Determination of the density of concrete by ultrasonic velocity

D Korolkov\textsuperscript{1,4}, A Mordvinov\textsuperscript{2}, and A Trebukhin\textsuperscript{3}

\textsuperscript{1}Saint Petersburg State University of Architecture and Civil Engineering, 4 2nd Krasnoarmeyskaya St., 190005, Russian Federation
\textsuperscript{2}Tyumen Industrial University, Volodarskogo str., 38, Tyumen, 625000, Russia
\textsuperscript{3}Moscow State University of Civil Engineering, 26, Yaroslavskoye shosse, Moscow, 129337, Russia

E-mail: \textsuperscript{4}korol9520@yandex.ru

Abstract. This article discusses the issue of determining the density of concrete using the ultrasonic method of testing concrete structures. The article discusses traditional methods for determining the density of concrete from selected samples and using radioisotopes. The advantages and disadvantages of these methods are highlighted. The authors proposed the use of an ultrasonic method for determining the density of concrete. From the equations of the propagation velocity of ultrasonic waves in solid media, the density of the material is expressed for the case of transverse and longitudinal waves. The authors proposed to use the derived equations to determine the density of concrete during ultrasonic testing of concrete and reinforced concrete structures. The authors provide explanations for determining the parameters of concrete included in the equations. The factors that influence the determination of the ultrasound velocity are given. Using the proposed formulas, you can calculate the density of concrete structures.

1. Introduction

Knowing the density of reinforced concrete and concrete structures is important not only to calculate the load, but also to calculate the physical protection against radiation.

The standard method for determining density is the testing of selected samples \cite{1}.

The density of the concrete of the sample $\rho_w$ is calculated by the formula:

$$\rho_w = \frac{m}{V} \cdot 1000$$  \hspace{0.5cm} (1)

$m$ – mass of the sample;

$V$ – volume of the sample.

The density of concrete at a normalized moisture condition $\rho_H$ is calculated by the formula:

$$\rho_H = \rho_w \frac{1 + W_H/100}{1 + W_M/100}$$ \hspace{0.5cm} (2)

$\rho_w$ – density of concrete at moisture $W_M$, kg/m\textsuperscript{3};

$W_H$ – normalized concrete moisture, %;

$W_M$ – moisture content of concrete at the time of testing, %.
The volume of samples of regular shape is calculated by their geometric dimensions. The dimensions of the samples are determined with a ruler or a caliper with an error of no more than 1 mm.

The volume of samples of irregular shape is determined using a volume meter or hydrostatic weighing according to the method described in [1].

The mass of the samples is determined by weighing with an error of not more than 0.1%.

But sometimes a situation may arise when it is impossible to take a sample to determine the density of concrete due to radiation contamination of the surface of the structure.

There is also a radioisotope method for determining the average density of concrete [2].

As sources of radiation are used (artificial radioactive sources of gamma radiation (cobalt-60, cesium-137, iridium-142), X-ray equipment, beta neutrons - electrophysical accelerators.

X-rays and gamma rays are made up of photons. Colliding with the electrons of the shells of the atoms of building materials, the photons lose some of their energy and change the direction of movement. As a result, radiation attenuation occurs. This effect is estimated by the attenuation coefficient \( \mu \), which depends on the density of the material.

Neutrons emit polonium-beryllium, plutonium-beryllium, and americium-beryllium sources. When neutrons interact with atomic nuclei, scattering and absorption occurs. Distinguish between elastic and inelastic scattering. In the case of elastic, the reflection of neutrons by the nucleus of the atom is observed, in the case of inelastic, the neutron is absorbed by the nucleus and then leaves the nucleus with a reduced energy. The principles of radiation registration are based on the ionizing effect of radiation on gaseous and solid media (gas-discharge tubes, ionization chambers, semiconductor detectors) or on the fluorescence of certain crystals when exposed to radiation.

Thus, the intensity of radiation transmitted through concrete with thickness \( d \) and density \( \rho \) (Fig. 1),

\[
Y = Y_0 \cdot B \cdot e^{\mu / \rho} \cdot \rho \cdot d
\]  

where \( Y_0 \) — is the radiation intensity without the test sample, mm/min;
\( \mu \) - is the attenuation coefficient;
\( B \) - is a factor that takes into account the geometry of the arrangement and the radiation energy.

The activity of the source of gamma radiation should be such that about 5000 pulses could be counted within 1 min.
Figure 1. Application of radiometric methods to study the density of the material of construction. a - through-transmission method using the photoelectric effect; b - the method of scattered gamma radiation using the Compton effect; 1 - radiation source in the container; 2 - lead hood; 3 - tested structure; 4 - counter in a container.

Currently, this method is practically not used due to the complexity of handling radioactive substances, as well as due to the need to comply with strict safety requirements.

In this regard, it becomes necessary to use other approaches to assess the density of concrete, which would allow instrumental measurements to be carried out without risk to health. Ultrasonic studies are most suitable for these spruces, which are widely used for diagnostics of concrete structures [3–19].

2. Methods

Oscillations excited at any point in the medium (solid, liquid or gaseous) propagate in it at a finite speed, depending on the properties of the medium, being transferred from one point of the medium to another. The further a particle of the medium is located from the source of oscillations, the later it will begin to oscillate. In other words, the phases of oscillations of the particles of the medium and the source the more differ from each other, the greater this distance. When studying the propagation of vibrations, the discrete (atomic-molecular) structure of the medium is not taken into account, and the medium is considered as continuous, that is, continuously distributed in space and having elastic properties.

The process of propagation of oscillations in a continuous medium is called a wave process (or wave). When a wave propagates, the particles of the medium do not move with the wave, but vibrate about their equilibrium positions. Together with the wave, only the state of vibrational motion and its energy are transferred from particle to particle of the medium. Therefore, the main property of all waves, regardless of their nature, is the transfer of energy without transfer of matter.

Elastic (or mechanical) waves are mechanical perturbations that propagate in an elastic medium.

If the particles vibrate parallel to the direction of wave propagation, then the wave is called longitudinal. If they vibrate perpendicular to the direction of propagation, then the wave is called transverse. Sound waves in gases and liquids are longitudinal. In solids, waves of both types exist. A shear wave in a solid is possible due to its rigidity (resistance to shape change). The most significant difference between these two types of waves is that the transverse wave has the property of polarization (oscillations occur in a certain plane), while the longitudinal wave does not.

The speed of sound is a characteristic of the medium in which the wave propagates. It is determined by two factors: elasticity and density of the material.

In solids, in addition to longitudinal and transverse waves, compression (extension) waves, torsional and surface waves can propagate. If the controlled environment is infinitely large, then only two main types of waves arise in it - longitudinal and transverse.

In construction practice, an environment is conventionally considered "infinitely long" if it meets two requirements:

- when the ultrasonic wavelength is an order of magnitude smaller than the dimensions of the controlled medium, in any direction;
- when the influence of re-reflected waves from the boundary of the medium is negligible (for example, due to wave attenuation or in special modes of pulsed radiation).

The propagation speed of ultrasonic waves in solid media depends on their elastic constants. Most building materials are isotropic (metals, alloys, plastics). Concrete is also conventionally considered isotropic. The elastic properties of such materials are characterized by the modulus of elasticity $E$ (Young's modulus) and Poisson's ratio $\nu$. The velocity of longitudinal $c_l$ and transverse $c_t$ waves is determined through the elastic constants of the medium using the following dependences:

$$G_l = \frac{E}{\sqrt{\rho}} \cdot \frac{1-\nu}{(1+\nu)(1-2\nu)} = \frac{K+\frac{4}{3}G}{\sqrt{\rho}}$$
\[ c_t = \sqrt{\frac{E}{\rho}} \cdot \frac{1}{2(1+\nu)} = \sqrt{\frac{G}{\rho}} \]  

(5)

E – elastic modulus (Young’s modulus);  
\( \nu \) – lateral deformation ratio (Poisson’s ratio);  
\( \rho \) – density of the material;  
G – shear modulus;  
K – bulk modulus:

\[ K = \frac{E}{3(1-2\nu)} = \frac{EG}{3(3G-E)} = \frac{2G(1+\nu)}{3(1-2\nu)} \]  

(6)

c₁ – longitudinal wave velocity;  
cₛ – shear wave velocity.

3. Results and Discussion

Let us express the material density from equations (4) and (5).

Let’s square both sides of the equations.

\[ c_t^2 = \frac{E}{\rho} \cdot \frac{1}{2(1+\nu)} = \frac{K^4/\gamma G}{\rho} \]  

(7)

\[ c_s^2 = \frac{E}{\rho} \cdot \frac{1}{2(1+\nu)} = \frac{G}{\rho} \]  

(8)

The density of the material will be equal to:

\[ \rho = \frac{E}{c_t^2} \cdot \frac{1}{(1+\nu)(1-2\nu)} = \frac{K^4/\gamma G}{c_t^4} \]  

(9)

\[ \rho = \frac{E}{c_s^2} \cdot \frac{1}{2(1+\nu)} = \frac{G}{c_s^2} \]  

(10)

The value of Poisson’s ratio in accordance with clause 6.1.17 [20] is assumed to be 0.2.

If a building or structure has served a short period of time, then the value of the modulus of elasticity of concrete is taken depending on the compressive strength class of concrete in accordance with Table 6.11 [20]. The values of the concrete shear modulus are taken according to clause 6.1.15 [20] equal to 0.4Eb.

With prolonged action of the load, the value of the modulus of concrete deformation is determined by the formula:

\[ E = \frac{E_b}{1+\varphi_{b,cr}} \]  

(11)

\( E_b \) – initial modulus of elasticity of concrete, determined according to table 6.11 [20];  
\( \varphi_{b,cr} \) – concrete creep coefficient, determined according to table 6.12 [20].

Factors that influence the determination of the speed of ultrasound.

Measurement errors. When using the ultrasonic method, the error in determining the dynamic characteristics consists of several factors.

Error in calculating the propagation time of an ultrasonic pulse. Experience shows that the relative error of time measurement is no more than 0.1%.

Sample contact error. The probe is attached to the specimen using plaster, grease, etc. The presence of an intermediate medium will adversely affect the measurement results. The total assessment of this factor, as experience shows, is estimated at ± 2%.

Influence of concrete density. With a constant composition of concrete, its strength depends on the porosity. The more pores in concrete, the lower its density, and hence the strength. The pores impede the propagation of ultrasound, and therefore its speed functionally depends on the strength of the concrete. The fewer the pores, the greater the strength and the higher the speed of propagation of
ultrasound. For example, when the concrete porosity increases by 10%, the ultrasound speed decreases by 7%; if the increase in concrete porosity reaches 30%, the ultrasound speed is also reduced by 30%.

Influence of concrete age and conditions of its hardening. The hardening of concrete and the increase in its strength occurs mainly during the first month. As the concrete strength increases, the ultrasound speed also increases. Therefore, a significant increase in the ultrasound speed is observed only in the first month after the monolithic structure.

The hardening conditions of concrete also affect the propagation rate of ultrasound. Experiments have established that in steamed concrete, the ultrasound speed is lower than in concrete of the same strength with its natural hardening.

Influence of volume and type of aggregate. As you know, crushed stone or early stone of various mineralogical composition is used as a large aggregate in concrete. Concrete is a heterogeneous material, since the physical and mechanical characteristics of coarse and fine aggregates differ from the corresponding characteristics of cement stone. This circumstance determines different velocities of propagation of ultrasound in concretes of equal strength, made with the use of aggregates of different mineralogical composition. elastic properties of the aggregate.

In fine-grained concrete, the speed of ultrasound is influenced by the elastic properties of sand and cement. The mineralogical composition of sand practically everywhere varies within insignificant limits. Therefore, the varieties of sand have little effect on the speed of propagation of ultrasound. However, a change in the amount of sand significantly affects this indicator. So, an increase in the volume of sand by 10% entails a change in the speed of ultrasound by 5 ... 10%.

Effect of the amount of cement. It is known that with an increase in the amount of cement, the mechanical strength of concrete increases. Therefore, with the same content of coarse aggregate in concrete, a change in the amount of cement by 10...15% changes the propagation speed of ultrasound by 1...3%.

Influence of temperature. As the temperature rises, the ultrasound speed decreases. On average, when the concrete temperature rises by 10 °C, the ultrasound speed decreases by 40 m / s (approximately by 1%).

The influence of reinforcement. In the presence of reinforcement in concrete, the propagation speed of ultrasound increases. On average, in reinforced concrete, depending on the number and diameter of the reinforcement used, the ultrasound speed increases by 6...8% compared to concrete.

Influence of the stress state of concrete. The speed of propagation of ultrasound significantly depends on the stress state in concrete. When a concrete specimen is compressed by a gradually increasing load and its simultaneous sonication with ultrasound across the action of the force (or at a small angle of inclination, of the order of 2 ... 4%), an increase in the ultrasound speed is observed at the initial stage of loading. With a further increase in the load, the ultrasound speed begins to decrease. This behavior is due to the following circumstances. At the initial stage of loading, when the stresses in the concrete are low, its compaction occurs, which causes an increase in the ultrasound speed. At high stresses, cracks begin to appear in concrete, and this process increases with increasing load. With the appearance of cracks and with an increase in their number and length, the ultrasound speed decreases. decline. This behavior is due to the following circumstances. At the initial stage of loading, when the stresses in the concrete are low, its compaction occurs, which causes an increase in the ultrasound speed. At high stresses, cracks begin to appear in concrete, and this process increases with increasing load. With the appearance of cracks and with an increase in their number and length, the ultrasound speed decreases.

When a concrete specimen is stretched, the concrete does not compact, and therefore the ultrasound velocity constantly decreases with a gradual increase in the load.

4. Conclusions

The existing methods for determining the density of concrete structures were considered. The advantages and disadvantages of each of the presented methods are given.
The equations of the propagation velocity of ultrasonic waves in solid media were also considered. The density of the material is expressed from these equations. The authors proposed to use these equations to determine the density of concrete during ultrasonic testing of concrete and reinforced concrete structures. The authors give explanations on the definition of the parameters of concrete included in equations (7) and (8). The factors that influence the determination of the ultrasound velocity are given.

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