UHPC material development for 3D print

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Abstract

With the progressing wave of automation, robotization and thus 3D printing is not only reaching areas of engineering, but also areas where its application has not been common or expedient until now. One such field is construction. The precision and speed of machine production and the advancing technological development of robotic manipulators enable new use of these tools in sectors requiring precise work on a larger scale (building elements, but also entire buildings). The advantages of using these technologies in the construction industry include a potentially significantly higher speed of construction, material savings and physically and economically demanding human labor. Another significant advantage is the possibility to create objects or their parts that are almost unlimited in shape. In combination with the advantages of the UHFRC material (start-up speed, ideal for thin-walled constructions, high strength and durability), a very efficient and modern technology is obtained.

Until now, the use of automated technologies in the implementation of constructions has been limited mainly to subtractive methods (where material is removed until the final shape of the product is achieved), such as CNC milling, laser, plasma and water jet cutting, turning, etc. The development of additive manufacturing technologies and by gradually increasing the products created by this technology, its application in the construction industry became not only possible, but often also very expedient. The paper describes the development of not only the UHPC mixture but also other cement composites and their tests within the development of the entire 3D printing technology.

Keywords: UHPC,3D print, mixture development, experimental tests

1. Introduction

Concrete by its nature is very different from commonly printed materials such as plastic or metal – for the printing itself, heating and subsequent cooling of the input material cannot be used, but it is necessary to hydrate the cement. The fundamental issue faced by 3D printing of cement composites is designing the mixture so that after extrusion and repeated application of individual layers on top of each other, it resists its own weight and it is possible to print/build the printed element to a height. The mixture must be of suitable consistency so that it is pumpable and subsequently easily exits the extruder, but at the same time it must set quickly enough after extrusion or have a sufficiently stiff consistency to allow re-layering. This is further related to the very issue of the stability of a freshly printed printed object, which is not sufficiently hardened. These requirements for the mixture ultimately lead to the design of a relatively complicated cement composite containing a number of different additives, including setting accelerators. The resulting mechanical strength is certainly also important for the overall design of the resulting element, but less important from the point of view of the extrusion process itself.

A different discipline is printing using UHPC material. It was used in the execution of the sculpture "NA HORU" by the artist Federico Diaz by his studio SFD. This work required the combination of several disciplines for its creation. The sculpture was made of UHPC with the help of robotic fabrication, and the design of the composition of the material with the required parameters was in charge of the laboratory of the Klokner Institute of the Czech Technical University in Prague. A number of articles and publications have already been published about the parameters and properties of ordinary UHPC. In May 2022, the Czech Concrete Company ČSSI issued updated technical rules for the design and implementation of UHPC and elements made from it. One of the basic characteristics of the fresh UHPC mixture is its fluidity, or so-called self-leveling behavior. This property of fresh UHPC is of course completely unsuitable for the application of the mixture by additive manufacturing and cannot be removed only by reducing the water dosage. It is therefore necessary to ensure sufficient thixotropy of the material while maintaining high mechanical parameters. To maximize the thixotropic behavior of fresh material, it is necessary to focus on the use of a suitable additive and its dosage. Due to the manufacturing technology developed by SFD, it was not necessary to use an additive that accelerates solidification and hardening, thereby eliminating a relatively highly variable and complicated factor that would affect the final parameters of UHPC. The contribution is devoted to the design and application of cement composites for 3D printing within two projects. Federico Diaz's project dealing with the creation of a unique sculpture from UHPC called "NA HORU" and the 3D STAR scientific research project with the Technical University of Liberec.

2. Development of cement composites for 3D printing

The mixture was assembled from individual selected components typical for fine-grained microconcretes and mortars (fine-grained aggregate, cement, special additives and admixtures) in such a way that it met the requirements for both mechanical and physical properties, workability, pumpability of the mixture with a pump and stiffness after extrusion from the print head. The basis for the composition of the mixture was a thorough analysis of the sub-components in terms of granulometry and optimal adjustment of their individual ratios. In terms of thixotropy of the mixture and limitation of shrinkage, the mixture was supplemented with scattered reinforcement in the form of PP fibers. Preliminary tests were also carried out with mixtures with the addition of PVA fibers. The goal of fiber addition is the automated reinforcement of thin-walled elements, and scattered reinforcement (for example, with steel fibers) is one of the options for reinforcing the printed structure. Appropriate plasticizers and superplasticizers were added to the mixture in order to reduce the water coefficient and thereby improve the mechanical properties and also improve the consistency necessary for pumping the mixture.

3. Application of accelerator

The additive that accelerates the solidification of the mixture immediately after extrusion proves to be essential in the case of 3D printing, from the point of view of an immediate increase in basic strength. The early strength is the state in which the individual printed layer is able to withstand the pressure of the layers above it without plastic deformation due to compression, spreading, etc.. Detailed research was carried out mainly in the area of accelerating the solidification of the mixture using liquid solidification accelerators. The entire designed 3D printing system works with a mixture that is mixed, transported and pumped in a wet state to the print head, where a liquid accelerator is added in the last phase of extrusion. Its amount is adjusted according to the printing speed, the amount of extruded material and the complexity in terms of the shape of the printed element. This system allows virtually any printing environment (length of hoses required to pump the mixture, location of the mixing device versus the printing device and marginal parameters such as temperature, humidity or sunlight). The mixture is transported in a liquid or plastic state through the entire system without the risk of the mixture solidifying in the system in the event of a failure or technological pause. The acceleration occurs only at the very end of the printing process, and the reaction time, i.e. starting the hydration and solidification process, is in the order of minute.

The parameters of the resulting mixture were tested before pumping the mixture and after pumping the mixture with a solidification accelerator. Important inputs for mixture optimization were the temperature of the mixture over time after mixing, before and after pumping, the consistency of the mixture and its change over time. These parameters are important from the point of view of the design of the system for printing on the construction site or variable marginal environmental conditions. The consistency tests were carried out at different times in order to determine the pot life of the mixture, in order to determine the pot life in the pumping system and the amount of mixture in the pump dump. Any difference between laboratory-produced samples (by placing the mixture in molds) and testing the parameters of the composite after cutting/drilling from the printed object was continuously verified and the mixture was optimized based on the continuous results. The effort was to achieve the greatest possible consistency and homogeneity of the printed mixture before entering and after extrusion. As a result of modifications to both the printing technology and the mixture, the expected differences in the order of 5-10% were achieved. Deterioration of material parameters is expected due to different storage (layering and non-compaction) of the mixture. Pumping and extrusion increase the air content in the mixture and thereby reduce the bulk density.

Fig. 1: The print head of the TestBed device in KI on the left, the printed object in the 3D STAR project on the right

Within the extensive framework of the experimental program, a number of different types of tests of the material properties of the printing mixture at different stages of development, the mechanical parameters of the printed samples and, for example, the bond of this mixture with various types of inserted ladder reinforcement, were carried out.. The most characteristic are the material properties of the mixture at 28 days of age. For the purposes of 3D printing, from the point of view of the design of demanding printed structures, the properties of the mixture in the early stage of solidification/hardening of the mixture are also important.

4. Modification of UHPC for the need of robotic manufacturing

For Feferic Diaz's project, the UHPC mixture was modified and a different technology was used overall. Similarly, the procedure within the project is described in the article published in BETON TKS magazine. The basic components of the dry component were defined by the formula of the bagged product UHPC Valucem (manufactured by PREMIX servis s.r.o.). The superplasticizer based on polycarboxylates was also retained, but its dose, together with the dose of mixing water, had to be designed for the needs of robotic manufacturing. The main task of the employees of the Klokner Institute's concrete technology laboratory was to modify the UHPC material, which is by its nature a liquid material, in such a way that the mixture was maintained pumpable, but at the same time it was possible to perform technologically difficult robotic fabrication with this material. For this purpose, an experimental program was established, where additives of the VMA type (additive that modifies the viscosity of the material) were tested. These additives can be applied in the form of a liquid substance together with the dosage of mixing water or as a powder additive to the dry component.

Several test tests of the material's printability were carried out using a hand gun and variously modified tips, see Fig. 2. Along with determining whether the modified material is suitable for production by robotic manufacturing, the parameters of the fresh material were monitored. The temperature of the fresh material after mixing was an important parameter, as a high temperature can result in premature solidification of the material, and thus shorten the time needed to safely transport the mixture through the entire robotic manufacturing system, without the risk of the material solidifying in the transport hoses. The consistency of the fresh material was checked according to ČSN EN 1015-3 using a shaking table. The values of the maximum spillage of fresh material reached the value of 130 mm. If a material with a lower spill value was required, the consistency could be adjusted slightly without affecting the possibility of its pumpability.

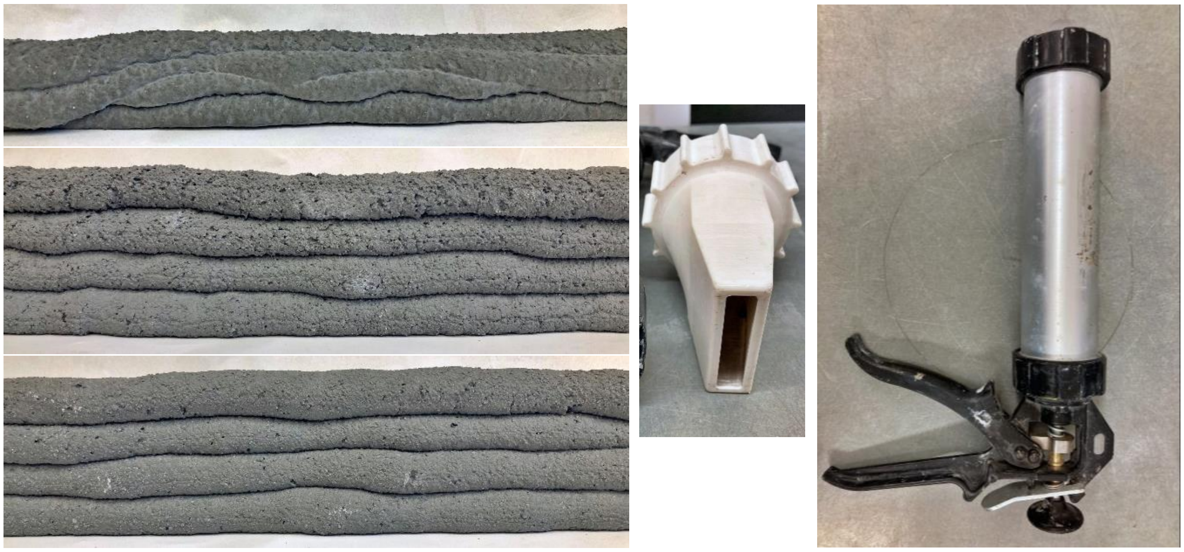

Fig. 2: Print test using a manual push gun and a modified tip

Part of the modification was also the use of microfibers, which have several functions. The fine microfibers adjust the consistency of the fresh mixture and its thixotropic properties and at the same time limit plastic shrinkage and therefore the formation of microcracks. For this purpose, polypropylene fibers with a length of 5 mm were used. The UHPC matrix achieves high strengths but exhibits a brittle failure mode. To achieve high ductility of this material, it is optimal to use scattered steel reinforcement. However, this option was rejected due to the possibility that the wires could protrude from the walls of the aforementioned work and thereby endanger visitors. PVA fibers were therefore a compromise and suitable use, when compared to steel fibers, the material does not achieve such high ductile properties and strengthening, but no longer brittle fracture occurs when broken. Carbon fibers were also the subject of experiments, but due to their high price, their effect was not found to be profitable. The following table 1 shows an overview of the fibers used and the resulting parameters of the hardened material determined on 40×40×160 mm beams according to the ČSN EN 196-1 standard. The interval of the resulting values of tensile strength under bending and compression is given by the variation of the components of the basic UHPC matrix (water, SP, VMA).

Table 1: Type of scattered reinforcement and material characteristics of the investigated composite

Type of fibres	Volume [kg.m^{-3}]	Flexural strength [MPa]	Compressive strength [MPa]
PP 5 mm	0,47	18-25	115-120
PVA 12,5 mm	5,00	17-20	110-115
	10,00	23-26	110-120
CF 7 mm	9,00	20-26	120-125

5. Modification of UHPC for the need of robotic manufacturing

Robotic manufacturing, which works on the basis of laying individual layers, introduces various defects with this technology, which affect the final parameters of the manufactured element. For this reason, it is necessary to include in the experimental program an examination of the strength characteristics of the material in different loading directions relative to the layering plane. Figure 3 illustrates 40×40×160 mm beam-shaped cut test specimens cut from a printed block using robotic fabrication. The samples prepared in this way are subjected to a tensile test under bending and compression, namely in the direction perpendicular to the layering plane and parallel to the layering plane. The bond of the layers can also be determined by a simple tensile test.

The interval of the resulting values of the tensile strength under bending and compression is determined by the variation of the components of the basic UHPC matrix (water, SP, VMA) and the quality of the connection of the layers. It is the quality of the connection that is the key parameter in determining the strength characteristics. The quality of the connection of the layers was monitored for a long time during the development of the material, the boundary conditions under which it is possible to lay one layer on top of the other in such a way that a sufficient connection occurs were determined. The basic condition for the correct connection of the layers is that there is no loss of moisture on the surface of the last laid layer. This can be suitably solved, for example, by the speed of printing or by modifying the consistency of the printed material. As part of further print optimizations, it was possible to achieve slightly higher strengths compared to the initial development state. The compressive strength during the production of the elements oscillated in the range of 115 to 130 MPa and the tensile strength in bending oscillated in the range of approx. 20 to 28 MPa.

Table 2: Type of scattered reinforcement and material characteristics of the investigated composite

Used fibres	Direction of loading	Flexural strength [MPa]	Compressive strength [MPa]	Tensile strength [MPa]
PP 5 mm	In parallel	18-21	90-100	4,2-5,7
	perpendicularly	18-21	100-110	
PVA 12,5 mm	In parallel	18-24	90-100	4,1-5,8
	perpendicularly	18-23	100-110	

6. Components of additive manufacturing

After reaching the final formula, the modified UHPC with dispersed reinforcement was prepared in a high-volume mixer and transported to the fabrication site using a spindle pump and hoses. An

essential part of the additive manufacturing technology, during which material is extruded through a nozzle and this material is gradually layered into the desired shape, is an extrusion tool (extruder). A very important part of extruders is the nozzle from which the material is extruded. It determines the dimensions and shape that the material receives during extrusion. Its internal geometry must adjust the cross-sectional shape of the extruded material without negatively affecting the flow rates (ie its internal shape must be designed in accordance with the principles of CFD - Computational Fluid Dynamics). An extruder for the production of large-format objects is usually mounted on a robotic 6-axis arm or a 3-axis system, allowing movement in the X, Y, Z axes. The advantage of 6-axis solutions is the possibility to variably rotate the extruder in all directions and thus create more complex geometries using a complex movement and the principle of extrusion.
Figure 4 illustrates the fabrication of the plate element of the reservoir, which is part of the "NA HORU" sculpture.

Fig. 4: Extrusion of the plate element of the reservoir under the statue on the left. The sculpture in the outdoor space between the buildings of the Borislavka complex on the right

7. Conclusion

As part of the development project, a sculpture called "NA HORU" was designed by the artist Federico Díaz. The concrete laboratory of the Klokner Institute was invited to implement it, in order to fulfill the intention of creating this sculpture by robotic fabrication with UHPC material. The material was successfully modified with the help of suitable additives modifying its viscosity and the addition of dispersed PP and PVA fibers. With these modifications, the requirements for robotic manufacturing technology were met, and at the same time, the requirements for the resulting mechanical-physical parameters of the material produced in this way were met. During development, fresh material criteria (temperature, consistency) were determined, which must be met for smooth production. Together with the control of the parameters of the fresh material, the collection of test samples was carried out, on which the monitored mechanical parameters were continuously verified. Due to the thinness of the elements, carved beams of 40x40x160 mm were used for the purposes of the tests. The compressive strength oscillated in the range of 115 to 130 MPa and the tensile strength in bending oscillated in the range of approx. 20 to 28 MPa. The result of joint work is the already installed statue of the project implemented by KKCG and known under the name Bořislavka, Prague 6 in Fig. 4.

8. Acknowledgements

The contribution was created with the support and presents some results of the research project OP VVV CZ.02.1.01 / 0.0 / 0.0 / 16_025 / 0007424 3D-STAR and was created with its support. Also some results were obtained from research project of Technological Agency number FW06010422.

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