Study of changes in strength properties along section thickness of high-strength centrifuged and vibro-centrifuged concrete

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Abstract. Improving the efficiency of precast concrete products and structures can be achieved by creating thin-walled products of effective cross-sections from high-strength concrete the formation of which requires application of centrifugal methods of compaction. The paper discusses literature data on the issue of forming the structure of centrifuged concrete by the thickness of the section wall, taking into account different densities of the components of the molded concrete mass under the action of centrifugal forces during mold rotation during concrete compaction at a constant speed. The authors conducted a series of experimental studies to establish the nature of the change in strength properties along the thickness of cross section of products from heavy concrete made by centrifugation and vibrocentrifugation. As a result of experiments, it was found out that the density of samples of centrifuged structures decreases in cross section from the outer layer to the inner one. The greatest values of ultimate strength under axial compression and tension during bending are characterized by the outer layer, the smallest are characterized by the inner layer. The middle layer in terms of strength indicators is close to the average strength of the whole product. A feature of changes in compressive and tensile strength during bending of vibro-centrifuged products and structures compared to centrifuged layers is a smaller difference between the outer and middle layers and a significant difference between the outer and inner layers. It was established that the variability of the structure of high-strength concrete is less pronounced compared to the lower-grade concrete.

1. Introduction

The development of modern construction takes the path of improving the designs and shapes of buildings, which is facilitated by the improvement of the physical and mechanical properties of building materials. The use of high-strength concrete and steels leads to the creation of lighter thin-walled reinforced concrete structures and is possible only with an advanced technology of manufacturing the elements and developed theory aimed to produce calculations for them.

The improvement of the efficiency of precast concrete products and structures can be achieved by creating thin-walled products of effective cross-sections from high-strength concrete, for the casting of which it is advisable to use centrifugal compression methods [1].
From the literature data [2–5] it is known that the concrete structure along the wall thickness of an as-formed pipe, taking into account different densities of the components of the molded concrete mass under the influence of centrifugal forces when the mold rotates during the compaction of the concrete mixture at a constant speed, becomes sharply inhomogeneous. This phenomenon is explained by the fact that centrifugation is both a method of forming pipes and a method of separating concrete mixture. In most cases, on the outer surface of the product there is concrete of regular texture, then fine-grained porous concrete, and on the inner surface there is a layer of cement stone with scarce impregnations of aggregate covered with a sludge layer that is to merge when the centrifugation is over.

The heterogeneity of the concrete structure is aggravated by the presence of pores and capillaries of various nature, formed during the hardening of as-formed pipe, since the water that previously filled both the ducts and the pores as well as capillaries of other origin evaporated. The number and size of pores and capillaries depend on the volume of water introduced into the concrete mixture, the dispersion of cement, its mineralogical composition, the quantity and the nature of mineral additives, hardening conditions, and other processing factors [6, 7].

To obtain a dense and uniform structure of centrifuged concrete, previous researchers of the centrifugation process most often attempted to select a concrete mix that would allow concrete to be created by centrifugation of the required density and strength. A fairly homogeneous concrete structure of the pipe walls can be obtained by using aggregate of different densities in one batch, which, when centrifuged, is distributed over the thickness of the product wall according to its bulk weight. However, in most cases, the pipe plants do not want to use these methods because of the difficulties in both the selection of concrete composition and the supply of aggregates or other components of the mixture. In most cases, especially in the production of non-pressure pipes, ready-mixed concrete of common composition is used.

Under the influence of normal pressure distributed unevenly along the wall thickness of the molded product from a minimum on the inside to a maximum on the outer surfaces, the liquid phase cannot simultaneously be squeezed out of the entire thickness of the concrete. When the concrete mixture is pressed with constant pressure, the aggregate grains clamp finely divided liquid fraction, interfering with squeezing out of excess mixing water.

Since the excess mixing water is squeezed out under constant pressure along radially oriented filtration channels, it is obvious that the cross-section of these channels increases as it approaches the inner surface of the compacted mixture, similar to a river bed as it approaches the mouth of the river. Moreover, the larger the initial water-cement ratio, the greater the total amount of squeezed water and, therefore, the greater the cross-sectional width of these channels. In addition, the cross-sectional dimensions of the channels also depend on the thickness of the sealing layer. This circumstance leads to an increase in the water impermeability of the pipe walls during layer-by-layer centrifugation, when the cross-section of the ducts of each layer is minimal, directly proportional to the thickness of the layer, and, in addition, the mouths of the ducts fill up when forming the next layer. At the end of centrifugation, the movement of fluid along the ducts slows down and, if the centrifugation time is too long, it stops. However, the ducts remain filled with liquid and after hardening, there are radial pores that drastically reduce the water impermeability of the products.

In addition to the amount of squeezed water and the thickness of a packed layer, the cross-sectional dimensions of the filtration ducts are significantly influenced by another factor, i.e. the speed of squeezing water through these channels. It must be said that the speed of squeezing water during the compaction process varies very significantly.

It is obvious that the maximum width of the channel in the cement paste corresponds to the maximum rate of squeezing out water. Under the traditional molding conditions and under the influence of constant pressure, the maximum amount of squeezed out water is observed at the very beginning of the centrifugation process, and then it gradually decreases. Thus, the channel of the duct, formed at the very beginning of the process of compaction of the concrete mixture, becomes redundant. The question arises whether it is impossible to squeeze out the required amount of water
through the channels of a smaller cross section at a more constant speed. A smooth molding condition, which provides for a very slow growth in the sealing numbers of mold rotations, will lead to a significant decrease in the speed of squeezing out water.

Let us introduce the concept of centrifuge acceleration intensity, which characterizes a smooth (slowed down) increase in the number of mold revolutions from distribution to sealing for a certain period of time as the main factor determining the formation of the most dense and strong structure of centrifuged concrete.

In the traditional molding conditions under the constant pressure, the aggregate grains prevent free compaction of the cement paste.

Centrifugal compaction of the concrete mixture is mainly associated with the movement of coarse aggregate along the wall thickness of the molded product in the direction from the inner surface of the pipe to the outer surface, and the liquid phase of the mixture in the opposite direction. The movement of the coarse aggregate is much easier with a minimum amount of friction in the system. This can be achieved by selecting the optimal ratio of sand and gravel in the concrete mixture, as well as by selecting a water-cement ratio taking into account the moisture content of coarse and fine aggregate.

During centrifugation, the water-cement ratio during compaction is reduced. Plastic concrete mixes are better compacted; however, at the same time, with the phenomenon of separation, the amount of sludge drained from the pipe at the end of centrifugation increases. Together with the sludge, a significant part of the cement merges, which is presented in the form of suspension in the sludge. From this point of view, hard concrete mixtures are much more efficient. Nevertheless, in traditional centrifugation modes, a more or less satisfactory quality of the pipes is obtained only when using sufficiently plastic concrete mixtures with an initial water-cement ratio of more than 0.6 and a cone draft of more than 5 cm. When forming pipes in the smooth centrifuge dispersal mode, it is possible to use sufficiently slump concrete with an initial water-cement ratio of 0.45–0.5 and a cone slump of 2–4 cm.

The change in the process of separation of water from the cement-water system during centrifugation was considered. At the initial stage of compaction, with insignificant centrifugal forces, water is separated in physicomechanical bonds, which has lower binding energy than adsorption water. This period is characterized by the absence of structural bonds between particles of the solid phase. In other words, particles of a solid phase under the influence of a centrifugal force field settle in the mixture move in the liquid phase, displacing it into the inner layers. This process lasts until structural bonds arise between all cement flocs. A small amount of water remains in micropores and capillaries of the system, usually in the form of liquid-water menisci with small radii of curvature and high binding energy. In the following steps, at high centrifugation speeds, water separation decreases. During this period, the remaining capillary, as well as loose-bound adsorbed water is separated. By the end of centrifugation, the water should remain in the concrete mixture exclusively in physical and chemical bonds.

This circumstance makes it necessary to limit the duration of centrifugation, especially when only maximum pressure is applied to it. Excessively long rotation of the centrifuge at constant sealing speed of the mold will ultimately lead to dehydration of the concrete mixture and reduce the strength of the centrifuged samples. Therefore, when centrifuging, it is very important to determine the optimal parameters of molding conditions.

Since the centrifugation process is both a method of compacting the concrete mixture and a process of its separation, which, in contrast to the process of compacting the concrete mixture, negatively affects the strength and other characteristics of the concrete mixture. The concrete mixture is good if the aggregate grains move under the action of centrifugal forces to the outer layer through the cement paste, which they cannot squeeze onto the inner surface at its normal viscosity, but compact it with each other. Therefore, a well-compacted concrete mixture is characterized by a high content of cement paste with a low moisture content and, therefore, less separation of concrete mixture. On the contrary, during centrifugation of a very mobile mixture, a large separation occurs, as a result of which the compaction leaves much to be desired [8].
A decrease in the acceleration rate of the centrifuge gives another very important effect when forming tubular products designed to move liquids containing a significant amount of organic and inorganic impurities, namely non-pressure and pressure sewer and culverts. In the process of molding a denser and more uniform structure of concrete, the walls of the pipes improve the quality of their inner surface by reducing the separation of concrete mixture during smooth acceleration of centrifuge and more careful packing of the aggregate grains not only on the outer surface of the products, but also on its inner surface.

The degree of compaction during centrifugation depends on the amount of water squeezed out of the concrete mixture. At the same time, the water-holding capacity of cement, which is determined by the fineness of cement grinding, as well as the amount and type of mineral additives is of great importance. Tripoli powder is a common additive to Portland cement, but during centrifugation most of this finely dispersed additive is carried out on the inner surface of the pipe being molded and, at the end of centrifugation merges with the sludge. This fact significantly reduces the effectiveness of additives during centrifugation. It is advisable either to reduce the number of additives in cement intended for centrifuged pipes, or to use non-additive cements. However, there is no special cement production for pipe production; therefore, a significant role in saving material resources is played by the reduction of sludge during centrifugation. From this point of view, pipe molding in the conditions of smooth acceleration of centrifuge also gives an additional positive effect, since not only the absolute output of the liquid into the slurry is reduced, but also the number of fine fractions in the slurry composition due to a decrease in the separation of concrete mixture [2–5, 8].

2. Methods and materials
In the research laboratory of the Department of Technology of Binders, Concrete and Building Ceramics, DSTU, the authors conducted a series of studies to establish the nature of the change in the strength properties of the section thickness of heavy concrete products made by centrifugation and vibration centrifugation methods.

In order to streamline the collected experimental data, according to the methods described in previous works, the authors produced and studied concrete products of class B60 manufactured by centrifugation and vibrocentrifugation methods and brought to uniformity for the convenience of analytical comparison of the results [9–11]. The values of the concrete properties such as axial compression strength and tensile strength in bending were subject to comparison.

3. Results
The authors experimentally selected compositions of centrifuged and vibrocentrifuged concrete, which made it possible to obtain high-strength concrete of class B60 and higher in laboratory conditions. The cross section of centrifuged and vibrocentrifuged products was divided into three layers of equal thickness: external, medium and internal. The experimental results are presented in Tables 1–4 and graphically shown in Fig. 1–4.

**Table 1.** Test results of high-strength centrifuged concrete (hscc) by the layers of the products cross-section on such indicator as ultimate compressive axial strength at the age of 28 days

| Concrete Design Class | Test results against cross-section layers of the samples | Section test results without layering |
|-----------------------|--------------------------------------------------------|--------------------------------------|
|                       | Density, kg/m³ | Strength, MPa | Density, kg/m³ | Strength, MPa | Density, kg/m³ | Strength, MPa |
| B60                   | 2531          | 82.2          | 2498          | 72.0          | 2478          | 72.9          | 2510          | 76.5          |
|                       | 2522          | 81.5          | 2508          | 75.3          | 2482          | 73.2          | 2500          | 72.9          |
|                       | 2518          | 82.7          | 2510          | 74.8          | 2488          | 71.7          | 2498          | 74.1          |
|                       | 2529          | 83.0          | 2495          | 73.8          | 2489          | 71.4          | 2512          | 74.5          |
|                       | 2525          | 80.9          | 2492          | 75.5          | 2484          | 71.0          | 2502          | 75.3          |
|                       | 2523          | 83.4          | 2500          | 72.6          | 2492          | 70.8          | 2495          | 75.5          |
| Average               | 2525          | 82.8          | 2501          | 74.9          | 2486          | 72.3          | 2503          | 75.5          |
The layers of the products cross under axial compression and tension during bending between the strength of the whole product (without dividing into layers). The difference in the limits of strength bending, and the outermost layer is characterized by the highest tensile strengths under axial compression and tensile same trend is observed with the strength characteristics of high changes as follows: It decreases along the cross section on such indicator as

**Table 2.** Test results of high-strength centrifuged concrete (hscc) by the layers of the products cross-section on such indicator as tensile strength at the age of 28 days

| Concrete Design Class | Test results against cross-section layers of the samples | Section test results without layering |
|-----------------------|--------------------------------------------------------|-------------------------------------|
|                       | Density, kg/m³ | Strength, MPa | Density, kg/m³ | Strength, MPa | Density, kg/m³ | Strength, MPa |
| B60                   | 2531          | 8.86          | 2498          | 7.64          | 2478          | 7.75          | 2510          | 8.18          |
|                       | 2522          | 8.78          | 2508          | 8.04          | 2482          | 7.78          | 2500          | 7.75          |
|                       | 2518          | 8.92          | 2510          | 7.98          | 2488          | 7.60          | 2498          | 7.89          |
|                       | 2529          | 8.96          | 2495          | 7.86          | 2489          | 7.57          | 2512          | 7.94          |
|                       | 2525          | 8.71          | 2492          | 8.06          | 2484          | 7.52          | 2502          | 8.04          |
|                       | 2523          | 9.01          | 2500          | 7.71          | 2492          | 7.50          | 2495          | 8.06          |
|                       | 2525          | 8.94          | 2501          | 7.99          | 2486          | 7.68          | 2503          | 8.06          |
| **Average**           | 2523          | 8.94          | 2501          | 7.99          | 2486          | 7.68          | 2503          | 8.06          |

**Table 3.** Test results of high-strength centrifuged concrete (hscc) by the layers of the products cross-section on such indicator as ultimate compressive axial strength at the age of 28 days

| Concrete Design Class | Test results against cross-section layers of the samples | Section test results without layering |
|-----------------------|--------------------------------------------------------|-------------------------------------|
|                       | Density, kg/m³ | Strength, MPa | Density, kg/m³ | Strength, MPa | Density, kg/m³ | Strength, MPa |
| B60                   | 2527          | 86.3          | 2518          | 84.2          | 2498          | 75.1          | 2516          | 81.7          |
|                       | 2518          | 87.9          | 2514          | 83.8          | 2499          | 75.4          | 2510          | 80.4          |
|                       | 2529          | 88.9          | 2528          | 86.0          | 2505          | 74.9          | 2500          | 82.6          |
|                       | 2525          | 89.5          | 2512          | 85.1          | 2489          | 75.1          | 2515          | 83.2          |
|                       | 2523          | 89.0          | 2519          | 84.3          | 2492          | 72.8          | 2519          | 79.9          |
| **Average**           | 2523          | 88.8          | 2520          | 85.5          | 2494          | 75.4          | 2514          | 82.2          |

**Table 4.** Test results of high-strength centrifuged concrete (hscc) by the layers of the products cross-section on such indicator as tensile strength at the age of 28 days

| Concrete Design Class | Test results against cross-section layers of the samples | Section test results without layering |
|-----------------------|--------------------------------------------------------|-------------------------------------|
|                       | Density, kg/m³ | Strength, MPa | Density, kg/m³ | Strength, MPa | Density, kg/m³ | Strength, MPa |
| B60                   | 2527          | 9.36          | 2518          | 9.10          | 2498          | 8.13          | 2516          | 8.80          |
|                       | 2518          | 9.55          | 2514          | 9.39          | 2482          | 8.05          | 2522          | 8.74          |
|                       | 2514          | 9.30          | 2530          | 9.06          | 2499          | 7.72          | 2510          | 8.65          |
|                       | 2529          | 9.67          | 2528          | 9.32          | 2505          | 7.99          | 2500          | 8.91          |
|                       | 2525          | 9.74          | 2512          | 9.21          | 2489          | 8.01          | 2515          | 8.98          |
|                       | 2523          | 9.68          | 2519          | 9.12          | 2492          | 7.74          | 2519          | 8.59          |
| **Average**           | 2523          | 9.66          | 2520          | 9.26          | 2494          | 8.05          | 2514          | 8.86          |

4. Conclusion
As the result of the experiments, it was found out that the density of samples of centrifuged structures changes as follows: It decreases along the cross-section from the outer layer to the inner one. The same trend is observed with the strength characteristics of high-strength centrifuged concrete: the outermost layer is characterized by the highest tensile strengths under axial compression and tensile bending, and the inner layer is the smallest one. The strength indicators of the middle layer is close to the strength of the whole product (without dividing into layers). The difference in the limits of strength under axial compression and tension during bending between the outer and inner layers is about 15 %.
Figure 1. The dependence of the tensile strength on axial compression on the layer cross-section of the centrifuged product: 1 – outer layer; 2 – middle layer; 3 – inner layer; 4 – one piece product

Figure 2. Dependence of tensile strength in bending on the layer of the cross-section of centrifuged product: 1 – outer layer; 2 – middle layer; 3 – inner layer; 4 – one piece product

Figure 3. Dependence of tensile strength on axial compression from the layer of the cross-section of vibrocentrifuged product: 1 – outer layer; 2 – middle layer; 3 – inner layer; 4 – one piece product

Figure 4. Dependence of tensile strength in bending on the layer of the cross-section of vibrocentrifuged product: 1 – outer layer; 2 – middle layer; 3 – inner layer; 4 – one piece product
The peculiarity of changes in compressive and tensile strength during bending of vibrocentrifuged products and structures compared to centrifuged products in layers is a small difference (3–5 %) between the outer and middle layers and a significant difference between the outer and inner layers (15–20 %).

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