Physical modification of concrete mix and concrete

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Abstract. Numerous studies have established that the physicomechanical properties of concrete, in addition to cement activity, type of aggregates, etc., are determined by the V/C value of the concrete mixture [1, 2, 3, 4, 5, 6, 7, 8, 9, 10]. The dependence of the strength and water tightness of concrete on H/C follows from the physical nature of the formation of the concrete structure. Studying the process of cement hydration showed that cement, depending on the quality and duration of hardening, binds only 15 ... 25% of the water of its mass [11, 12, 13]. During the first month, at least 20% of the water by weight of the cement is bound. At the same time, to give the concrete mixture plasticity, improve the conditions of binder hydration, a significantly larger amount of water is introduced, since at W/C = 0.20 the concrete mixture remains practically dry and it cannot be qualitatively laid, molded and compacted. Excess water, without entering into chemical reactions with cement, remains in concrete in the form of water pores and capillaries or evaporates, leaving air pores. Undoubtedly this is the main reason for the decrease in the strength and waterproofness of concrete.

1. Introduction

For the formation of a mixture of given workability and optimal conditions for the hydration of a binder, it is necessary to use concrete mixtures with high moisture content. Using the provisions of [14], we can conclude that the formation of an optimal concrete mix is possible based on the use of a cement test diluted with water, relative to a test of normal density. The amount of dilution Z is determined from the dependence:

\[ Z = 1/([B/C]) - 1/(BC)_{\text{beginning}} \]  \hspace{1cm} (1)

where [B/C] is the normal cement density test;

\((BC)_{\text{beginning}}\) is the initial water-cement ratio of a given cement paste or concrete mix.

In this case, favorable conditions for hydration of the binder are created, structure formation is optimized, and, in particular, the volume of air pores is reduced.

However, to optimize the properties of concrete, to obtain ultimate strength, it is necessary to remove excess mixing water. The physicomechanical properties of concrete will be directly dependent on the amount of residual mixing water [1, 15]. If the concrete mix is compacted by squeezing a certain amount of free water, then the strength of concrete will be inversely functional with the residual H/C, since it determines the porosity of cement stone and concrete. Therefore, to obtain
concrete of extremely high strength and density, the pre-laid mixture must be additionally compacted under conditions of maximum dehydration of concrete. To preliminarily identify the factors affecting dehydration, we consider the process of compaction of a concrete mixture laid in a mold representing a cylinder with a solid wall. Assume that the mixture is compressed under normal pressure applied to the piston. If the volume of cement mortar \( V_{c.r.} \) available in the concrete mixture is less than the pore volume \( V_{pore} \) between the grains of the coarse aggregate, then normal pressure will be perceived only by the coarse aggregate, and the cement mortar will not take any pressure in this case. The influence of vibration-peristaltic pressing in these cases is likely to be negative, since, under the influence of normal force, there may be cases of fragmentation of individual grains of a large fraction, which leads to a decrease in the strength of concrete.

If \( V_{tsr.} = V_{sp} \) between the grains of the coarse aggregate, then the normal pressure will be perceived by the grains of all components of the concrete mix. Under these conditions, the effect of vibration-peristaltic pressing will be unstable. If \( V_{tsr.} \) will be a certain amount greater than \( V_{sp} \), then the normal pressure will be perceived only by the cement mortar, and the effect of vibration-peristaltic pressing will depend on the ability of the cement-sand mortar to deform. The solution will deform if the amount of cement paste is greater than the pore volume of the fine aggregate. Under these conditions, the entire load should be absorbed by the cement paste. With excess water in the cement paste, the entire load will be absorbed by the water. Therefore, to increase compaction efficiency vibration-peristaltic pressing requires that the cement paste is an environment in which grains of coarse and fine aggregates are located.

With complete tightness of the form, the mixture is compacted only due to a certain decrease in the volume of air involved, i.e., the effect of vibration-peristaltic pressing will be insignificant. This effect will increase with an increase in the permeability of the walls of the mold, as in the presence of filtration holes, free water under the influence of the pressure difference inside the mold and beyond starts to move towards the filtration holes. So, in the process of removing excess water and entrained air, the cement particles will begin to approach each other, which, in turn, will lead to the rapprochement of the grains of large and small aggregates. Normal-pressure transferred to the water and causing its removal will facilitate the approach of the particles until the external pressure is completely absorbed by the dispersed phase.

2. Methods

The duration of vibro-shock-peristaltic pressing of the concrete mixture to the required density, with variable normal pressure, is likely to depend on the number and permeability of the filter holes, with an increase in which the compaction time of the mixture will decrease [16].

The above arguments suggest that the most effective compaction of a concrete mix by vibration-peristaltic pressing will be achieved under the following conditions:

a) the absolute volume of the solution in the concrete mixture should exceed the pore volume of the intergranular space of the large aggregate by an average of 20...30% [17]. This will help to eliminate the formation of an incompressible hard coarse-grained skeleton;

b) the volume of cement paste in the concrete mixture should exceed the pore volume of the intergranular space of fine aggregate by 30...40%, which excludes the transfer of load from some sand grains directly to others;

c) the filtration capacity of the walls of the Forms, inside which the concrete mixture is compacted by vibration-peristaltic pressing, must meet the requirements of maximum dehydration for a relatively short compaction period.

In accordance with the foregoing, the effectiveness of concrete compaction by vibro-shock-peristaltic pressing depends on its composition, on the filtration capacity of the walls of the molds inside which the compaction is carried out, as well as on the level and mode of hyper-compaction.

As a result of the analysis of modern technologies, it was found that physical modification is possible by removing excess mixing water added to the concrete mixture to give it the necessary fluidity and workability.

As shown above, the removal of free water during the compaction of the mixture increases the use of the potential properties of cement to increase the density, water tightness, and strength of concrete.
Currently, in the technology of complex elements, several methods are known for dewatering the concrete mixture: centrifuging, pressing, evacuating, vibropressing, etc. One of the most effective methods is vibro-shock-peristaltic pressing since the necessary conditions can be created for maximum dewatering of the concrete mixture.

Based on the foregoing, it can be assumed that high-strength concrete, used, in particular, for the manufacture of low-pressure and non-pressure pipes can be obtained by compaction of the mixture by vibration shock pressing with intensive dehydration.

In the production of pipes, extrusion of free mixing water from a concrete mixture was carried out through a perforated surface of an external form covered with a special filter cloth [6, 18].

The main disadvantage of using such filters is the high consumption of manual labor. Therefore, the objective of this research is to find filters that have a simple structure that is easily accessible under industrial conditions and squeeze free water from a concrete mixture in a relatively short time. For this purpose, we investigated through conical holes arranged on the surfaces of the forms used [16]. The optimality of these filtration holes was evaluated by comparing their performance, i.e. allow free water to pass as much as possible with a low loss of cement paste. The geometry, density, and shape of the holes require special research.

The process of squeezing the liquid and gaseous phases from the molded material is the main process of structure formation and modification of concrete properties. The reason for removing liquid and gas from concrete is the pressure drop across the wall thickness of the pipe being formed towards the perforated surface of the formwork. Removing the liquid and gaseous media of the concrete mixture is an exfiltration process, i.e. removal of liquid and gaseous fluids from the material into the environment [19].

The main role in the formation of an extra-dense concrete structure is played by the process of concrete dehydration. The extraction of excess mixing water from the concrete mixture under the action of the applied normal pressure is a filtration process [1, 20]. An important role in it is played by the difference in the chemical potentials of the interacting phases and various gradients that arise in the system depending on the type of energy source, under the influence of which free water moves. The movement of free water under the influence of a humidity gradient occurs towards less moistened pores until the moisture is completely equalized.

Therefore, to remove free mixing water from the concrete mixture under the action of pressure, it is necessary to perform work (energy consumption) to overcome the bonding forces of water with cement particles and to move it into the system. Naturally, the main task of studying the transfer of excess mixing water from the concrete mixture is to determine the dependence of the parameters of vibration-peristaltic effects and the filtration rate on various technological parameters and the normal pressure value.

3. Results and discussion

It is known from fluid hydrodynamics that in a moving stream the pressure drop is directly proportional to its speed. It is obvious that when filtering excess mixing water from the concrete mixture, the pressure in it should also decrease under the influence of an external normal load, and it must be assumed that when the excess water moves in the space between the solvated cement particles in the diffuse boundary layers, a pressure difference will be created.

Water molecules in diffuse layers experience the action of forces directed to the surface of the solid phase, which decreases with increasing distance from the surface of the particles. At a certain filtration rate, a negative pressure of such magnitude can arise when the resultant of forces, one of which attracts water molecules to a solid surface, and the other draws it into a moving jet, will be directed away from the solid surface. In this case, the oriented water molecules in the diffuse layer will leave the sphere of influence of the attractive forces and will be involved in the moving flow.

When an external compressible load is perceived by a system of neutral pressures in the water filling the pores of the concrete mixture, hydrostatic pressure arises, which is immediately transmitted to adjacent grains of the aggregate and, as the mixture is compressed at the wall of the conical core, extends to the following layers of the mixture. In this regard, the hydrostatic pressure in the mixture...
decreases by the value, respectively, of that part of the total pressure experienced by the aggregate grains located at a certain depth from the surface of the conical part of the vibratory core.

Under the vibro-shock action of peristaltic waves on the concrete mixture, natural vibrations of aggregate grains are excited in it, which, in turn, leads to a certain dilution of the cement paste and redistribution of fluid in it. In a viscoplastic cement mortar test, a turbulent hydrodynamic process occurs, which under the influence of peristaltic wave pressure is accompanied by squeezing water from the layers of the mixture closer to the core, which leads to concrete compaction. In these cases, filtration channels directed towards the external form are formed, through which excess water is filtered under the action of peristaltic pressing. The outer form, in turn, has numerous specially designed filter cone holes [16]. The whole process of the initial vibration compaction, the extraction of water, and the air-water phase, as well as the subsequent hyper-compaction of concrete, can be represented as a complex three-stage process. This process is complex and consists of three stages different in the mechanism of action:

The stage of repacking components (the first stage of compaction). It consists in the destruction and restructuring under the influence of vibrations of the unstable structure of the skeleton of concrete aggregate aggregates. The grains that form it at the moment of destruction of the structure under the influence of their mass tend to occupy the lowest position, change mutual orientation, and form a new stable structure. Grain aggregates are not randomly placed in it, but it is most beneficial under the condition of obtaining a minimum volume of the skeleton. Simultaneously with the reconstruction of the skeleton, the bulk of the air is removed, mainly through perforated filter holes. After the end of the first stage of air, no more than 3...4% of the total volume of the concrete mixture remains.

Considering the peculiarities of the behavior of the concrete mixture at the first stage of vibration compaction, it can be noted that the re-laying of the components proceeds intensively only in the absence of significant static loads on the mixture. This creates the conditions for optimal re-laying of the components of the concrete mix. As experiments show, the time required to complete the first stage of compaction in the active (“vibro-boiling”) layers of the concrete mixture is relatively small and does not exceed 20...30 s even for hard mixtures.

Stage of convergence of the components (second stage of compaction). It begins when the restructuring of the concrete mix structure is over and after this change in it, the order of location of the aggregate grains by conventional means is practically impracticable. In the conducted approximation experiments, the relative displacements of the aggregate particles occur as a result of the redistribution of the mortar component and the cement paste through the volume due to the removal of the residual part of the air, as well as excess mixing water through the perforated external filter holes. Unlike the first, the second stage of compaction intensively proceeds under extremely constrained conditions, under the action of the applied combined vibro-shock-peristaltic effects.

To complete the second stage requires a longer time than for the first. The duration of this stage depends on the stiffness of the concrete mixture, the wall thickness of the concrete structure, the mode of vibration-peristaltic pressing, the filtration capacity of the mold and the initial value of H / C. For example, in the manufacture of unreinforced concrete pipes (with a diameter of 1000 mm, a length of 1500 mm and a wall thickness of 150 mm) from moderately hard mixtures, the stage of convergence of the components lasted 3 ... 5 minutes almost two orders of magnitude larger than the first stage. The completion of the second stage is clearly determined by the end of significant deformations of the concrete mixture, after which the structure of fresh concrete can be considered established. Further vibration practically does not increase the density and strength of concrete, nor does it improve the quality of its surface.

Stage of complex compaction of the concrete mixture (third stage of compaction). Experiments show that after the second stage of compaction is completed, some additional (compression) compression can still be achieved by combining intense peristaltic pressure with shear reciprocating movement of the external perforated shape relative to the vibrating cord. Since this measure is carried out without stopping vibration impact, a useful effect in the form of increasing the strength and density of concrete is achieved in a relatively short time (up to 1 ... 3 min.). The effect under consideration is achieved as a result of squeezing out the residual part of the excess mixing water with the air dissolved in it, as well as the hyper-consolidation of the contacts between the filler grains.
It can be seen from the foregoing that the process of compaction of the concrete mixture at different stages is subject to various laws. At the first stage, the concrete mixture behaves as a viscous-bulk medium subjected to vibrational movements. In the second stage, resisting the cohesion of the components and the extraction of the water-air phase, the mixture reacts to an external sealing effect, like a visco-elastic-plastic body characterized by a certain deformation modulus. In the third stage, the optimal combination of the filtration properties of the concrete mixture and the perforated mold is of decisive importance. In this case, the freshly formed mixture is deformed according to the laws of the dynamics of multicomponent media.

Attention should be paid to the qualitative difference between vibration compaction of concrete mix and hypercondensation of concrete in this case. Conventional one-stage compaction is replaced by a high-intensity three-stage hyper-compaction, as a result of which the compaction coefficient \( Ku \) approaches a theoretically possible value of one. Three-stage hyper-compaction will be especially effective in obtaining a concrete mixture with optimal vibration viscosity, elasticity, and the ability to absorb energy in the process of vibrational vibrations. This important conclusion determines the need to develop a reliable method for assigning concrete compositions that meet given conditions. Moreover, using the research of O.A. Savinova and E.V. Lavrinovich [21] concrete mixture can be represented as a viscous fluid with a constant visco-
sity coefficient.

In addition to determining the optimal composition of concrete, it is also necessary to determine the physicomechanical properties of the concrete mixture and concrete. The simplest is to determine the integral characteristic of the deformability of concrete or the effective modulus of deformation of the concrete mixture. To do this, consider the first stage of compaction of the concrete mixture described above.

Consider the axial deformation of a column of the concrete mixture containing air bubbles and located in the first stage of compaction (Fig. 1). We will proceed from the condition that when filling the form with concrete mixture, air volume \( V_0 \) is involved (per unit height). The above nature of the distribution of pores in the product, this condition does not contradict. In this case, at the first stage of compaction of the mixture, the air content varies in height, and at a certain distance \( x \) from the surface will be:

\[
V_x = \frac{1}{1 + \rho \cdot x / P_{atm}} \tag{2}
\]

where \( P_{atm} \) is the atmospheric pressure; \( \rho \) is the mixture density.

An auxiliary graph for determining the effective elastic modulus \( E_e \)

![Figure 1](image)

Applying some additional pressure \( P \) to the surface of the concrete column, then, based on the physical Boyle-Mariott law, we accept:

\[
(\rho \cdot x + P_{atm}) \cdot V_0 / (1 + \rho \cdot x / P_{atm}) = (\rho \cdot x + P_{atm} + P) \cdot V_0 \cdot 1 / (1 + \rho \cdot x / P_{atm} - V) \tag{3}
\]

where \( V \) is the value by which the volume of air inclusions decreases when pressure is applied \( P \).

From (3) it is easy to obtain the relationship between \( P \) and \( V \):
\[ V = \frac{P \cdot V_0}{(\rho \cdot x + P_{atm} + P)} \cdot \frac{1}{(1 + \rho \cdot x/P_{atm})} \]  

(4)

At \( P \ll x + P_{atm} \), expression (4) can be replaced by an approximate dependence:

\[ V \sim P \cdot V_0/P_{atm} \cdot 1/(1 + \rho \cdot x/P_{atm})^2 \]  

(5)

Thus, when loading a column of concrete mixture under one-dimensional deformation, for example, laid in a constant section shape, and uniformly distributed axial load, we can consider the mixture as a quasi-elastic body with some effective normal elastic modulus \( E_e(x) \). Comparing (5) with the well-known formula for determining the change in an elastic rod under the influence of axial load (i.e., Hooke’s law \( E \cdot \delta / \varepsilon \)), we obtain a formula for determining the effective elastic modulus \( E_e(x) \) of a concrete mixture at a distance \( x \) from the top of the pillar:

\[ E_e(x) = \frac{P_{atm}((1 + \rho \cdot x)^2)}{\varepsilon_0} \]  

(6)

where \( \varepsilon_0 = V_0/V_c \) is the ratio of the initial volume of air involved when laying the concrete mixture to the full volume \( V_c \) of the vibrated product.

As a result of an analytical study, we find the average value \( E_e^* \):

\[ E_e^* = 1/h \int_0^h E_e(x) \cdot dx = \frac{P_{atm}/\varepsilon_0}{(1 + \rho \cdot x/H_{atm})^2} \int_0^h (1 + \rho \cdot x/H_{atm})^2 dx = v \cdot P_{atm}/\varepsilon_0 \]  

(7)

where

\[ v = 1 + \rho \cdot h/P_{atm} + 1/3 (\rho \cdot h/P_{atm})^2 \]  

(8)

To calculate the coefficient \( v \), we can use the expression

\[ v_p = (1 + \rho/P_{atm})^2 + (1 + P/P_{atm}) \cdot \rho \cdot h/P_{atm} + 1/3 (\rho \cdot h/P_{atm})^2 \]  

(9)

The graph for determining the coefficient \( v \) in expression (7) is shown in Figure 2.

Table 1 shows the experimental data on the deformability of various types of concrete mix and the value of the effective modulus of normal elasticity \( E_e^* \). From the above data, one can see a tendency to an increase in the elastic modulus with an increase in the size of the filler, which is explained by the different ability of the mixtures to attract and retain air.

![Graph for determining the coefficient \( \nu \).](image_url)

Experimental data for determining the module \( E_e^* \) for various concrete mixtures

| Type of mixture | Mixture characteristics | \( E_e^* \) MPa | \( \varepsilon_0 \) | \( \varepsilon_k \) |
|-----------------|------------------------|-----------------|-----------------|-----------------|
| I               | Fine concrete          | 1…2             | 0.12…0.09       | -               |
| II              | Fine concrete          | 2…4             | 0.11…0.08       | -               |
|                 | \( d_{max} = 10 mm \) |                 |                 |                 |
| III             | Heavy concrete         | 3…6             | 0.10…0.06       | -               |
The ability of a concrete mixture to absorb energy during vibration-peristaltic influences is also of great importance for hyperapparted mixtures. The disclosure of this pattern allows us to predict the technological parameters of compaction. However, at present, this ability has not been adequately studied, due to the complexity of the deformation mechanism of the medium under consideration, accompanied by internal friction of the aggregate grains, the course of the cement paste and energy losses as a result of volumetric deformations of air inclusions.

Analyzing the data of various experimental studies [21, 22, 23], we conclude that at the present stage of research, when determining the compaction stresses, one can use an elastic-viscous concrete model:

$$\delta = E_0^* \varepsilon + K_0 \frac{d \varepsilon}{dt}$$

(10)

where $K_0$ is the coefficient of viscous resistance determined experimentally.

For hyper-compacted concrete, the elastic part of the stresses ($E_0^* \varepsilon$) significantly exceeds the visco-plastic component of stresses. At the end of the compaction, the hyper-compacted modified concrete behaves like a solid.

4. Conclusions
1. It has been established that during physical modification and hypercondensation of a concrete mixture using vibro-shock, shear, and peristaltic compaction, the process of structure formation leads to a change in the morphology of the hydrated binder compared to ordinary vibrated concrete.

2. A system of patterns of vibration-peristaltic effects on the concrete mixture was obtained, which brought out significant differences in the compaction process from a single impact and vibration compaction. At the same time, the occurrence of high-intensity compression and tension zones alternating in time in the column of the mixture to be compacted was proved and quantitative characteristics were obtained for determining the parameters of compression.

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