Experience with the development of digital fabrication of cementitious material

David Citek, Stanislav Rehacek, Karel Hurtig, Milan Holy, Oto Melter

Klokner Institute,
Czech Technical University in Prague,
Solinova 7, Prague 166 08, Czech Republic

Summary
The article deals with the experience with the development and use of 3D printing for the construction of building and design objects, for example experimental footbridges. Using several cases of structural elements, the whole process is described from the design of the elements, the composition of the mixture, the printing process, the verification experimental tests to the final object. The experimental construction of the Solopysky footbridge is presented as the main reference in the paper. The experience to date shows the complexity of the design process of the structure, where the printing itself is only a small part of the fabrication of the element. For a reliable design of each structure an individual approach is required starting from specific mixtures, a special printing path or a method of printing the object. The durability of objects remains a current issue, as they are still new constructions due to the age and knowledge of the technology.

1 INTRODUCTION

The core technology of 3D printing of cementitious mixtures is now quite well known but there is still no standard proven production solution or comprehensive standardised design procedures. This technology is still subject to research and development [1]. From a structural engineering point of view, the possibility of tensile reinforcement of a 3D printed structure or the design of a structure that does not require the addition of tensile reinforcement is currently of interest. There are several applications of the discussed technology concerning structural elements [2][3] but so far the range of possible structural elements from 3D printing is very limited, especially in terms of the type of reinforcement possible. The nature of concrete is far from the usually printed materials such as plastics or metals. Cementitious binders require a cement hydration process to cure, which under normal conditions takes place much slower in its fastest phase on the order of days and is not completely finished even within a few years. These requirements for a mixture that can be transported by hoses, extracted and layered in short times on top of each other eventually lead to the design of a cementitious composite of a rather complicated composition that contains several different additives including setting accelerators [4]. This paper describes the development and testing of printable materials and objects using the 3D printing method with an example of the resulting realized structures. The research conducted at the Klokner Institute aims to make 3D printing of cementitious materials as close as possible to common applications in the construction industry [5]. The mixture used was developed by Klokner Institute specifically for this implementation. It consists of individual selected components typical of fine-grained micro concrete and mortar to meet the requirements for mechanical properties, workability and pumpability of the fresh mix and buildability of the printed material. For the printing of the structure a continuous print route was designed using parabolic envelope curves that were parametrically filled with a circular fill. After checking the characteristics of the footbridge, it was installed at the pond near the village Solopisky.

2 DEVELOPMENT OF DIGITAL FABRICATION

2.1 Mixture for 3D print

The Klokner Institute of CTU has developed its own fine-grained printing material based on cement for 3D printing. Although there are several commercially available printing materials already developed, the option of self-development was chosen to ensure that the properties of the mixture meet the requirements for sufficient strength of building elements and that its properties can be freely modified in the future according to specific applications. Several different types of tests were carried out as part of the experimental development, in particular on the material properties of the printing compound. The compound was completely developed and optimized for the proposed device. The mixture currently used consists of a cement binder, fine aggregates of up to 1 mm fraction, fine fractions and admixtures affecting the consistency. At the same time, polypropylene fibres are added to the mix to influence thixotropy and volume changes in the fresh state. The main parameters tested include compressive strength and flexural tensile strength. Other accompanying tests are fresh mix tests, namely consistency or temperature. Due to the subtlety of the printed structures, the tests are carried out on samples of appropriate dimensions. The most common test specimens are 40 x 40 x 160 mm beams or 100 mm cubes.

Other important tests include tests of the bond of the mixture with different types of embedded reinforcement. PP fibres do not have a static function, they only limit shrinkage and the formation of cracks in the initial phase of concrete hardening. Due to the nature of the technology, it seems possible to re-enforce the composite with dispersed steel or composite reinforcement. However, for this type of reinforcement, a press head must be prepared, which can usually cause blockage of the reinforcement and clogging of the system. The cubic strength of a specially developed press compound for this purpose is usually around 50-60 MPa after 28 days of curing. These parameters depend on the input or output consistency of the mixture. The application of a curing accelerator has the effect of accelerating the curing of the mixture in the initial 5-10 minutes, its application may have a negative effect on the final strength values. However, the resulting material parameters of the current mix show a reduction in average strength values of approximately 5 %. For this reason, too, the initial mixes were optimised to relatively higher compressive strength values than conventional concretes, in order to provide sufficient margin in case of optimisation of the mix in terms of consistency and rate of setting.The mix was composed of individual selected ingredients typical of fine-grained microcrete and mortar (fine aggregate, cement, special additives and admixtures) to meet the requirements for mechanical properties, workability and pumpability of the fresh mix and buildability of the printed material. The possible difference between the laboratory produced samples (by placing the material in the moulds) and testing the parameters of the compost-building after cutting/drilling from the printed object was continuously verified. The aim was to achieve the highest possible consistency and homogeneity of the printed mixture before entry and after extrusion. Modifications to the printing technology and compound resulted in expected differences of 5-10%. Deterioration in material parameters is expected due to the different deposition (layering and non-compaction) of the mixture. The extrusion increases the air content of the mixture and thus reduces the bulk density. The bulk density of mixture is around 2100 kg.m-3. The compressive strength at 28 days of age was 64.5 MPa with a modulus of elasticity of 32.1 GPa [5].

Table 1 Composition of used mixture.

Component	Content [kg.m-3]
Silica sand 0-1,25 mm	967
Micro fillers	495
Cement CEM II 52,5 N	358
Superplasticizer	25
Water	225

2.2 Experimental equipment

The project developed the TestBed device used for test prints, which is shown in Figure 1. It is a massive gantry crane with a print head that has a working area of 3 x 1 x 1 m. The device was completely designed and constructed by TUL staff and housed in the laboratories of the Klokner Institute. The complete 3D printer system includes a mixing device (mixer with a capacity of up to 250 litres), a concrete pump and a print head. All these components are interconnected and automated to the maximum extent possible and controlled by the printer operator.

Fig. 1 TestBed – printing device (left), example of printing setup (right)

A 150 litre spindle pump is used to pump the mixture into the print head located on the gantry using a 35 mm diameter hose system. The printing itself is then controlled by a screw drive directly in the print head. The current system is capable of printing at a speed of 150-200 mm/s. The device can develop speeds many times higher, but the limits are set by the solidification rate of the mixture. The developed cement-based mixture is pumped from the pump through hoses to the print head, where it is mixed with a solidification accelerator. This is deliberately applied to the mixture at the end of the process to prevent the mixture from solidifying in closed areas in the event of a print interruption. The amount of solidification accelerator injected is controlled by a very precise flow meter and everything is handled online at the workstation. The dimensions of the printed object are limited by the size of the gantry crane or the space of the laboratory. Current equipment is used to optimize the printing mixture and print structural fragments.

2.3 Experimental tests

An important part of the process of 3D printing of structural objects is the load testing of the printed wall and ceiling elements and the comparison of the results of these tests with the results of structural calculations. As part of the development process, a number of object types were printed and tested in various configurations to determine the parameters important for the static recalculation. An example of such a test printed thin-walled wall element is the wall segment shown in Figure 1 below. The width of the print path may generally be in the range of 20-50 mm for a given print head with interchangeable nozzles. The figure shows a wall segment with a print thickness of 20 mm. A sub-focus of the development is also the complex design of wall elements in terms of thermal insulation and technological possibilities to incorporate insulation into a complex shape element. The printed segments are filled with different types of thermal insulants, which are investigated for their ability to fill complex structure, volume changes and overall load-bearing capacity of thin-walled elements. The next figure shows an example of a test of column elements using optical recording of the test using a digital image correlation (DIC) method. This is very effective in helping to evaluate and locate crack initiation (Fig. 2).

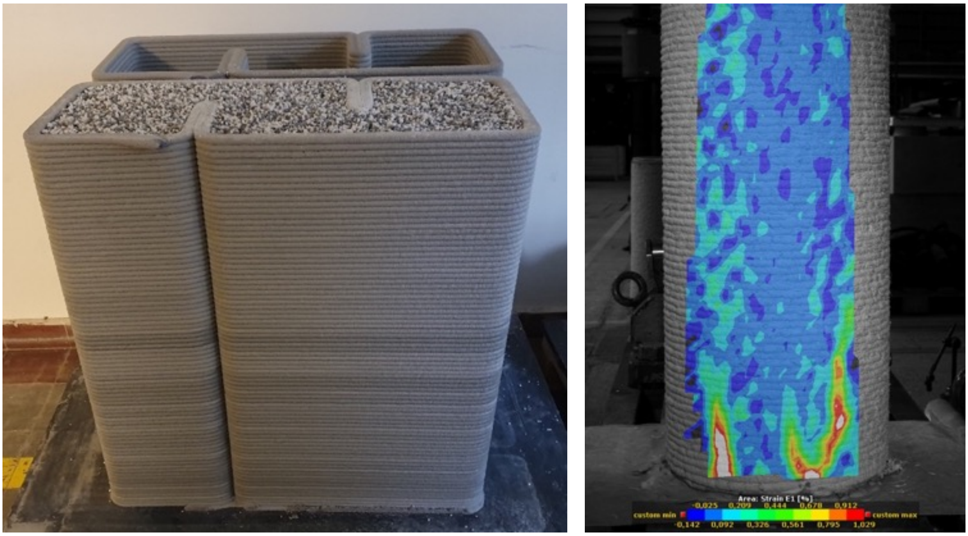

Fig. 2 Experimental wall specimen (left), image from DIC during 3D printed column

The measured values are compared with the theoretical values calculated using various calculation programs. Among them, the software tool Atena, designed for advanced, geometrically and physically non-linear modelling of concrete structures, is the first choice. This program is developed by the Czech company Červenka consulting s.r.o., whose employees are also involved in the research. The ultimate goal is to optimize the computational process so that, for the foreseeable future, it will be possible to reliably design printed thin-walled structures based solely on computer models, as is common today.

In addition to the wall elements, experimental printing of truss ceiling elements was carried out. The use of 3D printing technology for horizontal structures has its limitations. As a result, 3D printing of horizontal support elements is likely to be limited to prefabricated parts that are printed either in the factory or on site. For the reinforcement of a bent printed element, systems are being developed around the world where flexible reinforcement is deposited continuously during printing using a directly modified print head, and systems where the printed material is reinforced only with dispersed reinforcement with filaments of different types and properties. Both options are being investigated. The beam is reinforced with 6 mm steel reinforcement, which is inserted manually between the print layers during printing. The support reinforcement is placed only in the bottom strip and in the drawn diagonals. The upper moulded strip is structurally reinforced with two 6 mm steel reinforcement profiles to allow for handling of the element during transport and assembly. This is a prototype beam which was hand fabricated and tested primarily to verify the mutual bond of the press layers and the bond of the press compound with the reinforcement. The beam has a length of 3 m to allow for the spatial possibilities of printing and testing.However, it is designed to be suitable for residential development with a span of 6.0m. Trusses with a span of 6 m can be designed to have a comparative material thickness of approximately 100 mm. Tests of the beam loaded in four-point bending showed very good behaviour of the element, which showed no evidence of delamination of the press layers and the type of failure, where the reinforcement of the bottom flange broke, was in good agreement with the structural design assumption. The individual tests contribute to a deeper understanding of the sub-issues that need to be addressed when the structure is transitioned from conventional methods to 3D printing.

2.4 Measurement during the print

An important element in printing is online print monitoring to locate any inhomogeneities. A thermal camera was used to monitor online the temperature progression during printing, which was placed close to the printed object and calibrated at the start of printing. The camera was positioned to optimally capture the entire element or the currently printed parts in the field of view. Imaging was performed and recorded at intervals representing the individual layers so that the measurements could be evaluated and subsequently calibrated against temperature values obtained from temperature sensors directly in the matrix of the printed object. One of the tasks of the online monitoring was to capture any inhomogeneities in the object as far as the printed mixture is concerned. As part of the object printing and thermal camera recording, the dosing of the accelerating additive was interrupted in one layer for the test. Looking at Fig. 3, it can be seen that the layer in question is visible not only in the hardened cement composite but also in the thermal camera image (Fig.3).

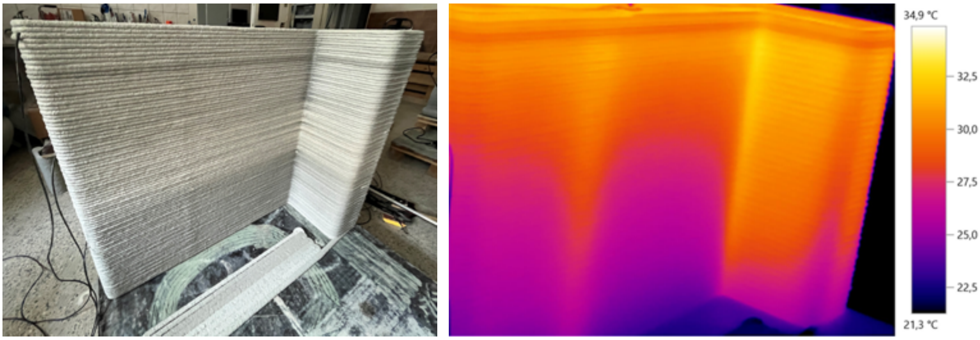

Fig. 3 Experimental wall specimen (left), image from thermocamera

If the resolution of the thermal camera is sufficiently suitable, it is thus possible to monitor these imperfections due to the change in the mixture directly during printing. The thermal camera image also shows the contacts between the inner ribs and the outer wall with a different colour. This method can be used to assess possible defects (cracks) from uneven heating of the structure and modify the printing process according to the results. This method is usefull for determining a non homogeneity in structure. This method is useful for determining a non homogeneity in structure. An important parameter monitored during printing was the temperature and humidity in the vicinity of the printed object and in the interior of the printed object. These values are important for setting the boundary conditions both in the numerical model and for comparing the temperature evolution and concrete maturation under different conditions.

3 EXPERIMENTAL FOOTBRIDGE IN SOLOPISKY

3.1 Description of the footbridge

One part of the project was the design of the printed structure that will be used in actual use in a horizontal position. For this purpose, experimental segments of the footbridge were designed to be printed without embedded reinforcement. The main dimensions of the experimental footbridge are: span 5.10 m, width 56 cm, height 100 cm (Fig.4). The total weight of this structure is approximately 1400 kg. The footbridge is designed as a three-joint structure without steel reinforcement, using only the internal arch structure of the print footprint for load transfer. The advantage of the static scheme is that the structure can be divided into two smaller sections suitable for both printing and transport. The maximum printing area of the gantry machine was used for printing.

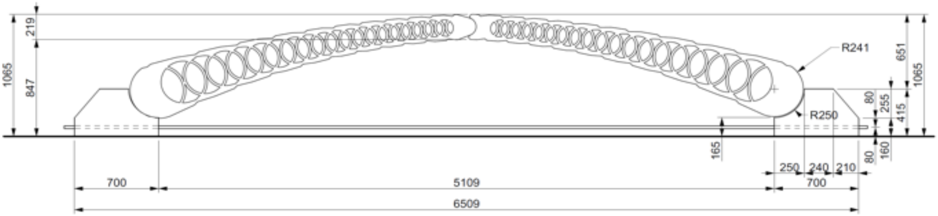

Fig. 4 Final footbridge design drawing

3.2 Design of the footbridge

The footbridge was designed as a verification object, the dimensions of which will correspond to standard construction elements. As a 3D-printed element without additional reinforcement, the footbridge also represents a more ambitious deployment of 3D-printed structures than is usual, where conventional 3D-printed objects are usually garden planters, urban furniture or vertical walls. The architectural language of 3D printed structures is also a big theme. Like any fabrication technology, 3D printing has a number of limitations, but also advantages that need to be considered when designing. It is important to distinguish between kitsch and the new freedom to freely shape ornamental structures. The basis of the design was parabolic skyline curves, which were parametrically filled with circular fill. This filling is constructed in such a way that the overlapping circles form the outer surface of the footbridge while creating an ideal continuous path for printing without interruptions or sharp corners. The parabolic shaping of the entire structure ensures that it is only loaded by pressure. Our long experience in designing experimental 3D printed objects on a smaller scale has been applied here. The design of the footbridge was subjected to a calculation, which was then experimentally verified by a continuous load test.

3.3 Fabrication

The testbed printing system used to print this tray is a three-axis gantry system that can manipulate the print head in a 3200x1000x1000 mm space. Several smaller samples of the footbridge, approximately 1 m in length, were first printed to verify the design of the print path and the expected benefits of the circular fill for speed and smoothness of printing. Despite the relatively long experience of printing a number of experimental objects, this footbridge was the first realistic stress test of the entire printing system simulating an industrial deployment. The printing itself took approximately 6 hours, during which 0.6 m3 of printing material was consumed. The two halves of the experimental footbridge were printed simultaneously and together weighed approximately 1.32 t. A layer height of 10 mm and a nozzle diameter of 20 mm with a maximum speed of 120 mm/s depending on the curvature of the print path were chosen for the printing.

3.4 Experimental verification of load capacity

After printing, the footbridge was mounted on temporary supports with a drawbar in the yard of the Klokner Institute. The slip layer in the joints is made of lead sheet, which by creeping into the rough printed surface also ensures even pressure distribution in the contact joint of the arch halves and in the joints at the abutments. The footbridge was equipped with potentiometers to measure the movement of the structure at the joints at the base and apex, at the quarter spans and at the abutments to check their relative positions. Loading was carried out in cycles of 350 kg with check measurements between each loading cycle. During the measurements, the graph shows a gradual decrease of 2.5 mm at the top of the footbridge. This is probably due to the effect of creep in several layers of corrugated lead sheets at the joints and the increasing ambient temperature during the measurements. Subtracting this drop, the residual deflection at the top was 0.8 mm when the footbridge was loaded with 1750 kg of load, corresponding to a permanent load of 5.7 kN/m2 (Fig.5). The results corresponded very well to the numerical model, which was made in Atena software.

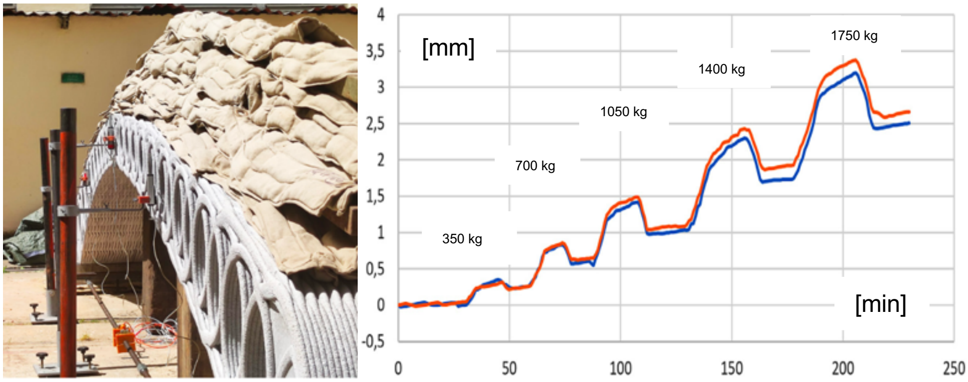

Fig. 5 Load bearing test of the footbridge. Loading diagram.

3.5 Installation

After a successful load test, the footbridge was disassembled into two smaller pieces and easily transported to the site. The footbridge was mounted on the outlet of a small private pond, where the undeniable advantage was the possibility to place it above the transverse threshold of the pond spillway, which thus replaced the lower axis. The threshold and the surrounding terrain were photogrammetrically photographed. The resulting 3D model was then used to create a section as a reference for the foundation design. The threshold was extended with steel reinforced concrete blocks, which were attached to it with additional steel reinforcement. The original monolithic retaining blocks were then placed on top of these extensions in a fresh layer of concrete. Each abutment was additionally connected to the concrete foundation block by three threaded rods. The bars were then prestressed to provide a pressure reserve in the joint between the abutment and the concrete base block. The footbridge has been monitored since it was printed and installed outdoors in December 2021. Visual inspections have so far revealed no significant cracks that were not caused by the initial shrinkage of the mixture after printing, and the footbridge surface appears in good condition with no noticeable degradation (Fig.6).

Fig. 6 Installation of a footbridge at the pond near the village Solopisky

4 CONCLUSIONS

The motivation of the project is not only the development of the design and technological background of 3D printing, but also the design of structural elements, the philosophy of the entire structure and the design of elements with regard to the printing technology. It turns out that 3D printing capabilities can satisfy both time and cost optimization requirements, as well as very laborious efforts for shape differences and unconventional design, as well as stress shape optimization.
Due to the absence of comprehensive design standards and regulations, it is still necessary to approach constructions individually. The number of parameters must be obtained from the printing process itself, and especially from the load tests of the printed objects.
The experimental footbridge described in the article verified the possibility of printing load-bearing horizontal structures without additional reinforcement and is one of many views on how to comprehensively approach 3D printing of building structures. On the basis of laboratory tests of the printing material, it is possible to consider not only the strength parameters suitable for such a stressed structure, but also very good resistance to weather influences. With this experimental footbridge, where the side printing wall is exposed to the greatest extremes, it will be interesting to observe the effect of frost in the grooves between the printing layers in the long term. These sites generally appear as potential sites of failure of printed objects, either by water or gradual degradation by established emergent vegetation. The footbridge has been monitored since it was printed and installed outdoors and will continue to be monitored continuously, providing further valuable information on the reliability of 3D printed structures in the future.
Visual inspections after about 4 years have not yet detected any significant cracks or other types of degradation that would affect the static load-bearing capacity of the element, which points to the possibility of using 3D printed objects in extreme conditions.

Acknowledgements

The results were obtained and the article was prepared with the kind support of the project OP VVV CZ.02.1.01 / 0.0 / 0.0 / 16_025 / 0007424 3D-STAR and project TACR FW06010422.

References

[1] Dilawar, R.; Usman, M.; Ali, A.; Majit, U.; Faizan, M. et al. Inclusive characterization of 3D printed concrete (3DPC) in additive manufacturing: A detailed review. Construction and Building Materials 394 (29), 1–20 (2023).

[2] Hansemann, G., Schmid, R., Holzinger, Ch. et al. Additive Fabrication of Concrete Elements by Robots. Lightweight Concrete Ceiling. In: Fabricate 2020: Making Resilient Architecture, pp. 124–129. UCL Press, London (2020)

[3] Hager, I., Golonka A., Putanowicz, R. 3D printing of buildings and building components as the future of sustainable construction? Procedia Engineering 151(2016), 292-299 (2016).

[4] Suchomel, V. Bureš Sequentional on-site Printing of Building Structures, In: VSB - Technical University of Ostrava, Conference Architecture in Perspective, 2022-03-23

[5] Čítek, D.; Řeháček, S.; Dobiáš, D.: EXPERIMENTAL RESEARCH ON 3D PRINTED CONSTRUCTION FROM CEMENT BASED COMPOSITES, In: Proceedings of 22nd International Multidiscipli nary Scientific GeoConference SGEM 2022. Sofia: STEF92 Technology Ltd., 2022. vol. 22. ISSN1314-2704. ISBN 978-619-7603-48-4.

[6] Citek D., Hurtig K., Kolisko J., Kotes P.:CEMENTITIOUS MATERIAL DEVELOPMENT FOR ADDITIVE FABRICATION,(2024) MM Science Journal, 2024-June, pp. 7410 - 7414, DOI: 10.17973/MMSJ.2024_06_2024040

[7] Rymes J., Cervenka J., Jendele L., Bures V., Citek D. : Integrating 3D Modelling and Nonlinear Numerical Simulations in Concrete Additive Manufacturing, (2024) fib Symposium, pp. 2957 - 2964,