOADING

Experiments that are performed with cubic concrete specimens under loading show the following picture with four characteristic zones (Fig. 3).

In zone I, the velocity and attenuation are almost constant. This region corresponds to the state in which loading does not yet initiate the formation of cracks. In zone II, which ranges approximately from 0.6 to 0.8 of the maximum material strength, the velocity and attenuation change insignificantly; this region corresponds to the stress that causes isolated local microcracks that are localized mainly near a free surface. Zone III is characterized by a rapid decrease in the ultrasonic velocity and a rapid increase in damping. This corresponds to the further development and propagation of microcracks in a certain part of a specimen. This region has an upper limit of up to 0.95 of the maximum strength. Zone IV corresponds to the material damage; here, an abrupt velocity drop and an abrupt attenuation rise can be observed. This means that the system of microcracks has filled the entire volume (or some cross section) of the specimen. It has been properly substantiated in the literature that concrete strength considerably increases during aging and the threshold below which the forming cracks do not lead to a fracture increases.

At present, it is generally accepted that if at least an approximate strength–velocity curve can be obtained under certain conditions it is then possible to evaluate concrete strength with acceptable accu-

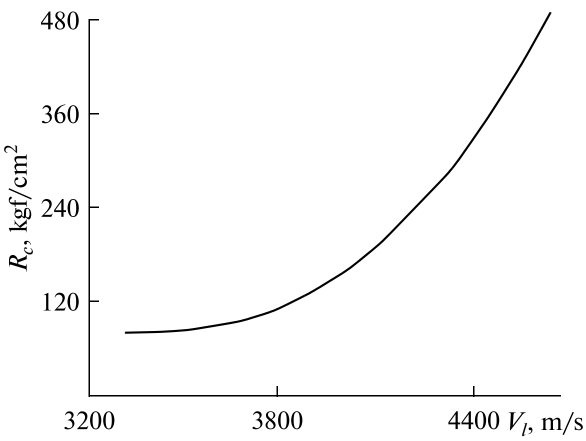

Fig. 4. The correlation between concrete strength and the velocity of an ultrasonic pulse.

racy. In practice, such a curve is usually constructed in parallel using nondestructive and destructive methods on special specimens. Figure 4 shows an example of such a curve.

7. FACTORS THAT INFLUENCE THE STRENGTH–VELOCITY CORRELATION

(1) The effect of the cement type. The main regularity is that the higher the percentage of calcium silicate is and the lower the amount of impurities, the higher the strength of concrete is.

(2) The relative content of cement. As the cement percentage in concrete increases, the velocity of an ultrasonic pulse increases at a slower rate than the strength does. When cement is added until a preset possible density value is reached (e.g., 400–450 kg/m^3), the ultrasonic velocity subsequently decreases, despite the further increase in strength. Thus, the application of ultrasonic methods becomes rather problematic if the percentage of cement is at a level that is close to its limiting value. The influence of such a percentage on the strength–velocity correlation for loaded concrete is the dominant factor that determines the principal part of the error in the ultrasonic NDT method for concretes.

(3) The influence of aggregate properties. The properties of the filler and its form substantially influence the strength–velocity correlation under a load, because the filler content in concrete is ~80%. The velocity of sound in the filler is higher than in concrete; therefore, this influence is mainly determined by the velocity of sound in the aggregate filler. However, the mechanical strength of concrete is in reality less sensitive to changes in the properties of the filler than the velocity of sound is.

(4) The influence of the composition of granules. This composition determines the conditions for the propagation of an ultrasonic wave in concrete through the correlation between the wavelength and diameter of the aggregate filler. On the other hand, the composition of granules influences both the concrete strength and velocity of sound: as the number of small fractions increases, the strength increases as well, but this is accompanied by a decrease in the ultrasound velocity.

(5) The influence of the humidity. At a certain specified value of the velocity of sound, concrete that is immersed in water shows a decrease in the sensitivity to changes in its strength under a load in comparison to concrete in air. This can be explained by the fact that concrete in water has a higher velocity of the passage of an ultrasonic pulse, owing to the saturation of pores with water [45]. Nonlinear effects in the velocity change as a function of humidity were considered in [73].

(6) The influence of concrete aging. This influence can be explained as follows. Physicochemical changes that proceed during the solidification of concrete are associated with very important processes; in particular, they increase the velocity of an ultrasonic wave much more significantly, as compared to the strength increase. Further solidification increases concrete strength but has a very weak effect on wave velocity. Moreover, the velocity of an ultrasonic pulse may even decrease with aging because of the gradual formation of microcracks and moisture loss.

8. CONCLUSIONS

Based on the analysis of publications in the foreign literature, it can be stated that experimental studies show a clear tendency toward operation with the "velocity measurement" method, but this idea is hardly applicable to strength testing. In this case, the experimental data show a slow increase in velocity decay with an increase in frequency. In the next publication, we plan to review foreign theoretical investigations in the field of acoustic methods that are applied to NDT of concretes. This review will show that theoretical predictions yield more rapid attenuation. Modern studies must be aimed at the convergence of results that are based on experimental and theoretical methods.

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