Concrete Development for 3D Printed Constructions of Footbridge

D.Citek[1*], S.Rehacek[2], K.Hurtig[3], J.Kolisko[4] and O.Melter[5]

[1,2,3,4,5] Klokner Institute CTU in Prague, Prague, Czech Republic
Email: david.citek@cvut.cz

[*]Corresponding author

ABSTRACT

The paper deals with the possibilities of using 3D printing for the construction of footbridges without reinforcement. Using the Solopisky footbridge as an example, the whole process is described from the design, the composition of the mixture, the printing process, the verification test to the actual assembly of the final object. The mixture used was developed by Klokner Institute specifically for this implementation. It consists of individual se-lected components typical of fine-grained micro concrete 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. 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 printing, the footbridge was mounted on temporary supports with a drawbar in the courtyard of the Klokner Institute and there was carried out experimental verification of load capacity. The footbridge was fitted with potentiometers to measure the movement of the structure. Loading was carried out in cycles of 350 kg with check measurements between each loading cycle. After checking the characteristics of the footbridge, it was installed at the pond near the village Solopisky.

KEYWORDS: *Additive fabrication, 3D printing, Footbridge, Experimental printing, Concrete.*

1. Introduction

Cement binders require a cement hydration process to cure, which under normal conditions takes place at its fastest stage at a significantly slower rate of days and is not fully completed even within a few years. Cement hydration is the process of first setting and then hardening of the cement-bonded material. The setting process depends on many factors, but generally this phase takes place within hours. The hardening process is loosely related to the setting process. A fundamental issue, 3D printing of cementitious composites is facing, is designing the mixture in such way that after extrusion and repeated layering, it resists its own weight, and the printed element can be printed/built up vertically. The mixture must be of a suitable consistency to be pumpable and subsequently easy to leave the extruder, but at the same time it must set quickly enough after extrusion or have a rigid consistency to allow the layers to be reapplied on top of each other. This is further related to the very issue of the stability of a freshly printed object that is not sufficiently cured. These mixture requirements ultimately lead to the design of a cementitious composite of a rather complicated composition containing several different additives, including setting accelerators. The resulting mechanical strength is certainly also important to the overall design of the final element, but less important in terms of the extrusion process itself.

2. Experimental part

At the beginning, fine-grained micro concrete was compound (e.g. see Table 1). According to requirements on maximum size of grain, sand with grains of 1,25 mm was used. A requirement for the compressive strength of the molding to be at least 60 MPa was required, therefore CEM II 52,5 N cement was used in combination with a superplasticizer. Also, polypropylene (PP) fibres with length of 12 mm were added to prevent plastic shrinkage.

This basic mixture was tested to buildability when the viscosity modifying admixture (VMA) is added. The question was, if we are able to provide such material, that can be build by layers. Adding VMA to the mixture cause increase of material stiffness and thixotropy. These characteristics allow to print individual layer that withstand the pressure of the layers above it without plastic deformation due to compression, spreading, etc. Varienty of VMAs were tested. After few trials for each type of VMA, printable cement based material was produced (e.g. see Fig. 1). By using pistol (e.g. see Fig 2) filled by fresh mixture, the layers were manually printed out. For each type of VMA, the optimum dosage for manually printed material was experimentally determined. In Table 2, type of VMA, water content, quantity of admixture, consistency of fresh mixed material determining by the method specified by standard EN 1015-3, bulk density of the material, flexural strength and compressive strength, are listed. Bulk density, compressive and flexural strength are determined on beam specimens with dimensions of 40×40×160 mm at the age of the material of 28 days.

Table 1. Mix design of preliminary tests

Component	Content (kgm^{-3})
Silica sand 0-1,25 mm	967
Micro fillers	495
Cement CEM II 52,5 N	358
Superplasticizer	25
Water	225

3. Practical part

3.1 Description and design of the footbridge

One part of the project was the design of a printed structure that will be applied in actual use.. For a prototype structure was chosen a footbridge, using whole printable area of our print platform. Main dimensions of the experimental footbridge are: span 5,10 m, width 56 cm, height 100 cm. Total weight of this construction is approximately 1400 kg. Foot-bridge is designed as a three-joint bridge structure without steel reinforcement. The construction uses a static three-arch scheme. The advantage is the possibility of dividing the structure into smaller parts suitable for printing and at the same time for transport.

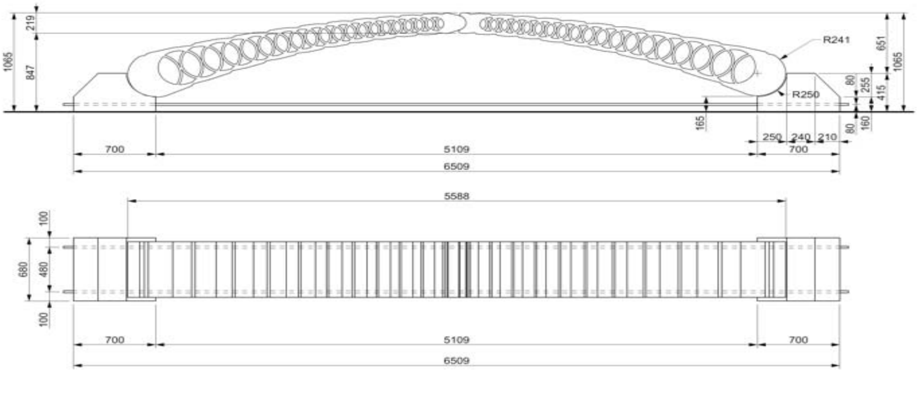

Figure 1. Final footbridge design drawing

The footbridge was designed as a verification object, whose dimensions will correspond to standard building elements. As a 3D printed element without additional reinforcement, the footbridge also represents a more ambitious deployment of 3D printed constructions than usual, when common 3D printed objects are typically garden flowerpots, urban furniture or vertical walls. The architectural language of 3D printed structures is also a big topic. Like any manufacturing technology, 3D printing has many limitations but also advantages, which must be considered during the design process. It is important to distinguish between kitsch and the new freedom to freely shape ornamental structures. The design was based on parabolic envelope curves, which were parametrically filled with circular infill. This infill is constructed in such a way that the overlapping circles form the outer surface of the footbridge and at the same time, create an ideal continuous track for printing without any interrup-tionsor sharp corners. The parabolic shaping of the entire structure ensures that it is loaded only in compression. Our long-term experience in designing experimental 3D printed objects of a smaller scale was applied here to design shape and the print path. The footbridge is a three-arch structure with a span of 5.1 m, designed as a predominantly compressed structure. The design of the footbridge was subjected to calcula-tion, which was then experimentally verified by a continuous load test.

Figure 2. Printed layers of cem. based material

3.2 Description and design of the footbridge

The Testbed printing system used for printing this footbridge is a 3 axis gantry sys-tem capable of handling the print head in a 3200x1000x1000 mm space. First, several smaller footbridge samples of approximately 1 m length were printed, on which the design of the print path and the expected advantages of the circular fill for speed and smoothness of printing were verified. Despite the relatively longterm experience with printing a number of experimental objects, this footbridge was the first really real stress test of the entire printing system simulating deployment in industry. The printing itself took approximately 6 hours, during which 0.6 m3 of printing material was consumed. Both halves of the footbridge were printed at the same time, which then together weighed approximately 1.32 t. A layer height of 10 mm and a nozzle with a diameter of 20 mm were chosen for printing with a maxi-mum speed of 120 mm/s depending on the curvature of the print path.

3.3 Fabrication

After printing, the footbridge was mounted on temporary supports with a drawbar in the courtyard of the Klokner Institute. The sliding layer in the joints consists of a lead sheet, which by its creep into rough printed surface also ensures a uniform pressure distribution in the contact joint of the arch halves and in the joints at the abutments. The footbridge was fitted with potentiometers to measure the movement of the structure at the joints at the foot 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 drop of 2.5 mm in the top of the footbridge. This is most likely due to the effect of creep in several layers of corrugated lead sheets at the joints and the rising ambient temperature during the measurements. After subtracting this drop, the residual deflection at the top was 0.8 mm, when the footbridge was loaded with 1750kg ballast, corresponding to a continuous load of 5.7kN/m2.

3.4 Long term monitoring

As part of the material's resistance to environmental aspects, a test was carried out according to ČSN 73 1326+Z1 using method C. The results of this test met the lim-its for the degree of environmental influence XF4 prescribed in the ČSN P 73 2404 standard. It will be interesting to observe the effects of frost in the grooves between the individual printing layers in the long term. In general, these features of printed objects appear as possible failure points, either by water or by gradual degradation by emergent vegetation. The footbridge has been monitored since it was printed and installed outdoors in December 2021, and now after being installed on the dam of the pond in October 2023, monitoring will continue. Visual inspections have so far revealed no significant cracks that were not caused by the initial shrinkage of the mixture during solidification after printing, and the footbridge surface appears in good condition with no noticeable degradation.

3.5 Installation

The footbridge was mounted on the outlet of a small private pond, where the undeni-able advantage was the possibility to place it above the transverse sill of the pond spillway, which thus replaced the lower drawbar. The sill and the surrounding terrain were photogrammetrically scanned. The resulting 3d model was then used to create a section as a reference to design the foundations. The sill was extended with steel reinforced concrete blocks, which were attached to it by additional steel rebar. The original monolithic abutment blocks were then placed on top of these extensions in a fresh layer of concrete. Each of the abutments is additionally connected to the concrete base block by three threaded rods. The bars were then prestressed to provide a pressure reserve in the joint between the abutment and the underlying concrete block.

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 construction elements, the philosophy of the entire structure and logistics on the construction site. It turns out that the possibilities of 3D printing can satisfy the requirements for optimization in terms of time and costs, as well as very laborious effort for shape differences and non-traditional design, as well as shape optimization in terms of stress.This experimental footbridge verified the possibility of printing load-bearing horizontal structures without additional reinforcement and is one of many views on how 3D printing of building structures can be comprehensively approached. On the basis of laboratory tests of the printing material, very good resistance to weathering can be considered. For this footbridge, where the side print wall is exposed to the greatest extremes, it will be interesting to observe the frost action in the creases between the print layers in the long term. These locations generally appear to be potential failure points for printed objects, either by water or by gradual degradation by established emergent vegetation. The footbridge has been monitored since it was printed and mounted outdoors and will continue to be monitored on an ongoing basis, providing further valuable information on the reliability of 3D printed structures in the future. Visual inspections have so far revealed no significant cracks or other kind of degradation.

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