Construction Robotics (2021) 5:203–210
https://doi.org/10.1007/s41693-022-00064-5

REVIEW

Building rethought – 3D concrete printing in building practice

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Received: 24 September 2021 / Accepted: 9 January 2022 / Published online: 8 February 2022

Abstract
After only a few of years of intensive research all over the world, 3D printing of buildings has been induced in practical application in construction industry. In the course of this, in 2021, the first 3D printed residential building was realised in Beckum, Germany. The aim of this paper is to give an insight to the impetus, the ideas and the individual steps to realize this project. We describe the technology used and give an overview about background of the material development and the requirements for the material. Furthermore the architectural design und planning process is displayed. However, existing design codes do not cover all special technical features of the new construction method. Consequently, we describe the concept how the building permission (approval) for the construction by following existing standards (DIN EN) for concrete and masonry construction was achieved and granted. Finally we give an insight in the construction process and conclude with lessons learned for future projects.

Keywords Additive manufacturing · 3D printing · Concrete · Building permission · Approval · First printed house in Germany

1 Introduction

Currently, the topics of saving resources and therefore shape-optimised construction are becoming increasingly important, especially with regard to the scarcity of resources of suitable aggregates (UNEP 2019; Beiser 2019; Höflinger 2019) and additives (BAW DBV 2021) for concrete production as well as to the energy consumption and CO_2 emissions of cement and steel production (UNEP 2017; Salet and Wolfs 2016; Suhendro 2014). Building elements that are designed in order to save material often follow the design principle "form follows force" and have therefore a complex shape that can only be produced with great effort, or is even impossible, by using conventional construction methods, such as filling a formwork. With additive manufacturing processes, however, complex shapes can be produced at a cost that is independent of the number of pieces. At the same time, the use of formwork can be completely dispensed with (Zäh 2006; Agusti-Juan 2017; Gebler et al. 2014). Furthermore, several pilot projects have already shown that a large material saving of concrete of up to 70% at comparable load capacity (Meibodi et al. 2017; López et al. 2014; Asprone et al. 2018; Menna 2017) or 80% minimum reinforcement (Mata-Falcon 2018) is possible through a suitable design. By dispensing with formwork, further material is saved and waste is avoided after use. These points lead to a positive ecological balance compared to conventionally manufactured components, especially in the case of complex elements (Agusti-Juan. 2017).

Furthermore, the shortage of skilled workers in the construction industry is a growing problem (Weitz 2021). The

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creation of new job profiles within the context of additive manufacturing processes on the construction site could create new perspectives and make the construction industry more attractive for young professionals.

After only a few years of intensive research worldwide, 3D printing becomes already a prospective alternative manufacturing technology for buildings. In addition to the particle bed-based processes (Selective Cement Activation—SCA (Lowke 2018, 2020; Weger et al. 2020; Shakor et al. 2019) and Selective Paste Intrusion—SPI (Prasittisopin et al. 2018; Weger 2020; Pierre et al. 2018; Weger. 2021; Weger and Gehlen 2021)), with advantages in surface resolution and complexity, as well as the shotcrete processes (Shotcrete 3D Printing) (Kloft et al. 2019), the depositing processes (extrusion) are most used and in the main focus worldwide (Salet and Wolfs 2016; Wangler 2016; Mattaus 2020; Buswell et al. 2020; Mechtcherine et al. 2021). The depositing processes make it possible to produce large concrete components in a relatively short time. In addition, the possible printing area is usually significantly larger.

With the construction of the first 3D-printed house in Germany located in Beckum, this new manufacturing technology was successfully used for the first time in this country for the production of a residential house, thus laying the foundation for the successful introduction of the 3D printing process into practice in the German construction industry.

2 Concrete extrusion technology

The 3D-printed construction elements in Beckum were produced using the depositing additive manufacturing process "extrusion". In this process, fresh cement mortar or concrete is fed by a pump through a hose to a manipulator and extruded through a nozzle. The fresh concrete strands are applied layer by layer and placed on top of each other. One of the great advantages of concrete extrusion is that components can be produced without formwork, see Fig. 1.

Fig. 1 Printing process with the BOD2, source: PERI

For the project described in this article, PERI used the BOD2 concrete printer. This printing technology comes from the Danish manufacturer COBOD, in which PERI has already been a shareholder since 2018. Each BOD2 consists of a gantry system with several modules. The number of modules is selected to suit the respective construction project. The gantry system is usable for both in-situ concrete projects and off-site element production. In addition, the gantry system avoids frequent moving and recurring calibration of the printer. A silo and a mortar mixing pump from the company m-tec were used to feed the printer with material.

3 Material requirements – development of a 3D printing mortar

With respect to global warming, the development of innovative, new materials should always be coupled with the requirement to minimise the associated CO_2 footprint. Furthermore, due to the increasing scarcity of resources, aspects such as recyclability and material efficiency should also be considered. A further key to become more resource efficient is to create a material (and construction elements) with a long service life.

One challenge, especially in the development of printable mortars, is to ensure that the individual layers of mortar or concrete – mostly distinguished due to the size of the used aggregates – do not harden too quickly in order to ensure the bonding of the individual layers.

If the printing speed is too slow or the printing breaks are too long (e. g. due to a printer failure, delayed material supply or planned overnight printing breaks), "cold joints" can occur. The cold joint refers to the transition zone between two strands that were not produced immediately one after the other ("fresh in fresh"). The advanced hydration and lower moisture content of the contact surface of the older strand compared to the fresh concrete of the new printing section can lead to a poorer layer bond (Buswell et al. 2018a; Matthäus et al. 2020; Wolfs et al. 2019; Kruger and Zijl 2021). At the same time, the layers must have sufficient green strength to support the subsequent layers with as little deformation as possible (Perrot et al. 2016; Reiter et al. 2018; Wolfs and Suiker 2019; Kruger et al. 2020).

These standards were also taken into account in the development of the special printing mortar "i.tech 3D".

The premix "i.tech 3D", developed by HeidelbergCement, is characterised first of all by the fact that it can be easily processed in the upstream mixing and transport process. This means that the material is both easy to liquefy and easy to pump. After leaving the printing nozzle, the mortar is

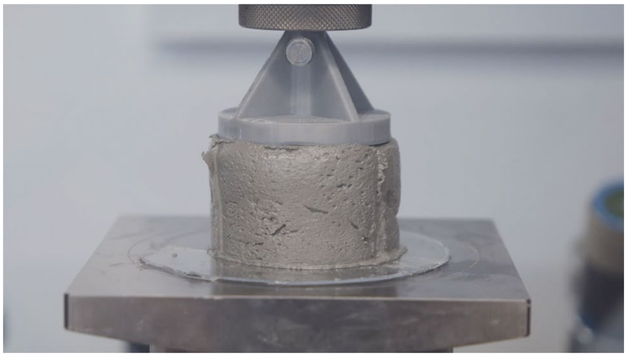

Fig. 2 Investigation of the stability of the pressure mortar in the laboratory, source: HeidelbergCement Group

Fig. 3 Animation first 3D-printed building in Germany, source: MENSE-KORTE

sufficiently dimensionally stable. The strength development is adapted in such a way that the layers can bond on the one hand and the mortar on the other hand is able to bear the loads from the next applied layers without significant deformation. In the Beckum project, for example, the application of the following printed layers took place after about 7 to 12 min in each case.

The balancing of these properties requires distinct know-how in concrete technology and a comprehensive test programme of many years, see Fig. 2.

On the one hand, the aggregate, binder and additives must be selected with regard to the properties to be achieved in the dry mortar. Secondly, the particle size distribution of the raw materials must be precisely matched. The use of further admixtures additionally controls the desired material performance (e.g. green strength development, workability or setting). The binder used in the premix was designed by aiming a CO_2 footprint that is about 70% lower than that of Portland cement.

The recyclability of the printing material – i. e. the possibility of reintroducing it into the material cycle after it has reached the end of its life – is ensured with "i.tech 3D" by the fact that it consists of purely mineral components.

The material achieves high strengths ($R_{c,28} \approx 60$ MPa according to DIN EN 196–1:2016, (HeidelbergCement Group 2019) as well as the good durability properties (weathering < 250 g/m^2 after 56 freeze–thaw cycles in the CIF test, without internal damage (Weger et al. 2020 Gehlen et al. 2020) enable the production of slender and at the same time durable printed components.

4 Design of the first 3D-printed building in Germany – architectural vision

4.1 Initial considerations

The idea to realise Germany's first printed residential building was raised from a Beckum dry construction company. Inspired by the idea, the main task was to transfer the technology, which had already been developed on a smaller scale, into practice, so that a real building could be created that met all the building code requirements of the German state of North Rhine-Westphalia. Since small printed building structures (pavilions) already existed in the surrounding European area, the challenge should be increased. Therefore, it had to be a building of a size and complexity equivalent to a high-quality detached residential building with two storeys. Starting with a fairly simple building structure in the initial design, it quickly became apparent that it would be essential to design a building that should optimise constructional, design and process challenges of today's building industry, see Fig. 3.

4.2 Design process

The initial design process for printed building structures is largely similar to that of conventional construction methods. The designer and the client jointly define the requirement profile for the building use, the building size and the architectural design. In terms of building architecture, concrete printing can already show its advantages for the first time. The planners are no longer limited in the realisation of their own ideas by cost-efficient, rectangular floor plan geometries, but can give free rein to their design ideas. In 3D concrete printing, free floor plan shapes can be realised without affecting costs or construction time compared to stringent shapes. Thus it was possible to design the building in Beckum completely freely in terms of floor plan, in order to demonstrate the potential of the printing technology.

However, in order to also serve practical purposes like e. g. the ability to mount cupboards or pictures on a wall and use standard furniture, a certain number of straight walls was included. With 3D printing, the design process takes place early on the digital building model, so that effects of planning changes become directly visible and provide planning security for all project participants.

4.3 Special features in the design of 3D-printed houses

The BIM-based building model is an essential part of the project management of concrete-printed buildings. On the one hand, planning with a 3D model means generating a great depth of planning at an early stage, but on the other hand it requires the project team of building planners, structural engineers and planners for technical building services to work together much earlier than it is the case with conventional construction projects. With additive manufacturing of buildings, wall recesses and slots for supply lines can already be planned in the 3D building model and precisely produced on site by the machine. In the Beckum project, for example, cut-outs for the electrical junction boxes and slots as well as risers for the sewage pipes could be integrated in the printed structure and then manually fitted with junction boxes or sewage pipes directly during printing, see Fig. 4.

This largely eliminated the need for subsequent rough installation by the building services trades. The functionality of a seamless digital process chain has proven to be an important element in the planning and local realisation of printed buildings.

4.4 Construction concept

The residential building in Beckum was designed as a solid construction with multi-layered wall structures. Through the interaction of the different wall shells with

Fig. 5 Construction process with suspended ceiling, source: MENSE-KORTE

individual widths of 60 mm, it was possible to generate cavities which, on the one hand, could accommodate the thermal insulation as fill-in insulation and, on the other hand, were used as a lost formwork for locally casted unreinforced concrete for statically highly loaded parts of the building. All vertical wall components were constructed without reinforcement. The horizontal components such as ceilings and the floor slab were conventionally reinforced, as partially prefabricated concrete elements laid on site on the printed wall panels and subsequently concreted on with ready-mixed concrete, see Fig. 5. The façade consists of a 60 mm wide strand of printing mortar and was connected to the load-bearing printed exterior wall structure with wall anchors made of stainless steel.

5 Concept to achieve a building permission (approval process)

When creating a 3D-printed building, it must be taken into account that the design, the printing technology and the material influence each other. Thus, an individual manufacturing concept must be created for each building.

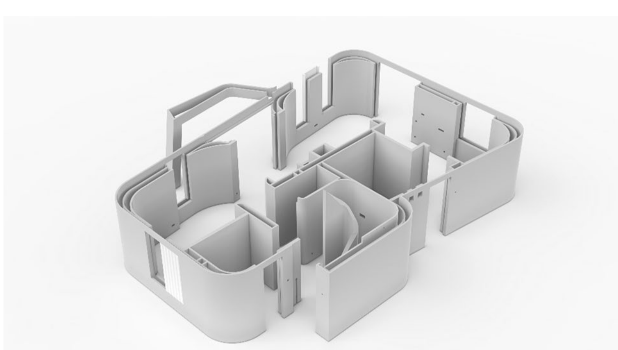

Fig. 4 BIM model of the printed house, source: MENSE-KORTE

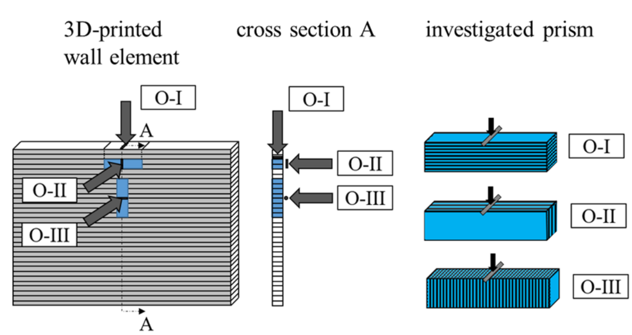

Fig. 6 Directional testing of component properties, based on (Weger et al. 2020), source: Engineering consultancy Schiessl Gehlen Sodeikat

This production concept includes, among other things, an architectural design adapted to the printing process, process-technical details such as the nozzle geometry and layer time (time until the nozzle has returned to its starting point), or the environmental conditions (temperature, wind, direct sprinkling etc.), which can affect the material composition or the on-site equipment (Bos et al. 2016; Buswell et al. 2018b; Mechtcherine et al. 2021; Putten et al. 2021).

Especially when assessing the material properties, it must be kept in mind that it is a layered construction, which can show a more or less pronounced anisotropic and heterogeneous behaviour (Bos et al. 2016; Le et al. 2012). This requires the determination of the material properties (strength and durability) in all three dimensions (O-I to O-III), see Fig. 6.

It should also be noted that there may be a scale effect, which was found, for example, in Weger et al. (2020) during a comparison of the bending tensile strength of small-format prisms sawn out and the testing of whole wall elements.

So far, there are no uniform testing principles or standards for 3D-printed components. However, once the manufacturing concept is known, analogies to existing, technically related regulations can be used or adapted to develop a (verification) concept for a project approval.

The building permission (approval) for this project was granted for the 3D printed mortar in combination with the 3D printed wall types and the 3D printer used. The approval was based on existing standards (DIN EC2 and EC6) for concrete and masonry construction and the static calculation was mainly based on masonry standards.

Therefore, on the one hand, the behaviour of the material was tested in the fresh (spread, initial and final setting) and in the hardened state (compressive and flexural strength, modulus of elasticity, adhesion between layers after various environmental influences, freeze–thaw resistance, pull-out as well as push-out resistance of wall anchors). All properties were determined on casted reference specimens, as well as on 3D-printed specimens in two or three spatial directions. On the other hand, large-format wall elements were examined. Both impact tests and a determination of the bending tensile strength were carried out on load-bearing and non-load-bearing wall elements. Furthermore, the resistance of the 3D-printed lost formwork to the fresh concrete pressure occurring during concreting was investigated.

Based on the results of the material tests and the large-scale investigations, characteristic and design values for the structural analysis as well as the durability could be determined.

Due to the not yet regulated production process, it was furthermore necessary to carry out a monitoring of the delivered material, the execution of the construction details

Fig. 8 Assembly of the COBOD BOD2 3D concrete printer

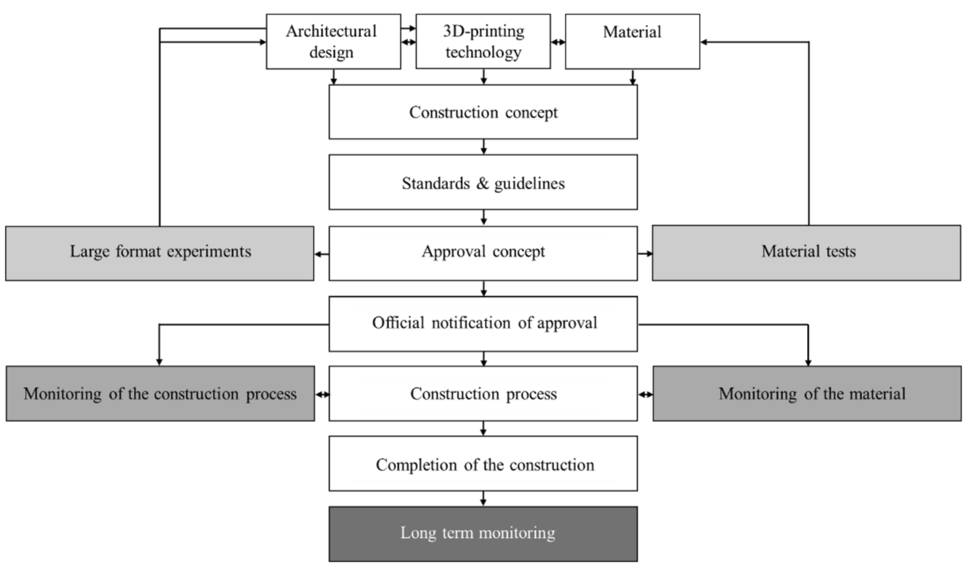

Fig. 7 Approval concept for the first 3D-printed residential building in Germany, based on (Weger et al. 2020), source: Engineering consultancy Schiessl Gehlen Sodeikat

during the printing process as well as a long-term monitoring, see Fig. 7.

Based on the concept and the results of the tests, a ZiE/vBG (ZiE: approval in individual cases, vBG: project-related design approval) was granted for the project.

6 Execution of the 3D printing on-site

After successfully obtaining the building permission, the concrete printer was transported from PERI to the construction site in Beckum. The gantry system was assembled in approx. 1.5 days on concrete foundations using a mobile site crane, see Fig. 8.

The premixed dry mortar was pneumatically conveyed from BigBags into a silo. Starting from the silo, the 3D printing mortar was mixed with water using the downstream mixing technology and conveyed via a hose to the printing nozzle. In the first step, the edge formwork of the floor slab was produced using the 3D printer.

In order to comply with the maximum layer times, the building was printed in individual sections. Here, the printing process can be adapted to different weather and temperature conditions by slightly varying the water content, the printing speed and the amount of material extruded.

This made it possible to achieve a uniformly shaped façade surface that remains non plastered. The articulated and visible layer structure emphasises the 3D-printed character of the building. However, the layers can also be smoothed by machine to achieve a different surface appearance.

The wall structures as well as the integration of openings and electrical installations could be realised as planned. These details and the printed fireplace are illustrated in Fig. 9.

Only very short print paths could not be created with the expected accuracy, so print paths of at least 30 cm in length will be planned in the future.

Since adjustments to the 3D model are easily possible and can be directly implemented to the printer, the experience gained from the printing process of the ground floor could be directly incorporated into the upper floor of the building. The upper floor was completed in only about eight printing days.

In this first 3D-printed building in Germany, the combination of 3D-printed prefabricated parts and in-situ printing could also be successfully implemented. In order to avoid longer downtimes of the 3D printer during the work of other trades, the parapet elements were printed with a BOD2 in the precast plant of the company Röser, a customer of PERI and HeidelbergCement, and transported to the construction site. There, the elements were placed and connected. Visually, the transition between in-site and prefabricated printing is not visible, as shown in Fig. 10.

Fig. 10 Germany's first 3D-printed building, source: HeidelbergCement Group

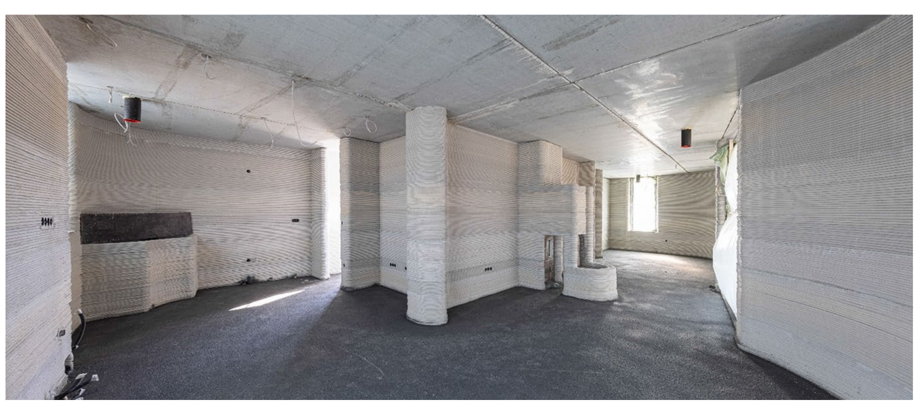

Fig. 9 Ground floor 3D-printed building Beckum, source: PERI

7 Conclusion and lessons learned

The construction of the first 3D-printed residential building in Germany in Beckum shows that additive manufacturing processes are a real alternative to conventional construction methods. In addition to the ecological and manufacturing advantages, a new design language can be applied to the architectural drafts and multifunctional components can be realised.

Lessons learned during the project majorly revolve around the overall construction process. While once the printer was running the actual print process was very smooth, however the preparations for the print were time consuming. Due to some slight deformations in the 3D printed structures, the elevations of the printed object did in the reality not equate to the model. Hence, regular adjustments to the model were needed to achieve e. g. level window sills around the whole building. This can be avoided in the future with the help of laser scanning during the printing process. Another issue faced was that the needed formwork for lintels was placed with the usual construction site tolerances in mind. Since the printed layers allow very little tolerance to be visually pleasing, the formwork had to be reset several times in order to achieve the needed tolerances. Last, material was delivered in so called BigBags in the size of 1t and pneumatically moved into a silo on site. This could only be done during dry weather and led to some down time of the printer. In the future, the common process of using a silo-truck will alleviate this issue completely. The integration of other trades like electrical and windows was as simple as envisioned in the planning process. Also the printed material is still mouldable after 1 to 2 h, which enabled easy manual rework where needed.

However, there are still no uniform testing principles or standards for 3D-printed components. This is currently the subject of activity of some national and international committees (see, among others, RILEM TC 267-DFC, RILEM TC ADC, ISO/TC 261/JG 80, ACI Committee 564, fib Task Group 2.11, DAfStb AG Digitaler Betonbau). Currently, test methods from concrete and masonry construction (e.g. EC2, EC6, ASTM, UL3041, ICC-AC509) are adapted, modified and partly newly developed.

In the field of research, additive manufacturing in civil engineering is also constantly being further developed in order to be able to implement new processes, but also issues such as the automated integration of reinforcement (see, among others, DFG TRR 277).

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