Constituent components of 3D printing in construction: mixture, reinforcement and their main characteristics

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Abstract. Construction 3D printing is one of the most promising areas in the construction of various structures. Thanks to the possibilities of automation, digital concrete production makes it possible to create complex structures that withstand the same forces as structures with standard geometry, but with increased structural efficiency and lower material consumption. This work is aimed at determining the main characteristics of mixtures for 3D printing and reinforcement strategies that are compatible with this technology. In addition, the article presents the results of a study of the strength characteristics of concrete used for 3D printing of building structures. The experiment was carried out by means of compression tests of concrete samples-cubes cut from the printed design with the dimensions of the rib 150, 100, 70 and 50 mm. This article can indicate the current state of affairs of 3D printing technology in construction, as well as indicate the direction of further research in this field.

1 Introduction

Today, the construction industry is on the verge of drastic changes. For decades, the material that combines steel and concrete occupied a dominant position in construction. Thanks to the ability to create various structures of any shape, original floor designs, bold shell designs, elegant bridge designs, reinforced concrete is popular among construction sector engineers. But regardless of these factors, reinforced concrete is also a material that is closely related to high CO_2 emissions caused by the production of clinker as the main component of cement, and a more detailed examination of the specified problem reveals that most CO_2 emissions occur due to the inefficient use of steel and concrete Instead of thin-walled shell structures, today's construction activity is dominated by thick-walled concrete components prone to bending loads. The consequence of this is a permanent increase in labor costs and costs associated with the use of system formwork, which has replaced economical building systems that require individual, time-consuming manufacturing of forms [1].

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One of the factors of the rapid development of the construction industry is the total digitization of all construction processes, starting from planning and ending with building operation. Automation of the production process plays one of the main roles here. The most widely used technology in this field may be the so-called 3D printing.

3D printing technology is the process of creating complete three-dimensional objects of almost any geometric shape based on a digital model. Currently, the most common method of 3D printing of concrete is the layer-by-layer application of strands of deformable plastic material by the extrusion method [1]. Extrusion is a process in which the material is pushed through a nozzle and placed by the head in a certain place as the print head moves in space. This method was first proposed by Dr. Beroch Hoshnevis in 2004 and registered under the trademark Contour Crafting [2].

The use of 3D printing technology will allow engineers to design more daring, free and materially efficient forms, as with traditional methods of construction from reinforced concrete, this is complicated by the use of formwork.

However, 3D printing is still in its infancy and its application is limited to certain areas due to technical shortcomings. In particular, in the construction industry, further research is needed to find precise mechanical control, suitable materials for printing, a dosing system using these materials, and reinforcement strategies for printed elements [3].

2 Properties and characteristics of mixtures for 3D printing

Compared to traditional construction methods, the requirements for materials used in 3D printing technology may have some differences. In terms of fresh material requirements, this means that the typical requirement for fresh concrete (in this case self-compacting) goes from being “fluid enough to fill a given shape by gravity pouring alone” to “ability to take shape and retain that shape until solidification” [2]. To meet the specified requirements, the material must have an optimal composition and consistency, as well as meet the technical characteristics of the equipment through which the material will be fed.

In addition, important characteristics of the material are its “open time”. Open time is the period of time during which material is continuously fed through the nozzle without stopping or clogging. Open time is determined by measuring the period of time during which the material is extruded continuously. The open time can be controlled by adding a dose of superplasticizer, retarder, and setting accelerator [3].

Also, one of the important indicators is the strength of the connection at the boundary between the layers. To date, not much attention has been paid to this issue. There is an assumption that the interlayer strength is related to the superficial, highly localized drying of the first layer, and insufficient moisture for hydration of the cement powder can reduce the strength of the interface between the layers [2]. To increase the strength of the interface between the layers, the following options are proposed: placing an additional layer of cement mortar between the layers, including a primer in the composition of the printing solution, or changing the geometry of the printing nozzle opening to create a printed layer with grooves.

No less disturbing issue is the durability of printed structures. Since today careful work is being done on printing materials, methods of reinforcing printed structures, hardware and software development, much less time is devoted to long-term effects. A factor that affects the durability of printed structures is the use of plasticizers, retarders and accelerators of setting, which can negatively affect the durability of fittings. The interlayer interval time has a negative effect on the printing solution. An increase in the time of the interlayer interval leads to an increase in porosity and, as a result, to the possibility of capillary water ingress.

It is also important to note the parameters of the printing equipment and its settings, which can significantly affect the quality of the printed design. The speed of movement of the printing head, the geometry of the opening of the printing nozzle and its size, the height of the placement of the nozzle above the printed structure − these parameters are an important aspect of printing concrete structures. Thus, even when using the same composition of the solution and when changing the above parameters of the 3D printer, the characteristics of the printed structure may change.

But the most important requirement for a concrete mixture for 3D printing of building structures is strength. The specified characteristic of concrete can be obtained by adjusting the composition of the mixture. The influence of the strength change factor on the properties of concrete for 3D printing of building structures can be established only on the basis of experimental studies of the characteristics of concrete.

Taking into account the above, the task was set to determine the strength characteristics of concrete, which is used for 3D printing of building structures and consists of: crushed stone; river sand; portland cement M500 Heiderberg cement; water; plasticizer and hardening accelerator.

Building structures were made layer by layer by squeezing the mixture from the container of the concrete paver through a nozzle with a diameter of 40 mm, obtaining a layer of the mixture with a width of 55-60 mm. The movement of the carriage, which is connected to the capacity of the concrete paver in the required direction, was set using a computer program in the G-code language.

To conduct a study of the strength and density of concrete from building structures printed on a 3D printer, samples were cut out − cubes with dimensions of 150×150×150, 100×100×100, 70×70×70 and 50×50×50 mm. Six samples of each size were cut for research. In this way, a total of 24 cube samples were made for conducting research.

The compressive strength of concrete in MPa was determined in laboratory conditions on cube samples according to the regulatory document [4]. Samples − cubes with dimensions of 150×150×150 mm and 100×100×100 mm were crushed on a P-125 press. Cube samples with dimensions of 70×70×70 mm and 50×50×50 mm were crushed on a UMM-20 press. The load lifting speed was 4 kN per second.

The limit of compressive strength was determined by the ratio of the destructive load to the cross-sectional area of the sample.

The average strength of concrete was determined according to the regulatory document [4, p.18], which provides that only the four largest should be taken from six sample tests to calculate the strength.

The density of the samples in kg/m^3 was determined according to the normative document [5] by their control weighing and the ratio of this weight to the volume of the sample. The volume of the sample was determined by marking it and measuring the dimensions in characteristic sections.

The average density of concrete was determined based on the results of studies of four samples, the same ones that were taken into account when calculating the average strength.

Figures 1 and 3 show diagrams of the dependence of the compressive strength and density of the concretes that were selected from the structures on the sizes of the samples that were used in the research, and Table 1 shows the generalized results of the strength and volume weight of the concretes and practically the indicators of scale coefficients are determined.

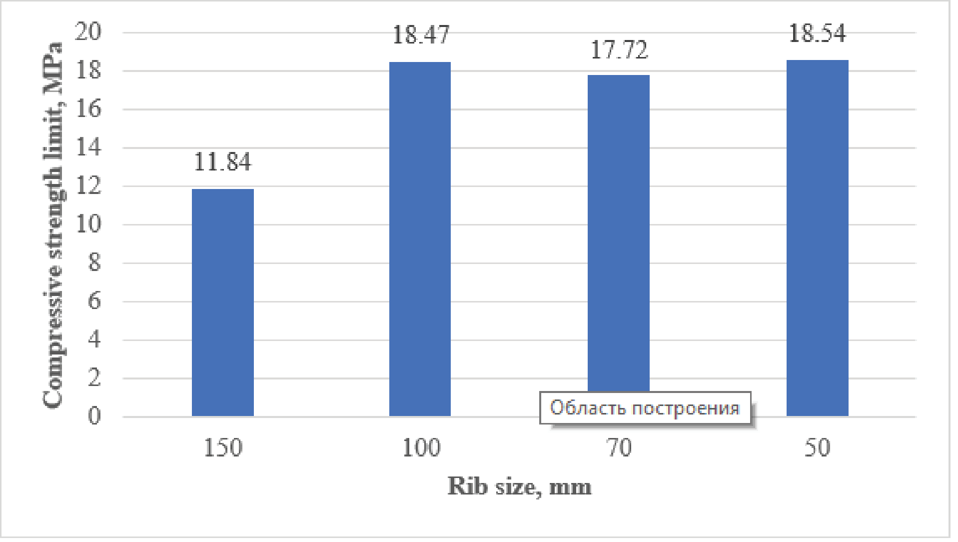

Fig. 1. Dependence of the compressive strength of concrete on the size of the samples

All concrete samples after strength tests had a typical nature of destruction. In Figure 2 the typical nature of the destruction and the structure of the inner surface of cube samples with dimensions of 100×100×100 mm are given.

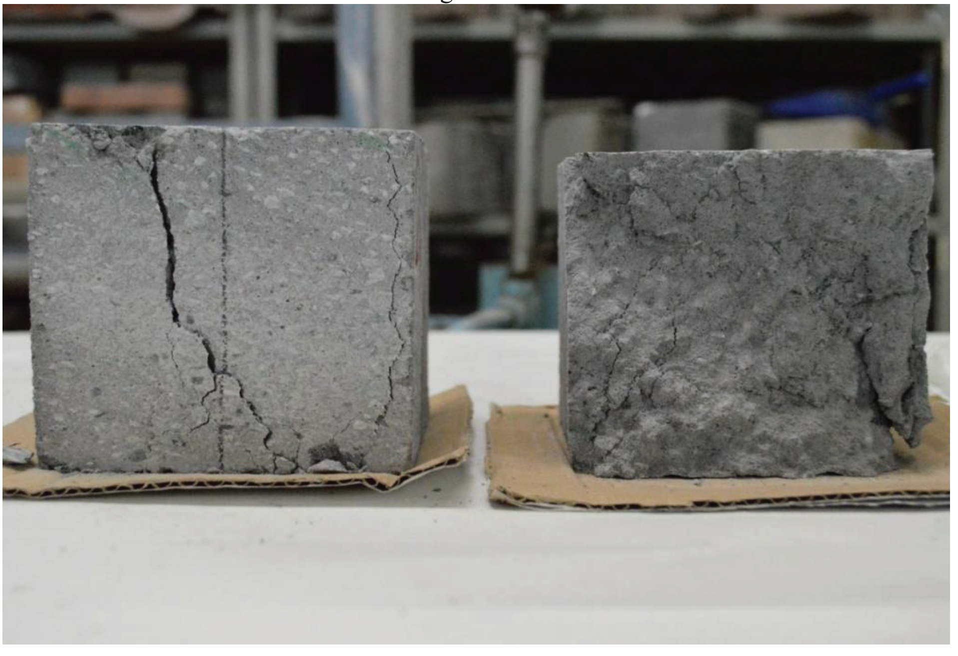

Fig. 2. Typical nature of destruction and structure of the inner surface of cube samples with dimensions of 100×100×100 mm

The structure of the inner surface of concrete is uniform. The binder is evenly distributed between aggregate grains. Adhesion of the binder to the aggregate grains. The porosity of the bond is minimal.

Table 1. Results of determination of scale coefficients of concrete.

№	Indexes	Cubes with rib dimensions, mm			
		150	100	70	50
1	Scale factor for compressive strength	1,0	0,64	0,67	0,64
2	Scale factor for average density	1,0	0,955	0,985	0,97

As can be seen from Figure 1, the compressive strength indicators of cube samples of concrete with a rib size of 150 mm are lower than the similar strength indicators of concrete samples with a rib size of 100, 70, and 50 mm. Here it is possible to state the regularity of the increase in the strength of the samples, but this increase is significant. The indicators of the compressive strength limit of cube samples with a rib size of 100 and 50 mm are almost the same and are 18.47 and 18.54 MPa, respectively.

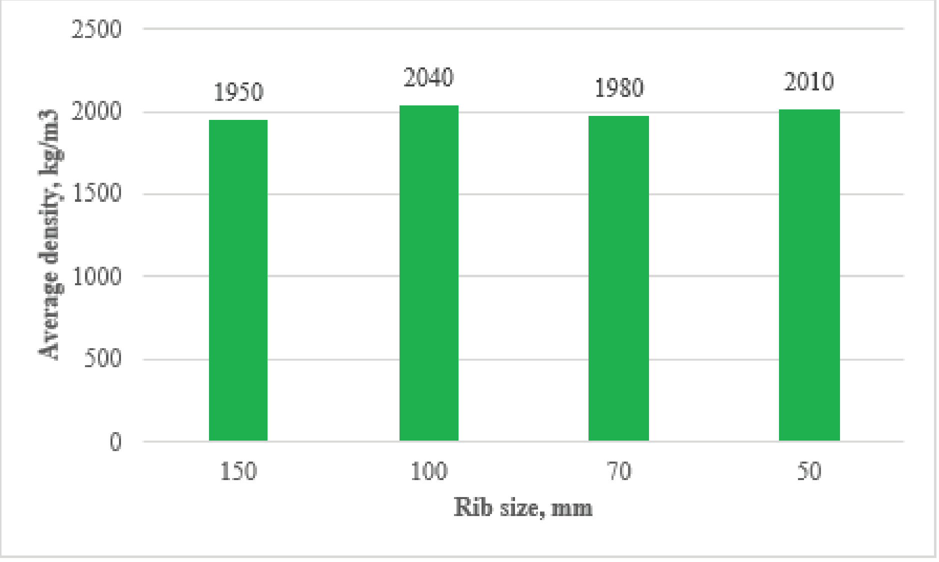

Fig. 3. Dependence of the average density of concrete on the size of the samples

The obtained scale coefficients for strength, which were determined in relation to the strength of basic samples with a rib size of 150 mm, equal to 0.64-0.67 (Table 1) are significantly smaller than similar coefficients that are given in the regulatory document [4].

Conducted research on the compressive strength of concrete showed that, taking into account the relatively small diameter of the nozzle and the rheological characteristics of the concrete mixture, it is rational to take cube samples with rib sizes of 50 and 100 mm as the base samples when assessing the strength of concrete.

The average density of concrete, which is determined on standard samples with a rib size of 150 mm, increases with a decrease in the size of the samples (Fig. 2). Cube samples with a rib size of 100 mm have the highest density, which is 2040 kg/m^3.

3 Types of reinforcement of reinforced concrete structures made by 3D printing technology

During the rapid development of 3D printing technologies, research and improvement of materials and equipment, quite insufficient attention was paid to the elements of strengthening concrete structures. Due to the unimproved system of reinforcement of building elements made by a 3D printer, they often have low indicators of bearing capacity for bending and stretching, and cannot replace reinforced concrete elements made in the traditional way, as a result, they have a small height, span lengths and, accordingly, rarely allow the realization of the most daring ideas architects and engineers.

The development of reinforcement strategies compatible with concrete extrusion printing allows the realization of safe and reliable concrete structures of non-standard forms. At the same time, these strategies must be able to provide sufficient reinforcement to meet all structural integrity requirements related to load-bearing capacity as well as in-service behavior.

As in the traditional method of erecting reinforced concrete structures and in 3D printing, steel reinforcing bars are the most common material for reinforcement. There are different approaches to combining 3D printing technology with conventional reinforcing bars: laying concrete on both sides of the reinforcing mesh, alternating laying of the mixture on the previously installed reinforcing mesh or frame − on the installed reinforcing mesh or frame first on one side, then on the other, etc. concrete mixture is injected. Reinforcement can also be added after the printing process, either outside or inside the printed element, using it as a permanent formwork. This approach can be further refined by printing the structure with voids, as well as placing reinforcement and filling the voids with cement mortar after printing. However, the use of conventional reinforcing bars is associated with two main problems: rigid bars limit geometric flexibility, and increased porosity at the interface of layers can accelerate corrosion of the reinforcing bar, which reduces the durability of the structure [6, 7].

Another traditional approach to reinforcing long-span structures is the use of pre-stressed reinforcement, which can be tensioned before printing (pre-stressing) or after the elements are printed (post-tensioning). Based on the analysis of the existing literature, when using 3D printing technology, only the method of post-tensioning of reinforcement was used. Reinforcement placed in voids created for tension, after tension voids can be filled with mortar or left without filling. This approach is very promising because it can provide geometric flexibility of structures [7, 8].

The next method of reinforcement is the laying of fiber concrete in printed structures. When using this method, a large degree of geometric flexibility of structures can be achieved. The fiber, usually made of steel or polyolefins, is combined with the concrete and served together. However, the use of fiber concrete is limited by a number of reasons. First, the fibers are dispersed in the matrix with unknown location and orientation, which introduces great uncertainty at the design stage. Secondly, the addition of fiber to the concrete mix directly affects the processing of the material. Most 3D printing technology processes are based on the use of pumps to transport the material to the extruder. Therefore, the composition of the material must be adjusted so that it can be pumped.

There is an approach to reinforcement where the fibers can be placed separately from the concrete. Immediately after each concrete layer, the robot layer adds fibers in the desired orientation and in the desired quantity on top of the existing layer. As soon as the nozzle is turned to print the next layer, the fibers are coated with concrete. This process allows aligning the fibers in the direction of the resulting tensile stresses and adjusting the fiber dosage according to structural requirements [9].

In addition to these reinforcement concepts, which are closely related to traditional methods, there are approaches specifically developed for 3D printing technology. One such approach is to add a thin reinforcing wire during printing that bends easily and adapts to almost any print path. Studies using high-strength smooth steel wire or impregnated carbon filaments show promising structural properties in the printing direction, but anchoring such reinforcement is a challenging task [10].

The use of carbon fibers as concrete reinforcement gives significant advantages in comparison with steel rods: carbon fibers are not prone to corrosion, have a much lower specific weight and a much higher tensile strength. As a result, thinner, more stable and more economical structures can be produced.

4 Conclusions

As part of this work, an overview of the constituent components used in 3D printing technology in construction was conducted and the main characteristics of the mixture and types of reinforcement of reinforced concrete printed structures were determined. Concrete mixtures used for 3D printing must have an optimal composition and consistency in which they have the ability to take shape and keep this shape until solidification. It is also necessary to take into account such characteristics of concrete mixtures as open time, durability and strength of the connection at the boundary between the layers.

In addition, the main types of reinforcement of reinforced concrete structures made using 3D printing technology are presented, namely: reinforcement with steel reinforcing bars, reinforcement with steel reinforcing bars with stress, reinforcement by laying fibers either directly in the concrete mixture or between layers of the concrete mixture, and the most promising method of reinforcing printed structures - laying strong, flexible and thin elements such as high strength smooth steel wire or impregnated carbon threads.

An experimental study was also carried out to determine the strength of the concrete mixture used for 3D printing of building structures. During the experiment, cubes with face sizes of 150, 100, 70, and 50 mm were cut out of concrete-printed structures, and their strength characteristics were determined by crushing them on a press. The test determined that the values of the compressive strength limit of cube samples with a rib size of 100 and 50 mm are practically the same and are 18.47 and 18.54 MPa, respectively. Therefore, it is rational to take these samples as basic samples when assessing the strength of concrete in further tests.

But despite significant achievements in the field of 3D concrete printing technology, there are still a number of problems that require refinement and even the possible development of new solutions regarding the improvement of mechanical equipment for 3D printing, methods of controlling the physical and mechanical properties of materials, methods of laying reinforcing material and analyzing the behavior of reinforced structures and others.

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