DEVELOPMENT OF A ROBOTIC FABRICATION SYSTEM FOR CEMENTITIOUS MATERIALS

OTO MELTER[1], DAVID CITEK[1], ALES HVIZDAL[1], MICHAEL GABRIEL[1], JIRI KOLISKO[1], PETER KOTES[2]

[1]Klokner Institute, CTU in Prague, Prague, Czech Republic

[2]University of Zilina, Zilina, Slovakia

DOI: 10.17973/MMSJ.2024_06_2024041

e-mail: oto.melter@cvut.cz

ABSTRACT

Our team at Klokner Institute under Czech Technical University in Prague is working in a joint effort with Technical University of Liberec and Klokner on a comprehensive 3D printing system for cementitious materials, including specially optimized robotic arm. The goal of this system is to decrease the environmental impact of construction industry by reducing the volume of materials and time required, as well as reducing need for human labor. 3D printing also makes possible to build complex functional shapes, that would be too complicated or prohibitively expensive to manufacture using standard industry methods. Combining expertise of these two institutions lead to development of a robust system, that seamlessly integrates in-house developed mechanics and print material. One of key areas of our research is also testing mechanical properties of printed parts which is essential to safely integrate this construction method in real-world use in the future.

KEYWORDS

3D print, cementitious material, extruder, data optimization

1 FOREWORD

This article is describing development of this system at Klokner institute, where is installed CNC testing platform called TestBed, used for fine tuning the print parameters in laboratory conditions and for printing first small-scale parts. (Print volume 3,2x1x1 meters).One of the essential parts will be also described – the printhead and the gradual process of many revisions until the now used prototype. Another integral part is software solution and knowledge base to design part itself and successfully prepare the print toolpath, which was developed in parallel with the rest of the system components.

We will talk about practical experience testing different concepts of printhead, beginning with system with open buffer until the now used enclosed continuous system. The printhead is still under further development as we make improvements to various subsystems, such as accelerator dispenser and testing new print toolpaths strategies, for example non-planar printing.

Within this project we achieved level of functionality of all the components, that is ready as a basis for testing larger scale production of printed parts. Now, after two years printing in laboratory conditions, comes time to apply our experience by participating in several construction projects. All our experiments lead to further improvements in the 3D printing system as a whole and the insights are used to influence the design phase as well.

2 CEMENTITUOS PRINT MIXTURE

2.1 Printing mixture requirements

At the beginning of the project, 3D print of cement composites was a novelty both in terms of the technology (machine solutions) as well as the technology of concrete and cement composites per se. The nature of concrete is distant from the usually printed materials such as plastics or metals and warming and consequent cooling of the input material cannot be used for printing.

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 so 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.

2.2 The main objective of the laboratory activities

For the 3D STAR project and 3D printing purposes, a special fine-grained cement mixture was developed in the laboratories of the Klokner Institute. The reason for the development of the custom blend in the first place was the possibility of arbitrary optimization of the developed blend at any stage of the project and for any type of application. A very important factor in the consideration of the mix design was that the printing equipment with the print head and the entire system from mixing to extrusion was the subject of research and development for this project. It was therefore necessary to address both issues in parallel and to respond in both sectors to the realities arising from the partial results of the different groups involved in the development. The second reason was the real unavailability of commercial blends at the beginning of the project and later their high cost. The third and equally important reason was to examine the possibility of creating the mixture on an improvised basis from locally available raw materials, thus ensuring the economic viability of the additive technology.

The advantage of in-house mix development is the ability to react to any external influences such as unavailability of raw materials, type of printed structure and variability of requirements for physical and mechanical parameters of the resulting mix required by the designer, architect, or structural engineer. During the research phase of the project, an extensive database of input raw materials was created that can be applied if the mixture needs to be modified according to the building being constructed.

3 DEVELOPMENT OF THE PRINTHEAD

3.1 Printhead prototype 1 – open extrusion system

The first version was developed by Technical university of Liberec, to serve as a baseline for initial testing. This printhead was designed as an open system with a concrete hopper of about 20 litres in the printhead itself. This hopper was continuously refilled by a standard concrete spindle pump located at the side of the printer. The print material is transported to the print head throught a DN 35 mm hose. The hopper was followed by a screw to control extruded amount (Figure 1).

Figure 1. First prototype of the printhead – open system with hopper.

The initial tests done with this printhead served to set approximate range of default values of the printing parameters and to further refine the range of consistency of the printing mixture. As a disadvantage, it soon became apparent that the open system was not very suitable for the required print parameters and especially for the developed mixture. This was particularly evident in the unreliable dosing of the mixture from the hopper to the screw and thus an inconsistent print trace. The open system with screw dosing required a significantly more fluid mixture. When the mixture was too fluid at the entry, it caused the mixture to become unstable after extrusion.

3.2 Printhead prototype 2 – closed extrusion system

After these initial tests, we opted to try a closed extrusion system, which promised much smaller and lighter printhead and better extrusion control. This printhead design is simpler in several aspects but requires more careful tuning of the entire dispensing system and precise synchronization of all components. However, this was not a problem due to the integration of the whole system in one control interface. The use of a closed system eliminates the need to use a large and heavy tank full of concrete and to deal with the difficulty of "reviving" the print mix in the hopper, making the entire printhead more compact, lightweight, and reliable (Figure 2 and 3).

There were several intermediate prototypes of printhead until we solved issues with mechanical strength of the head and other general design considerations, such as ideal inner cross section for our print mixture consistency and speed of printing, which is now 120 mm/s, with headroom to test up to approximately 300 mm/s. At the beginning of the transition to the new printhead system, it was necessary to search again for the default values of the settings for printing and to iterate the design several times to avoid destruction and jamming during printing (Figure 4).

These considerations were used in final prototype of this closed system printhead, and the design was adjusted to be more user friendly, both easier to operate and clean after print. We added quick release nozzle system and the whole printhead can be easily disassembled using four nuts.

Figure 2. Printhead prototype 2

Figure 3. Printhead prototype 2 main components

Figure 4. Printhead prototype 2 while printing

3.3 Printhead prototype 3 - setting accelerator injection

After the initial success with the closed extrusion system, we decided to pursue the variant where a liquid setting accelerator is injected in the last stage of the printing process (Figure 5).

This variant has several advantages for the complex system under development. One of them is the rapid response to changes in the surrounding climatic conditions, which is not possible when printing the mixture with powder accelerator in the bulk mixture. This enables us to flexibly react to environment conditions and tailor the amount of the setting accelerator exactly to the needs of the printed shape. It is possible to print object with layer times about 30 seconds (for example some column-shaped objects) and afterwards, using the same mixture, print objects with large base and layer times as long as need (for example 15 minutes and more). These large objects don't require the same amount of accelerator – this makes the resulting print material cheaper and mechanically superior. With this system the initial strength can by adjusted to initialize as soon as 3 to 5 minutes after extrusion.

Theoretically, the is an option to control the amount of injected accelerator during single print, depending on what part of the geometry is printed at the moment (straight wall, overhang…). This is to be further investigated.

To take advantage of these fact, we need to mix the accelerator in the last possible moment, as close to the end of the extruding system, as possible. This requirement contradicts the need to thoroughly mix the accelerator into the mixture.

Figure 5. Clear body printhead to visually assess the length of the accelerator mixing path

For this purpose, we have developed a system of specially shaped movable vanes, mechanically coupled to the drive for dispensing and mixing the printing matrix and we are testing several shapes of the accelerator inlet itself. The paddles not only have to mix the print mixture perfectly with the accelerator, but at the same time they should limit the flow of material through the print head as little as possible and must not be prone to clogging during printing. After the experimental verification of several basic paddle shapes, the variant was chosen which best met most of the requirements. This variant further underwent the development of a mechanical and material solution so that it better resists the abrasive environment in the print head. Even after pumping through several thousand liters of cement mixture, there are no significant signs of wear or damage.

The shape and position of the accelerator dispensing outlet inside the printhead was visually examined on a representative clear gel mixture with the accelerator replaced by colored liquid. At the same time, we replaced the aluminum body of the print head with a polycarbonate one to visually determine the minimum necessary length of the mixing path to homogenize the mixture after adding the accelerator (Figure 6).

Figure 6. The current printhead with setting accelerator injection, quick-release system

Figure 7. Example of thin-wall object with very short layer times. Extrusion width 20 mm, object height 85cm

A gear pump with a flow sensor was used to regulate the flow rate while balancing the back pressure in the tubing conveying the liquid accelerator to the print head. Among the advantages of this dosing method is the robustness of the system as a whole - if there is a stoppage during printing or an interruption when moving to the next print object, there is no risk of the print mixture getting solidified in the supply hoses or pump - the activated, fast setting print mixture is only in a very small volume in the machine itself, just in the printhead (Figure 7).

Figure 8. Consistency of surface, layer height 10 mm

3.4 Nozzles

The system is designed to use nozzle with diameters of 20-50 mm and standard layer height of 10 mm (Figure 8).

Outlet nozzles and their shape diversity were also subject to thorough development. In the beginning, rectangular, oval or circular nozzles with inner spine were developed in order to find a suitable ratio between the nozzle outlet volume and its plan dimension. The whole system was designed for quick installation/quick dismantling (Figure 9).

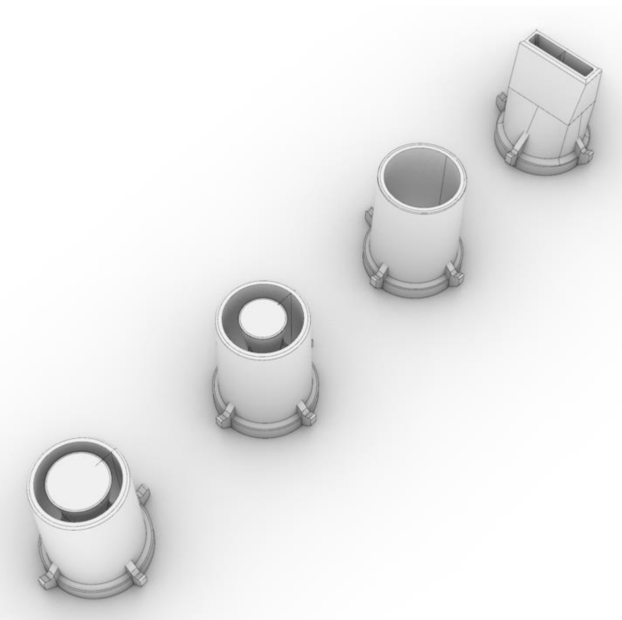

Figure 9. Various nozzle prototypes

All these nozzles are printed from durable plastics on 3D printers and therefore easily modifiable and replaceable. Nozzle extensions can also be used for more complex printed structures (Figure 10).

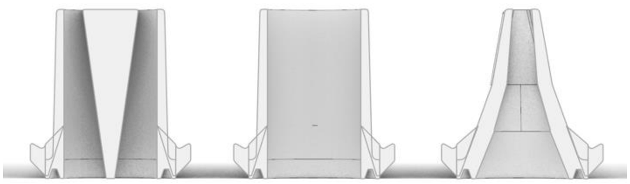

Figure 10. Nozzle prototypes cross sections

3.5 Printhead control

As was briefly described above, whole system is integrated under one control interface. This is necessary in order to be able to synchronize components providing pumping concrete mixture and setting accelerator. The main core system is provided by B&R Industrial Automation. Interface of this system is custom adjusted for the concrete printing purpose (Figure 11).

The amount of pumped concrete from the external hopper is synchronized with speed of printing and printhead internal mechanism to ensure consistent extrusion width even in the corners, where the print speed decreases in comparison to straight travel sections. These two values are synchronized by a multiplier, that is modifiable during the print itself. This gives us fine control and on the fly adjustability. The amount of accelerator added to the mixture is controlled in the same manner, in order to set optimal amount for temperatures and concrete mixture consistency as needed.

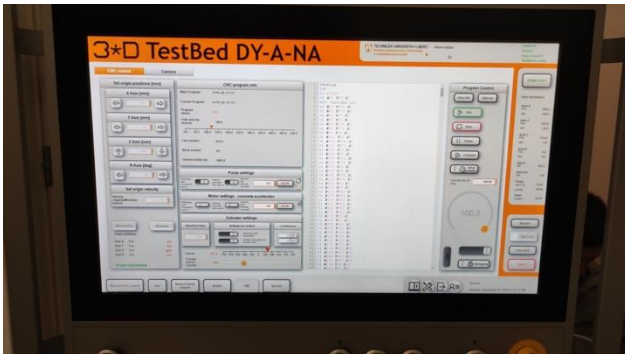

Figure 11. TestBed control interface

4 PRINT SHAPING

4.1 Printable shapes

The preparation of the necessary data for printing is an integral part of the additive manufacturing system. From the shaping of the print objects themselves to the selection of the appropriate printing strategy and input parameters. In the beginning, the shaping of the objects was mainly governed by the need to calibrate the print setup and print samples after measuring the basic mechanical properties of the printed material. Once these tests were done, it was possible to move on to shaping the objects to test the limits of the printing system and to find the optimal shape for 3d printing of the structures. In general, the experience from the tests is to shape the printed elements into curved shapes and to limit sharp corners as much as possible for 3D printing production (Figure 12).

Figure 12. Example of a shape with minimal amount of sharp corners

Experiments with crossing the print path in a single layer have been carried out with good results. Such printed intersection ensured good interlocking of the print mass and avoided occasional planar delamination of the print traces, as was sometimes observed with tangentially connected print traces. The subject of further testing was also the architectural and aesthetic treatment of the printed surface, which will also respect the above-mentioned findings (Figure 13).

Figure 13. Example of a print where the print path crosses itself in the same layer

5 PRINT DATA PREPARATION

For the first attempts, handwritten g-code was used - basically for printing simple shapes like squares and circles. For further experiments and the possibility of easier input of more complex shapes and intersections of print paths, a script was prepared in the graphical programming environment Grasshopper for Rhinoceros3D. At the beginning it was only a matter of converting the curves to g-code in the required format, later the possibility was added to slice the 3D object directly and parametrically set the print path before printing the object itself. Gradually more options for parameterizing some settings were added (Figure 14).

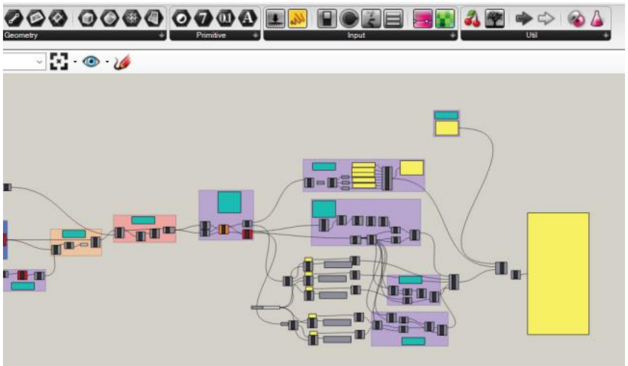

Figure 14. Grasshopper slicer

This slicer allows, among other things, to specify a print path with a variable z coordinate - so the individual printing layers do not have to be only horizontal - so-called non-planar printing. Slicer also allows automatic analysis of print parameters such as approximate print duration, amount of material used and expected print weight.

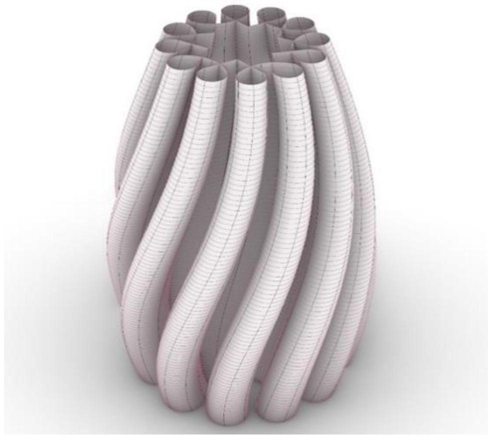

Figure 15. Self intersecting shape

Finally, the Starslicer software developed at the University of Liberec was used to create the printing model, which is a more complex solution developed specifically for the printing of cement mixtures. It basically includes the possibility of setting many parameters, such as adjusting the printing speed to the required printing time per layer or the possibility of a spiral printing path (Figure 15).

6 EXPERIMENTAL FOOTBRIDGE

6.1 Design

One part of the project was a design of a real printed structure. For a prototype structure was chosen a footbridge, using whole printable area of our print platform. This led to a footbridge with span of approximately 5m constructed from 2 half parts. Width was designed to be 0,5m. There were several different designs iterations until the final design proposal was chosen (Figure 16 and Figure 17).

Figure 16. Early design - elevation

Figure 17. Early design – visualization

Final design was optimized according to our previous experience with print path shaping a small-scale test prints and according to architectural design and print possibilities (Figure 18).

Figure 18. Final footbridge design drawing

Further investigation was focused on working with the geometry of the print path within the surface. This was done on the construction of the prototype footbridge. We adopted the aesthetics of the printed layers as evidence of the printing technology and worked to achieve aesthetical form true to the structure itself (Figure 19 and Figure 20). The combination of offsetting the intersections by half the height of the print layer resulted in an aesthetically treated surface free of cracks and defects. The advantage of such a varied surface is also the possible concealment of printing defects. The long-term durability of the surface is still subject to further investigation.

Figure 19. Printing the footbridge.

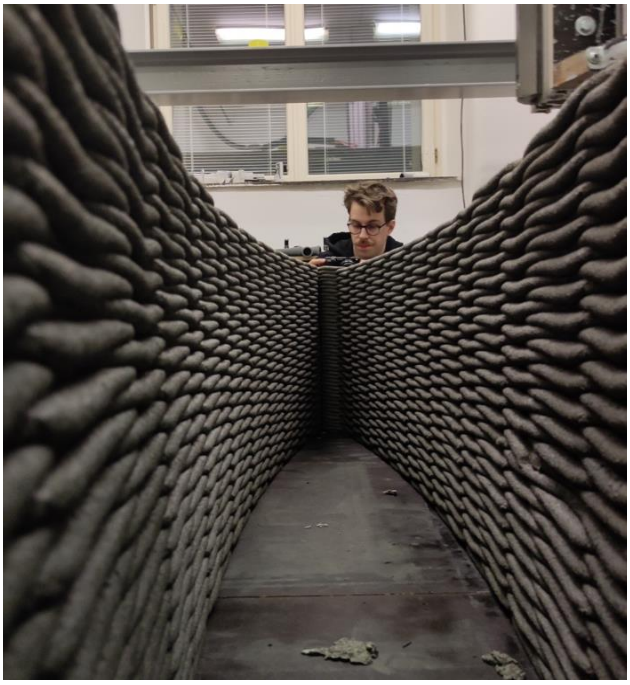

Figure 20. Surface of the printed footbridge

Figure 21. Setting the footbridge into final position

The final 3D printed structure of the footbridge weighs approximately 1,5t. After successfully printing and assembling the footbridge we performed experiments to assess the load bearing capacity of the structure (Figure 21 and 22). Loading was performed in cycles of 250kg, up to final total load of 1750 kg, which amounts to loading 700 kg/m^2. Maximum measured deflection of the footbridge in the midspan during final loading was 3,5 mm.

Figure 22. Load bearing test of the experimental footbridge

There will be long term observation of weathering and structural integrity of this printed strucure. There are plans for further 3D printed structures based on the experience we gained in this project. In the next phase we will aim to produce a reinforced 3D printed structure capable of safe operation in real life use.

7 CONCLUSION

The current paper summarizes the partial results of the 3D STAR project, in which TUL and KI CTU joined forces in the complex development and research of a 3D printing device with a printing mixture. 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. The result of the current project is a comprehensive system of 3D printing equipment, with which we have the opportunity to laboratory test both the equipment as such and tune the cement mix and whole technology in terms of various requirements or verify the limits of printed structures in relation to their static action.

ACKNOWLEDGMENTS

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.

REFERENCES

[D. Citek, V. Bures, O. Melter, A. Hvizdal, K. Hurtig, J. Suchomel, and J. Kolisko] Experimentalni vyvoj 3D tisku cementovych kompozit, In: BETON TKS, 1/2022 Technology, p.7-11, ISSN 1213-3116

[J. Kolisko, F. Diaz, D. Citek, K. Hurtig, M. Kroc] Vyuziti UHPC a aditivni robotickee fabrikace ve stavebnictvi, In.Sbornik 18. konference Technologie a provadeni, 2021

[J.Suchomel, V.Bures, J.Valek, D.Citek, J.Kolisko] Experimental development of 3D printing using cement composites, In.Abstract book WMCAUS, 2022

[S.C. Paul, G.P. van Zijl, M.J. Tan, I. Gibson] A review of 3D concrete printing

[van Zijl, Gideon & Suvash, Chandra & Paul, Suvash & Ming, Jen & Tan, M.J..] (2016). PROPERTIES OF 3D PRINTABLE CONCRETE.

[G. Ma, Z. Li, L. Wang], Printable properties of cementitious material containing copper tailings for extrusion based 3D printing, Constr. Build. Mater. 162 (2018) 613–627, http://dx.doi.org/10.1016/j.conbuildmat.2017.12.051.
[G. Ma, L. Wang] A critical review of preparation design and workability measurement of concrete material for largescale 3D printing, Front. Struct. Civ.
[Bos, Freek & Wolfs, Rob & Ahmed, Zeeshan & Salet, Theo.] (2016). Additive manufacturing of concrete in construction: potentials and challenges of 3D concrete printing. Virtual and Physical Prototyping. 11. 1-17. 10.1080/17452759.2016.1209867.
[T.S. Rushing, P.B. Stynoski, L.A. Barna, G.K. Al-Chaar, J.F. Burroughs, J.D.Shannon, M.A. Kreiger, M.P. Case] Investigation of concrete mixtures for additive construction, in: 3D Concrete Printing Technology, Elsevier, 2019, pp.137–160, http://dx.doi.org/10.1016/B978-0-12-815481-6.00007-5.
[Tay, Yi Wei Daniel & Panda, Biranchi & Paul, Suvash & Noor Mohamed, Nisar Ahamed & Tan, M.J. & Leong, Kah Fai] (2017). 3D printing trends in building and construction industry: a review. Virtual and Physical Prototyping.
[V. Mechtcherine, F.P. Bos, A. Perrot, W.R. Leal da Silva, V.N. Nerella, S. Fataei, R.J.M. Wolfs, M. Sonebi, N. Roussel] Extrusion-based additive manufacturing with cement-based materials – Production steps, processes, and their underlying physics: A review, Cement and Concrete Research, Volume 132, 2020,
[Flavio Craveiro, Shadi Nazarian, Helena Bartolo, Paulo Jorge Bartolo, Jose Pinto Duarte] An automated system for 3D printing functionally graded concrete-based materials, Additive Manufacturing, Volume 33, 2020,

CONTACTS

Melter, Oto, Ing. Arch.
Czech Technical University – Klokner institute
Solinova 1903/7, 166 08 Prague 6 – Dejvice
+420-22435-3521,oto.melter@cvut.cz,
http://www.klok.cvut.cz/en/