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PRIMENA TEHNOLOGIJE 3D ŠTAMPANOG BETONA U KONSTRUKCIJAMA

Rezime:

Tehnologija 3D štampanja betona omogućila je prostor za napredak u industrijalizaciji, optimizaciji i automatizaciji procesa u savremenom konstrukterstvu. U ovom radu dat je prikaz najčešće korišćenih metoda za 3D štampu betonskih konstrukcija, naglašene su prednosti i mane ove tehnologije, kao i pravaca daljeg razvoja. Prikazani su primeri dosadašnje primene u vidu izvedenih građevinskih objekata. Izvršena je analiza postojećih znanja u vezi uticaja deterioracionih mehanizama na 3D štampane betone. Takođe, izvršena je ocena ove tehnologije sa različitih aspekta održivosti.

Ključne reči: beton, 3D štampa, tehnologija, konstrukcija, trajnost, održivost

STRUCTURAL APPLICATION OF 3D CONCRETE PRINTING TECHNOLOGY

Summary:

3D concrete printing technology enabled a new progress in industrialization, optimization and automatization of processes in contemporary construction works. This paper shows the commonly used methods of concrete 3D printing. Advantages, disadvantages and perspectives for further development of this technology are emphasized. Structural applications as an example of using this technology are shown. The analysis of existing knowledge about the influence of deterioration mechanisms on printed concrete was made. Evaluation of 3D concrete printing technology in terms of different aspect of sustainability has been done.

Key words: concrete, 3D printing, technology, structure, durability, sustainability

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1. INTRODUCTION – BASIC PRINCIPLES OF 3D CONCRETE PRINTING TECHNOLOGY (3DCP)

3D printing technology appeared in the 1980s, as an innovative technology for the production of various elements based on the idea of Charles Hull [1]. The main motivation can be found in the idea of making elements of various complex shapes by gradually applying the material in layers with high manufacturing precision without using casting molds, complex tools, and machines. In relevant literature, this process is often called *Additive manufacturing* (AM-gradual production). 3D printing was initially applied for metal, polymers, ceramics, textiles, and other composite materials. Elements and parts obtained by this technique quickly found their application in various branches of the economy such as mechanical engineering, automotive industry, aero industry, and medicine [1].

The main device of this system is a special type of a printer. There are numerous types of printers different in size and degrees of freedom. Some of the most famous manufacturers of 3D printers for concrete are COBOD BOD2, Apis Cor, Contour Crafting, and XtreeE [2]. The most important part of the printer is the head or a tail. There are different nozzles with a rectangular or circular cross-section, as well as nozzles that lay the material forward or backward or at an angle. The computer system in the background is also an important part. The movement of the head is defined by the G-code generated from the CAD drawing. Therefore, it can be said that 3D printers are similar to CNC machines that are being commonly used in last decade, mostly in the production of steel structures.

Generally, basic methods of 3D printing are: Stereolithography (SLA), method of fusion deposition (Fused Deposition Modeling, FDM), Ink printing (inkjet printing), and production of contours (Contour Crafting CC, [3,4]), [5]. For the purpose of 3D printing of concrete, several of the above-mentioned 3D printing techniques have been used so far. The FDM method (Fused Deposition Modelling), is the most common method for making concrete structures with 3D printing technology. The principle of operation is based on the extruding of layers by pushing them out through a nozzle that moves along a precisely determined path defined according to the G code that was created according to the CAD drawing [3,4],Figure 1.

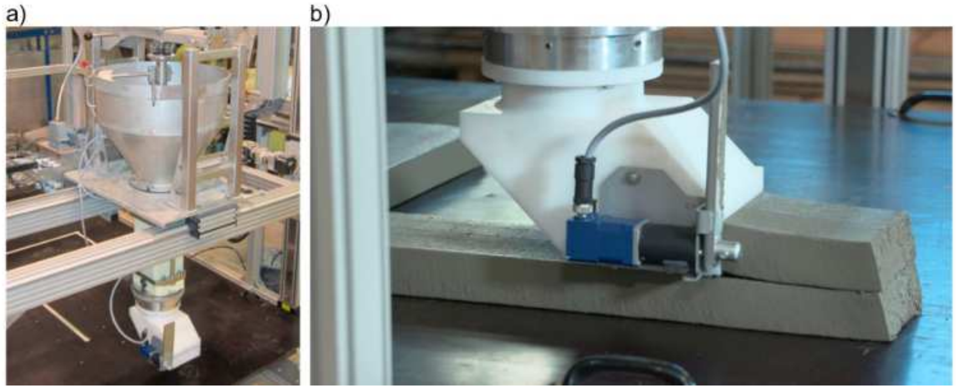

Figure 1 - FDM technology for 3D printing with extrusion of filaments (TU Dresden): a) the printhead of CONPrint3D printer, b) view of the nozzle with extruded filaments [6]

In addition to the extrusion of fresh concrete mix, a concept of material spraying is also used. The method called Shotcrete 3D Printing (SC3DP) has been successfully developed by a research group from the TU Braunschweig, Figure 2a. In the context of traditional construction, SC3DP is similar to pumped concrete, which has been successfully used for years in the construction of tunnels [7]. So, in this particular case, the material is not laid down, but is scattered and thus forms a layer [7,8]. This method can be particularly effective in the context of placing reinforcement in 3D printed concrete structures.

The ink printing method has been successfully used during the past 20 years by company D-Shape [9]. During this process which is similar to the inkjet powder bed technology, binder is sprayed on the printing material placing it layer by layer [9]. What makes D-Shape stand out on market is its special visual impression. The elements and objects obtained with this technology are particularly notable for their artistic value and represent architecturally important works. So far, numerous objects and elements have been successfully executed, Figure 2b. It should be noted that D-Shape has been actively working on the project of 3D printing of objects on Mars and Moon since 2007. [10].

a) b)

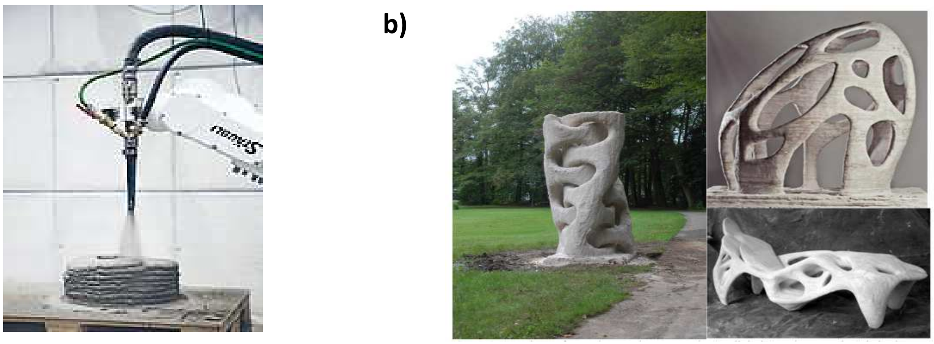

Figure 2 - a) 3D printing technology with concrete spraying (SC3DP) - example of a concrete column [8], *b) D-Shape technology - example of concrete sculptures.* [9]

Regardless the method of printing, the material that passes through the system is actually mortar because the maximum grain size is not usually larger than 3 mm. In addition to fine aggregate, different cement types (CEM I or CEM II) have been used so far. Also, a large number of chemical additives (setting accelerators, setting retarders, hydration controllers, superplasticizers, viscosity modifiers) and other components such as silicate fume, granulated glass blast, and limestone filler are added to the mixtures in order to improve the various properties of this material and to achieve required quality [10]–[18].

2. ADVANTAGES AND OBSTACLES IN STRUCTURAL APPLICATION

There numerous advantages of using 3D printing technology in the field of structural engineering: avoiding formwork, higher precision of construction, material saving, reduction in labor needs, speeding up construction time, the possibility of application in difficult environmental conditions, reducing costs, better working condition on the site and protection of the environment. However, several disadvantages have also been noted: needs for sophisticated equipment, higher initial costs, need for qualified labor, insufficient knowledge of printed material quality, insufficiently developed connections, lack of standards [18–22]. Nevertheless, there is a significant increase in number of companies and research groups dealing with this topic, Figure 3. In addition, the active participation of RILEM organization with two technical committees (TC PFC and TC ADC) will certainly contribute to developing of standards and regulations for the production and application of 3D printed concrete structures shortly.

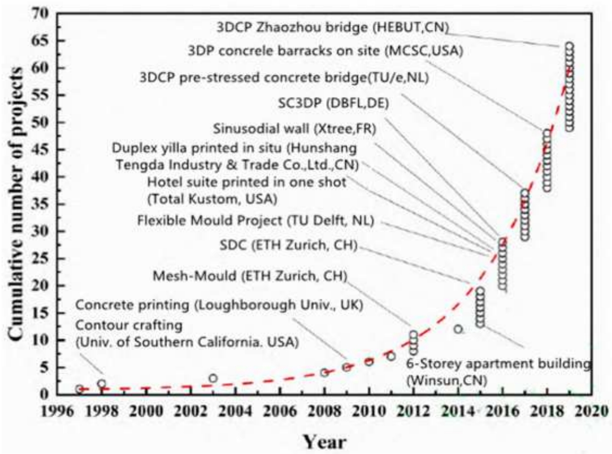

Figure 3 - An increasing number of scientific organizations and projects for 3D printing in concrete [18,20]

3D concrete printing (3DCP) has been applied for different purposes, from panels, facade elements, benches, furniture, columns and walls to pedestrian bridges and residential buildings, Figure 4 [3,10,18,19,23–25].

a)

b)

Figure 4 - Representative example of using 3D printing technology in concrete structures: a) bridge in Madrid, Spain, b) Milestone House

3DPC has also been used in the Republic of Serbia since last year. Company Natura Eco successfully printed the first-ever 3D printed concrete house on Western Balkan (ProtoDOM, Figure 5a). At the same time, at the University of Belgrade, Novi Sad and Nis a scientific research groups oriented to this technology were formed. First-ever university 3D printer for concrete in this region was installed at Faculty of the Civil Engineering University of Belgrade, Figure 5b.

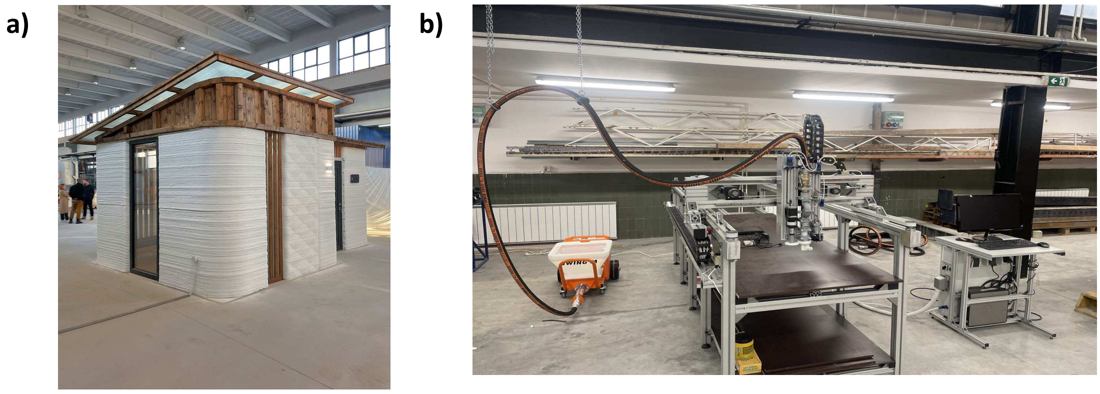

Figure 5 - Application of 3D concrete printing in Serbia: a)ProtoDOM NaturaECO, b)3D concrete printer at Faculty of Civil Engineering University of Belgrade

Significant obstacle for wider application of 3DCP technology is the incorporation of reinforcement into the printing process, i.e. positioning of reinforcement at the proper place into printed structural element [26]. Currently, there are three basic concepts for placing of reinforcement in printed concrete structure (Figure 6):

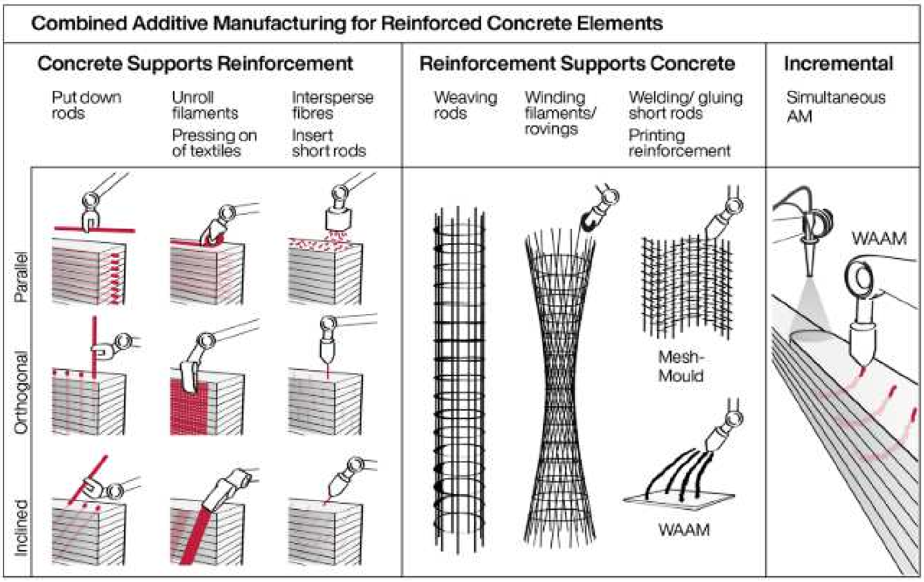

Figure 6. Examples of possible approaches to combining reinforcement and concrete during 3D printing within the new classification [27]

1) the concept where the reinforcement is a support for the concrete – there is a formed reinforcement cage, mainly made of steel and carbon around which the concrete is printed by laying or spraying,

2) the concept where the concrete is the support for the reinforcement - first the concrete part of the structure is printed, after which the reinforcement is placed. There are different possibilities: a) reinforcement is placed inside the printed contour (the layers form the formwork), b) reinforcement is placed as bars on the layers or through the layers, c) insertion of short rods and fibers into the fresh or hardened mixture. It should be noted that the reinforcement is inserted through the layers (vertically or obliquely at an angle) in a fresh or hardened state,

3) the simultaneous concept that actually represents the WAAM technique - simultaneous printing of both concrete and reinforcement.

The goal to only use a machine for reinforced concrete elements production is not reached, as the additional labor for placing of reinforcement is needed. The most efficient and easy-to-use method is the application of fibers in the concrete mixture instead of reinforcement.The highest efficiency, ease of use have methods where the reinforcement is in the form of fibers in the mixture itself. Nevertheless, that causes a problem on the other side – a concern whether the printed elements with fibers have sufficient robustness and ductility. This method certainly includes the WAAM, which at the moment has the highest chance of achieving the mentioned goal. However, this method currently requires great technological preparation and precision, which certainly results in increased costs.

Assembling of printed concrete segments into a reliable structural system is still an important issue for 3DPC community. General concept that is used during the construction is to print a concrete „formwork„ and fill it with concrete and reinforcement in the form of vertical columns at the corners of the object. There is also a „truss“ system in which printed diagonals connect the outer and inner walls made of 3D printed concrete, Figure 7a. That method can contribute to increased stability both during and after printing (in the hardened state). The disadvantage is certainly reflected in worse thermal insulation, as well as increased shrinkage between surfaces.

Vertical connections betwen printed elements are provided by concrete columns on the ends. Horizontal joints between printed elements are filled with concrete, Figure 7b. The foundation of 3DPC buildings is usualy cast in-situ reinforced concrete base plate. Anchors are left from the base plate and they provide connections between foundation and segments obtained by digital fabrication. Connection of printed segments with the roof plate is ensured in a similar way.

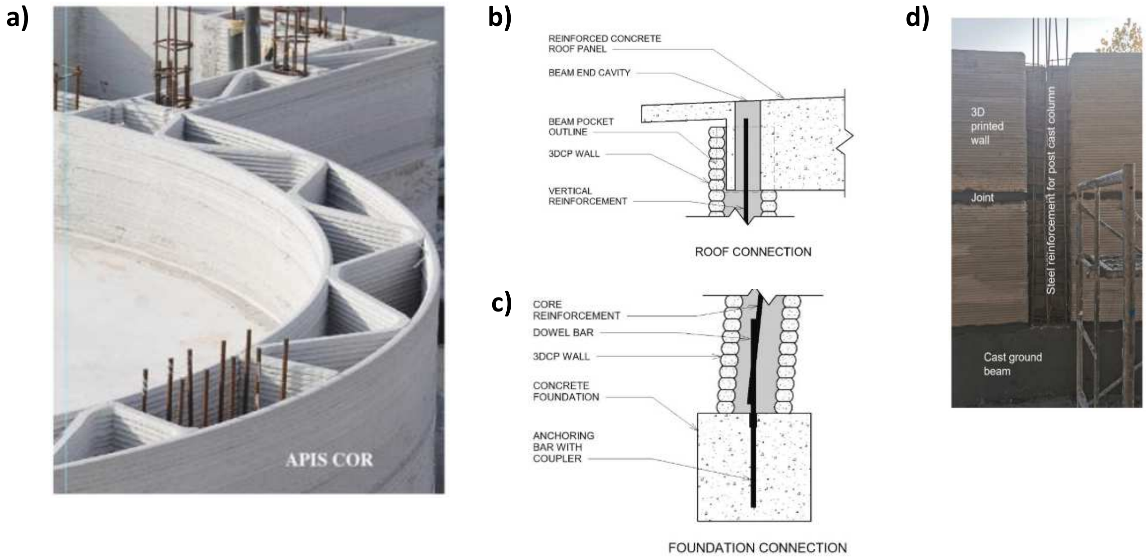

Figure 7 – Connections in 3D printed concrete structures: a) Dubai Office, b)-d) B-Hut [23]

3. HARDENED PROPERTIES OF 3D PRINTED CONCRETE

Based on the analysis of relevant articles and technical reports [6,13,25,28–30], usual experimental testing of hardened properties of 3DCP3D printed concrete are the following one:

1) Compressive strength – tested on printed specimens or specimens made in molds. The shape of specimens in both cases is a cube, usually 10x10x10 cm. In this way the effect of layers on mechanical properties can be determined. In the test, the force can be applied perpendicular, longitudinal or lateral to the layer orientation.
2) Flexural strength – determined in the same way as compressive strength.
3) Bond strength between layers is the critical point in the analysis of ultimate strenght of 3DCP structures. Lost capacity of bond as a failure mode should be avoided. At the moment, dominant method for testing interlayer bond strength is the axial (directly) tension test.

Experimental investigation on individual printed columns and walls under the axial load are not rare. Typical setup of experimental testing of 3DCP wall (in this case: 1.3 m x 0.9 m x 0.125 m) is shown at Figure 8.

(a) at breaking of 3DP concrete shell (b) right after breaking of 3DP concrete shell

Figure 8 - Example of 3DCP wall under axial load [30]

4. DURABILITY

Durability of concrete is defined by its ability to resist harmful environmental agents that damage the concrete - deterioration mechanisms. These mechanisms affect inner concrete structure (sulphate attack, freeze/thaw with or without de-icing salt) or induced reinforcement corrosion (carbonation and chloride penetration). The durability properties of 3DPC are different from traditionally casted concrete due to the use of different mixing proportions, high dosage of chemical admixtures, and layer-by-layer production methods [31]. Researchers have so far focused more on improving mechanical than the durability properties of printed concrete. Only a few researchers have studied the durability of 3DCP, and these results are presented below.

Chloride ion resistance depend on the connectivity of the pores at the layers interface [31,32]. Compared to casted concrete, 3DCP had higher chloride ion ingress [32–34], i.e. lower chloride resistance. As the time gap between printed layers increased, the depth of chloride ingress also increased [33,35]. Although the 3DPC resistance was lower, the value of D_{RCM} was $4x10^{-12}$ [34], which classifies it as high-resistance concrete [36]. On the other hand, 3DPC showed higher carbonation resistance compared to conventional concrete [32]. Certainly, the 3DPC carbonation resistance mainly depends on layer orientation in relation to the CO_2 diffusion direction.

Zhang et al [32] investigated the influence of the freeze/thaw cycle on the concrete dynamic modulus of elasticity and weight loss for 3DPC. 3DPC had a larger decrease in dynamic modulus compared to casted concrete. In contrast to the change in dynamic modulus of elasticity, 3DPC showed smaller weight loss compared to casted concrete [32]. Obviously, the dynamic modulus of elasticity was more sensitive to freeze-thaw cycles than weight loss for the 3DPC, contrary to casted concrete. A useful way to improve 3DPC resistance is to add air-entraining admixture or styrene-butadiene rubber which increase the flexibility of 3DPC, leading to improvement in bond properties [37].

It is well known that concrete with ordinary Portland cement has low acid resistance due to high alkalinity. Sulfuric acid (H_2SO_4) reacts with the calcium hydroxide (CH) of the hydrated cement paste, and produces gypsum. Since 3DPC usually contain larger amounts of cement, it is necessary to examine their sulphate acid resistance. The results available in the literature show that 3DPC have slightly better resistance compared to casted concrete [32,38]. Unlike casted concrete, the cracking of 3DPC propagates along the layer interface [32]. As the sulphate attack progresses, the matrix failure mode is interlayer cracking rather than aggregate peeling.

5. SUSTAINALBILITY

The term sustainability generally refers to three main pillars: societal, economic and environmental. The positive societal impact of using 3DCP is expected to be significant. The reduction of manual labour for preparing and lifting of formwork, pouring and compaction of concrete will enable the employment of skilled workers for handling the printer and controlling the printing process [39]. This could efficiently mitigate the shortage of skilled labour and open a possibility to improve the gender balance among construction workers, by employing more woman. Automation will also help reduce errors and improve safety at the construction site.

When we think about the economical aspect, productivity and cost of materials and labour are first to look at. Stagnating, recently even decreased, productivity in construction industry is a significant concern. The main causes for this are the resistance to introduce changes in a highly traditional sector, low industrialization and low investments in research and development. 3DCP introduces a new paradigm in the construction sector with decreasing the time of construction and liberation of the need for moulds in component manufacturing [40]. With current technology level and future developments in the robotic field, productivity of the construction sector can be significantly increased. By eliminating the formwork, the costs can also be reduced. In total concrete structure cost, formwork costs are around 28%, or up to 50% for complicated geometry [41]. If we include the decrease in time, it is evident that cost reduction can be achieved. However, 3DCP has greater amount of binder in its mixture, and that binder usually has greater amounts of cement. Also, in order to achieve specific requirements associated with 3D printing technology, different additives (both chemical and mineralogical) are needed. These aspects increase the price of concrete when compared with the traditional one, but the possibility to reduce them with further research development are significant.

Environmental aspect of concrete is usually analysed by looking at the cement amount, natural resource consumption, waste generation, water and energy usage. Environmental benefits of using 3DCP can be obtained through several aspects: the reduction of concrete waste, less water and energy compared with the traditional technology, possibility for structural optimisation due to flexibility of obtained shapes, higher productivity and less formwork material. Also, electricity needed for concrete pumps and 3D printers can easily be obtained from sustainable energy sources, like the energy of sun. However, due to its specific requirement, 3DCP currently incorporates only fine aggregate. As a consequence, it has greater amounts of binder paste, and lower amount of water needed for adequate strength development. Fine aggregate is usually of a natural origin and obtained from quarries. This presents a great influence on the environment, and it consumes significant amount of energy for extraction. The use of recycled concrete aggregate in 3DCP is still restricted due to the fact that fine recycled concrete aggregate has great water absorption and it is still not suitable for construction grade concrete [42]. Different alternatives for natural sand are being explored, but incorporation of coarse aggregate is one of the most important directions in the future research, especially for large-scale 3D printing [40]. Another negative environmental effect of 3DCP is higher amount of cement needed for required concrete properties. Having in mind that cement is the main CO_2 source in concrete, great part of current research is oriented toward lowering its amount, or using alternative binders. The most promising solutions so far are cement replacement with waste materials like slag and fly ash, alkali-activated materials (like geopolimers), particle packaging method and composite cementitious systems including limestone-calcined clay cement. Maybe the most promising alternative at the moment is the application of geopolymer concrete that has a rapid hardening nature, which can significantly improve the buildability without the need of any additional chemical accelerators [43].

6. CONCLUSIONS

Based on the considered reviews and own research, the following conclusions in the field of additive manufacturing technology in concrete structures can be drawn:

1) Application of 3DCP technology for structural purposes are numerous, proving its general feasibility.
2) Currently, methods of printed concrete specimens testing are the same as for casted concrete specimens. The influence of layers on strengths, particularly on bond strength is significant. New methods for testing of printed concrete are under devolopment.
3) Societal and economic aspects of 3DCP sustainability are expected to be significant, while environmental aspect have to be improved by partial substitution of cement with green alternatives.
4) The further directions of research are development and possible improvements in the field of technology, i.e incorporating of reinforcement in the process of 3D printing of concrete, as well as design of connections and joints between printed elements.
5) Technical requirements for structural 3DCP and elements are necessary to be defined in the form of technical sheets and standards.

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