WCTE 2016
World Conference on Timber Engineering
August 22-25, 2016 | Vienna, Austria

ADDITIVE MANUFACTURING OF BUILDING ELEMENTS BY EXTRUSION OF WOOD CONCRETE

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ABSTRACT:

An additive manufacturing process is presented in which large scale building elements are shaped by depositing fresh wood chip concrete with the aid of a numerically controlled extrusion system. In comparison to similar solutions based on mere mineral materials, the characteristic properties of the wood cement composite (e.g. low weight, low thermal conductivity, better workability) proved to be advantageous for the manufacturing process as well as for the final product.

KEYWORDS: additive manufacturing, 3D printing, construction, wood chip concrete, robot

1 INTRODUCTION

1.1 ADDITIVE MANUFACTURING

Computerised additive manufacturing, often also simply referred to as “3D printing”, was first introduced to the market in 1987 with stereolithography by 3D Systems [1]. Since then, numerous other market-ready technologies have been developed. Originally intended as a means to rapidly create models and prototypes, advances in material properties, scale and manufacturing speed have enabled these technologies to compete with traditional forms of production. Examples for this can be found in the fields of medical and dental technology, aerospace engineering or foundry moulding.

The underlying principle that all methods have in common is that solids are generated automatically on the basis of a digital 3D model by adding numerous small (compared to the size of the solid) units of material. Therefore, there are no specialised tools necessary to fabricate differently shaped objects, which makes additive manufacturing particularly economical where single parts and small batches are to be produced. In addition, additive manufacturing allows a high degree of geometric freedom and offers the opportunity to form parts, that otherwise cannot be produced, or only with great effort.

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1.2 ADDITIVE MANUFACTURING IN CONSTRUCTION

Because of its specifications (automation, small batches, geometric freedom), additive manufacturing also shows great potential for applications in the field of construction. Instead of following the restraints of the production method, the form of a building element can be optimised in regard to its intended use, building physics or structural requirements. Also, tailor-made components for existing buildings can be named as a promising application.

Figure 1: *Behrokh Khoshnevis, Contour Crafting [3]*

A first proposal for an additive construction process was made in 1995 by Joseph Pegna [2]. The process is based on selective binding of sand with cement. This is realised by applying dry cement locally to a fine layer of sand and activating the hardening of the mixture by applying water onto the layer. Additional layers are added until the desired concrete geometry is completed. Alternatively, multiple layers of dry sand and cement are hardened by exposing them to steam. However, the method was proven in small scale models only.

‘Contour crafting’, developed by Behrokh Khoshnevis, utilizes an extrusion process where a strand of concrete is dispensed through a nozzle. Layer by layer, the strand forms the outer shell of a wall structure which acts as a permanent formwork. The interior of the wall is also constructed by extrusion or is filled with concrete in a second step. Alternatively, the walls can be formed in their entirety by the extrusion of strands which are as wide as the wall is thick. Figure 1 shows a possible application in building construction where the extruder is mounted on a large gantry system with the aim of constructing entire buildings on site. Instead of concrete clay can also be used. [4]
Civil engineer Enrico Dini constructed ‘D-Shape‘, a 3D printer with a build platform of 4 x 4 m. The implemented method of selective binding is comprised of two repeating steps. First a thin horizontal layer of a mixture of mineral aggregate and a metal oxide is spread out. In a second step a large print head with 300 nozzles is moved over the dry layer and a saline solution is locally applied to the surface, where it reacts with the metal oxide forming a binder. Once the last layer is completed the surrounding unbound material can be removed revealing the solid object. [5], [6]
‘3D Concrete Printing‘, developed at the Department of Civil and Building Engineering at Loughborough University, is an extrusion process for concrete. In comparison to Contour Crafting it aims at higher geometric freedom and resolution. Figure 2 shows a 3D printed curved concrete element with integrated bench. [7], [8]

Figure 2: *Loughborough University, 3D Concrete Printing [7]*

Yingchuang Building Technique Co Ltd. WinSun, a company from Shanghai, China, produces building elements through extrusion of a concrete mix containing construction and demolition waste. Several buildings have already been constructed using this technique, among them a 5-storey residential building. [9], [10]
Today there exist numerous projects concerning additive manufacturing in construction comprising both selective binding and extrusion. The majority of those projects use concrete as building material. The motivation of the research presented in this paper was to investigate the question, how additive manufacturing for applications in construction can be realised by the use of wood.

1.3 ADDITIVE MANUFACTURING BY THE USE OF WOOD

Additive manufacturing by the use of wood can be realised in different ways. In multiple projects Gramazio & Kohler [11] have already demonstrated how this can be done by robotically joining discrete wooden elements, like battens or beams.
On the other hand the solid wood can be separated into its basic components, such as lignin, cellulose, or hemicellulose. These components then can be used to produce a material which can be processed in common 3D printing machines. ‘Extrudr Green-TEC’, for example, is a filament which is claimed by its producers to be comprised of 100 % renewable materials on the basis of lignin compounds [12]. It is intended for use in Fused Filament Fabrication (FFF) 3D printers.

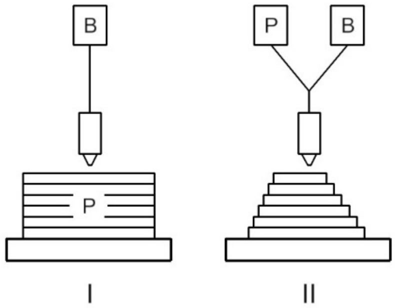

Figure 3: *Alternative methods of additive manufacturing by binding wooden particles (P) with a binder (B);*
I: selective binding, II: extrusion

Instead of joining discrete wooden elements or deconstructing the material into its base components an alternative way of realising additive manufacturing by the use of wood consists in binding wooden bulk material with some kind of binder. How this can be done by processes of selective binding has already been discussed in previous work [13]. Alternatively, the wooden particles can be mixed with the binder in advance, forming a paste-like material, which is extruded in strands to build up the object. The two alternative methods of additive manufacturing with bonded wooden particles, selective binding (I) and extrusion (II), are shown in figure 3. The range of binders which can be put to use for binding the particles is large. However, in the case of applications in construction aspects like strength, durability and fire protection have to be considered. The choice of cement as binder for the wooden particles, resulting in wood chip concrete, makes sure, that these requirements are met.

1.4 OBJECTIVES

In this paper, research work is described that aims at the development of a method for the additive manufacturing of large scale building elements via extrusion of a wood chip concrete. An extruder is moved by an industrial-sized robot in a way that by depositing strands of fresh concrete the object is constructed layer by layer without the use of formwork.
Instead of the usual sand and stone aggregates of concrete the use of the renewable resource wood results in a light and easily workable material. This offers advantages for the process as well as the final product. The low thermal conductivity of wood chip concrete and

the geometric freedom of the implemented manufacturing method enables the production of building elements optimised in regard to structure and building-physics. One promising area of application of this material-method-combination lies in the construction of optimised self-supporting façade elements for a simple, monolithic building.
The research work included the development of a recipe for an extrudable yet fast setting wood chip concrete, the design, construction and testing of a specialised extruder as well as gathering and adapting of digital tools for modelling and machine control. Tests on selected topics concerning the process and material were carried out and large scale test objects were built.

2 SYSTEM FOR THE EXTRUSION OF WOOD CHIP CONCRETE

2.1 OUTLINE OF THE SYSTEM

In general, a system for the additive manufacturing by numerically controlled extrusion of concrete is comprised of multiple components as seen in figure 4 on the left. The individual ingredients (A, B, C) for the fresh concrete are combined in a mixer (M). Within the extruder the concrete is transported by a conveyor, either a progressive cavity pump or a conveyor screw (F), to a nozzle (D) where it is dispensed in a continuous strand onto a building platform or on top of previously dispensed strands. The necessary movement for the extruder to form the strand is provided by an electronically controlled manipulator. If necessary, a reservoir (R) can be added to hold the fresh concrete. (a, b1, b2, c) indicate the transport paths of the material. Solid lines represent a continuous transport, e.g. through hoses or conveyor screws. Alternatively, dashed lines represent moving the materials discontinuously e.g. manually by shovel or bucket.

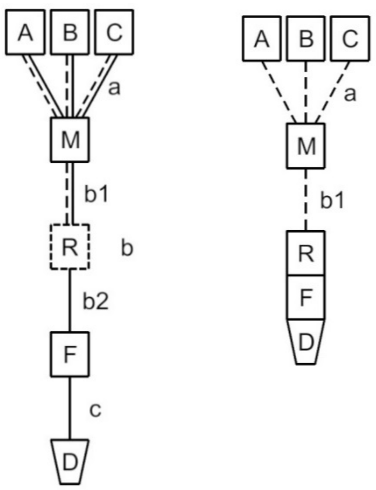

Figure 4: *general outline of systems for the extrusion of concrete (left) and chosen configuration (right)*

The different phases of the mixing and extrusion process each demand varying and even conflicting material properties. During transportation, the freshly mixed concrete must be pumpable, yet after being dispensed through the nozzle, the concrete must stiffen and harden rapidly. Short transportation lines within the system help in dealing with this dilemma. The mixing and extrusion system variant chosen for the project presented here follows the design seen in figure 4 on the right. The reservoir (R), conveyor (F) and nozzle (D) are combined into a single unit. The concrete is mixed by hand or with simple machines and fed into the reservoir in small batches (b1). This approach helps minimise the time between mixing and dispensing.

2.2 EXTRUDERS

The extruder developed during this project is based on the experiences gathered during a master's thesis with an extruder built from a household meat grinder [14]. The new extruder was constructed as a modular system from acrylic glass pipe which enables a better view of the material flow. Multiple conveyor screws were manufactured, each with a different pitch and progression (see figure 5). The screws are welded onto a ½" steel pipe and have an outer diameter of 54 mm.

Figure 5: *Conveyor screw with attached motor (left) and replacement screws with varying pitch and progression*

A custom shaped hopper was manufactured from polylactic acid (PLA) with the use of a RepRap fused filament 3D printer. This hopper is connected to the main extruder body through a second acrylic glass pipe attached to the first one at an angle of 45°. Multiple nozzles with varying convergence and different size openings (17.5, 20, 22.5 and 25 mm) were constructed from polyoxymethylene (POM). Additionally, acrylic glass spacers can be used to change the shape of the extruder and influence the material flow. A bipolar stepper motor with a holding torque of 3 Nm is used to power the extruder. The main body as well as the motor assembly with the connected conveyor screw are mounted on an aluminium modular profile system (see figure 6). This allows a precise positioning of the different screws inside the acrylic glass pipe. Extrusion tests with the different conveyor screws and nozzles were conducted. In these tests, screws with little to no progression in combination with a 20 mm nozzle achieved the best extrusion results. Based on this, the large scale demonstrators described in chapter 3.2 were printed using a conveyor screw with a constant pitch of 38 mm and a nozzle with a 20 mm opening and a 20° convergence.

Figure 6: *Modular extruder assembly*

2.3 MANIPULATORS

The manipulator controls the motion of the extruder relative to the building platform. Small scale testing can be carried out on a three axis CNC portal from BZT Maschinenbau GmbH. The portal has a processing way of approximately 670 mm x 890 mm x 110 mm (X, Y, Z) and is controlled by three bipolar stepper motors. For the experiments the extruders can be mounted directly onto the tool holder of the CNC portal. In figure 7 the original meat grinder extruder can be seen mounted on to the CNC portal.

Figure 7: *3-axis gantry with mounted extruder*

Alternatively, the extruder can also be suspended in a stationary position above the portal. In this case, a small platform (400 mm x 400 mm) is fixed to the tool holder of the CNC portal which then can be moved beneath the pump. The CNC portal as well as the extruder is controlled by hardware and software commonly found in the field of consumer fused filament 3D printing. The open-source 3D printer firmware Repetier and the accompanying freeware Repetier Host [15] were used to create movement instructions and send them to the 3D printer system.

For the manufacturing of large scale test objects an industrial KUKA KR 150 L110 6-axis robot was provided by the Chair of Building Realisation and Robotics (Prof. Thomas Bock) at the Technical University of Munich. The robot can reach a distance of 3500 mm and has a rated payload of 110 kg. In addition, the robot is mounted on a 7 m long rail which is implemented as a linear 7^{th} axis. The extruder with its aluminium profile system can be connected to the mounting flange of the robot with a steel adapter plate. Figure 8 shows the assembled extruder with an additional setup to help the flow of material mounted on the Kuka Robot.

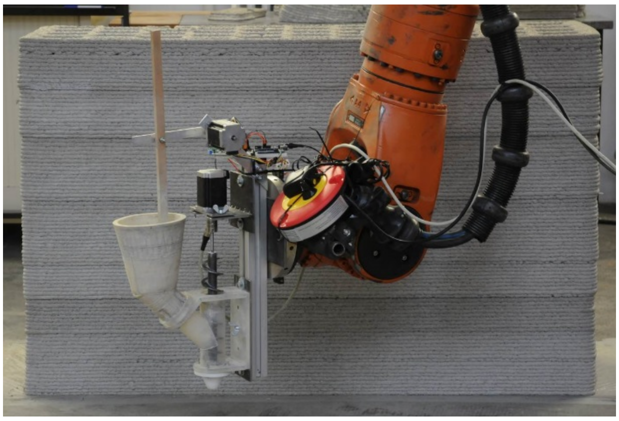

Figure 8: *Conveyor screw extruder with additional flow aid mounted on a 6-axis Kuka robot*

The robot is controlled by a Kuka KR C 2 controller and its own proprietary software. Because the extruder could not be integrated into the Kuka control, a separate controller unit was built in order to operate the extruder. With this setup, the extrusion speed can easily be changed during the printing process. However, this also means that the extruder must be manually started and stopped where necessary. To circumvent this problem, the movements of the robot in each layer are programmed in closed loops with identical start and end positions (see figure 12). This way, the extruder only has to be started once and can run continuously until the 3D printing process is finished.

3 EXPERIMENTS

3.1 MATERIAL DEVELOPMENT

Composite materials constituted by cement as binder and mechanically shredded wood as aggregate have been established in construction for many decades. Wood-wool slabs and cement-bound particle boards can be named as examples. Here the high strength and incombustibility of the mineral material cement is combined with the low weight and low thermal conductivity of the renewable material wood.

Wood chip concrete is generated by the same ingredients as the before mentioned examples but, contrary to them, building elements from wood chip concrete are formed without applying pressure. Merely mixed with regular cement the resulting concrete hardens very slowly due to soluble substances of the wood, such as fats, sap and especially sugars, which inhibit and slow down the hydration process [16], [17]. One possibility to avoid this is by washing out the soluble substances. Another one is the use of mineralised chips [18]. Alternatively, good results may also be achieved by selecting suitable concrete-wood-combinations [17].

Figure 9: *Test prints with WUTZ Spezialzement and beech wood chips [19]*

Initial tests were carried out with WUTZ Spezialzement [20], which is a white cement binder that has been modified specifically for the use with wood chips. Tests with beech wood chips were promising, as seen in the test prints shown in figure 9. However, this type of cement starts to set within minutes of mixing which makes it unsuited for the extrusion of large scale objects.

Figure 10: *Object created through extrusion of a light weight concrete using CEMWOOD CW 1000 mineralised wood chips (sample fabricated in [21])*

Instead of modifying the cement, the woodchips themselves can be processed in order to reduce the inhibitory effects and even increase the strength of the hardened concrete [18]. During the course of this project extrusion tests were conducted using CEMWOOD CW 1000 wood chips [22]. The chips have an elongated form with a length of 1 - 5 mm and are originally intended for the use in landscaping or as levelling or filler material. By using regular Portland limestone cement (CEM II A-LL 32.5 R) a chip-cement weight ratio of 0.29 could be achieved with a water-cement ratio of 0.45 using a 25 mm extruder nozzle (see figure 10).
Because the chips already include mineral and organic material, the wood chip-cement ratio does not provide an accurate number for the amount of wood within the concrete. Also, due to their geometry, the mineralised chips tend to create a blockage between the conveyor screw and the nozzle inhibiting the extrusion process. It is conceivable, that mineralised chips with a geometry better suited for the extrusion process could be manufactured, however, due to the constraints within the project this otherwise promising approach was not pursued further.
The final wood chip concrete mixture using Portland limestone cement and plain Pine wood chips was developed based on experiences gathered with purely mineral based light weight concrete. Previously conducted orientating experiments with the use of Portland limestone cement and granulated glass beads as an aggregate proved to be much simpler compared to recipes involving organic compounds. Even without the use of admixtures, multiple layer objects could be 3D printed as seen in figure 11.

Figure 11: *Extruded test object made with light weight concrete using granulated glass beads as aggregate*

In order to better understand the material requirements for a successful extrusion, the consistency of the glass granulate cement mixture was examined with a flow table test for mortars according to DIN EN 1015-3:2007-05 [23]. The findings showed that light weight concrete mixtures with a fresh density around 1,000 kg/m³ and a flow diameter of 160 - 170 mm were suitable for extrusion. Based on these findings, a wood chip concrete recipe could be created using admixtures in order to regulate the consistency and flow properties. Table 1 shows the wood concrete recipe used for all further tests and experiments.

Table 1: Developed wood concrete recipe

Component	Mass [g]
CEM II A-ll 32.5 R	1000
Lignocel 9 wood chips	160
Water	610
MasterAir 77 (air-entraining admixture)	22
Stabi M15 (stabiliser)	2
SikaRapid C-100 (accelerator)	16

The average flow diameter of the material is 160 mm with a density of around 1,000 kg/m³. The freshly mixed concrete can be transported smoothly through the conveyor screw extruder without blockage. The width and height of the extruded strands stays uniform during the printing process and multiple strands can be deposited on top of each other with little to no deformation. The resulting wood chip concrete has a density of 995 kg/m³ and a thermal conductivity of 0.25 W/(m*K).

Material strength tests of the hardened concrete were carried out on test objects created with the use of formwork as well as on 3D printed test objects which were later cut to size. All test specimens were stored at 20° C and 65 % relative humidity for 24 hours and then subjected to a water bath for either 7 or 28 days.

Compressive strength tests were conducted on 100 mm x 100 mm x 100 mm cubes according to DIN EN 12390-3:2009-07 [24] (see table 2).

Table 2: *Compressive strength in N/mm² after 7 and 28 days*

Specimen	7d	28d
Poured cubes	10.04	12.12
3D printed cubes	8.87	10.30

As with the compressive strength, bending strength was measured on poured as well as 3D printed specimens. The tests were carried out on 40 mm x 40 mm x 160 mm prisms according to DIN EN 196-1:2005-05 [25]. The 3D printed specimens were cut in two sets from a single 3D printed slab. In order to test for a direction dependent bending strength one set was cut parallel and the other perpendicular to the printed strands. Again, the specimens were initially left to harden for 24 hours at 20° C and 65 % relative humidity and then stored in a water bath for 7 and 28 days. The results of the bending strength tests are depicted in table 3.

Table 3: *Bending strength in N/mm² after 7 and 28 days*

Specimen	7d	28d
Poured prisms	3.35	3.87
3D printed prism (parallel)	3.57	4.08
3D printed prisms perpendicular	2.55	3.05

3.2 LARGE SCALE TEST OBJECT

Following the small scale tests on the CNC portal, larger objects were designed in order to test the material-method combination on a scale suitable for construction. The geometry of a lightweight, insulating external wall segment (Figure 12) was chosen to highlight the potential of the manufacturing method regarding applications as well as technical possibilities. Overly complex and irregular geometries, as are commonly used to demonstrate the capabilities of 3D printing, were explicitly not chosen to better determine the remaining deficiencies and imprecision in the production process.

The design of the wall segment takes manufacturing boundary conditions into account. Based on the 20 mm nozzle diameter, the individual printed strands have an oval shape with a 25 mm width and a height of 10 mm.

Due to the separation of the robot and extrusion control each layer must be printed as a complete loop. Furthermore, beginning and end point of the loop must match in order to permit continuous printing across multiple layers.

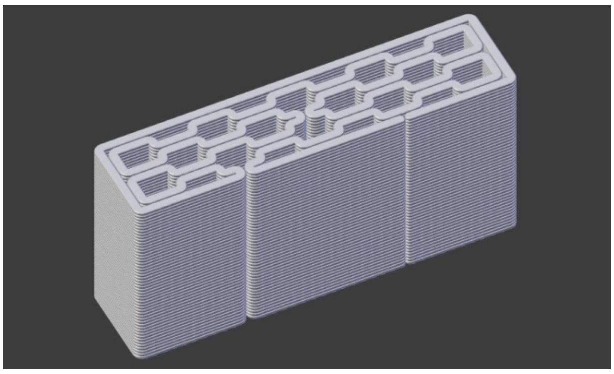

Figure 12: *Digital model of lightweight, insulating external wall segment to be fabricated by extrusion of wood concrete*

Following multiple preliminary tests with different layer designs a wall structure measuring 500 mm x 1500 mm x 930 mm was 3D printed as seen in figure 13. Each layer was printed at a constant robot velocity of 75 mm/s. The extruder speed was held at around 37 rpm although adjustments were made to account for changes in the concrete consistency. The wall was printed with up to 17 layers at a time and 42 layers per day with each layer taking approximately 4 and a half minutes to complete. The final printing time without breaks was 7 hours. In general, the strands of concrete could be extruded with precision and consistent geometry. Small defects or breaks in the strand were bridged and corrected by the following layer.

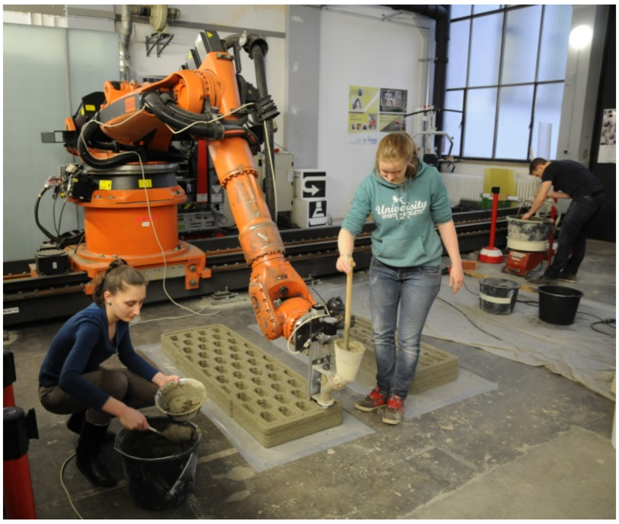

Figure 13: *wall segment built up by horizontal layers each measuring 500 mm x 1500 mm x 10 mm during printing process*

When not properly compensated, the slight changes in concrete consistency can cause discrepancies in the width of the individual strands. The first layer of each continuously printed segment shows a slight increase in width compared to the others. Even though this helps the bonding of parallel strands within the layer, the outermost strand is pushed outward by the adjacent inner strand resulting in visible discrepancies in the layer width at the beginning of each continuously printed segment. Furthermore, nearing the end of each prepared concrete batch, initial stiffening can cause the strands to thin, which in turn can lead to insufficient bonding of parallel strands within the individual layers. The gaps between individual strands are further widened over time due to concrete shrinkage.

Figure 14: *Completed large scale test objects*

In order to combat these phenomena the last 13 layers of the wall segment were printed with a slightly changed layer geometry. By mirroring every second layer, previously parallel running strands are bridged which helps to increase the layer stability. Additionally, by positioning the beginning and end point within the wall structure, adjustments to the extrusion speed can be carried out before the outer strand is printed. The completed wall segment together with two smaller specimens can be seen in figure 14.

3.3 OVERHANGS

The ability to print overhanging or bridging structures is crucial for the geometric freedom of an additive manufacturing process. Regarding this aspect, extrusion processes at first show disadvantages compared to other 3D printing processes using a particle bed which functions as support. Once overhangs can be built even only to a minor degree, the geometric freedom is increased significantly because this enables building special temporary support structures for cantilevering or bridging parts with a minimum of material consumption. Figure 15 shows an example of such a support structure suited for extrusion and built only with a slight inclination.

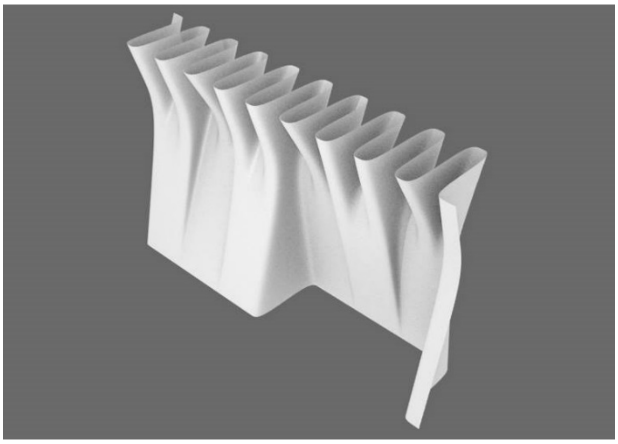

Figure 15: *Digital model of a support structure suited for the extrusion of wood concrete*

It was expected, that the low weight and good inner strength of the wood concrete would allow realising overhangs to a much higher degree than with standard concrete. To prove this a small series of tests was carried out. Figure 16 shows an overhang test performed on an object with a honeycomb structure. The object consists of ten layers, each layer measuring 230 x 400 x 10 mm and having a 3 mm horizontal offset compared to the previous one.

Figure 16*: Overhang test showing an overhang of 26 %*

An overhang of 26 mm could be measured. Considering the height of the object which measured 100 mm the overhang amounts to 26 %. This shows that with wood concrete overhangs can be built to a considerable degree. Further material development will allow to increase this amount even more.

3.4 SUBTRACTIVE POST PROCESSING

Compared to processes of selective binding, additive manufacturing by extrusion has advantages concerning building speed and material properties. However, in respect to geometric accuracy and resolution it initially shows disadvantages. This can be overcome by additional steps of additive or subtractive post processing on the near net shape printed part. The finishing can be limited to those areas, were a high degree of precision is required (e.g. for the joining of parts) or increased surface quality is demanded. This way high resolution and geometric accuracy become compatible with building speed.

Figure 17: *Subtractive finishing of additive manufactured parts from wood concrete (sample fabricated in [26])*

To verify the workability of the wood concretes used in the project, different subtractive treatments (sawing, milling, drilling, sanding) were experimentally investigated [26]. It appeared that all wood concrete materials could be easily treated with conventional tools for metal working. This fact represents a significant advantage of wood concrete compared to standard concretes. Figure 17 shows additively manufactured parts which have been milled locally to form two close fitting halves of a joint.

4 CONCLUSIONS

Additive manufacturing in construction promises the possibility to automatically fabricate free formed elements in small batches. In this paper an additive manufacturing process was presented, in which building elements are shaped by depositing fresh wood concrete with the aid of a numerically controlled system consisting of an extruder that is guided by an industrial robot. By building large scale test objects, the feasibility of the process was proved.

The extrudable wood concrete developed in the project consists of Portland-limestone cement and untreated softwood chips in a ratio by volume of 1:1 and different admixtures. The concrete was tested to have a compressive strength of about 10 N/mm² and a bending tensile strength of about 4 N/mm² and thus lies in the area of lightweight concretes with mineral aggregates. The density amounts to 995 kg/m³ and the thermal conductivity to 0.25 W/(m*K).

In addition to the fact that in wood concrete the mineral aggregate is replaced by a renewable material, the composite proved to have further advantages over mere mineral solutions.

Its low weight and good inner strength help to realise overhangs to a greater extent. This also allows the build-up of special temporary support structures for cantilevering or bridging parts with a minimum of material that will be removed after curing of the element. Together, this means a significant improvement of geometric freedom for processes of concrete extrusion.

Its good workability enables subtractive finishing in areas, were a high degree of precision is required or increased surface quality is demanded. The combination of additive and subtractive manufacturing steps represents a promising approach to make high resolution compatible with building speed.

For this special material-process-combination applications can be depicted in new buildings as well as in the existing building stock. By the possibility of fabricating tailor made elements this technology, especially in combination with digital building surveying, opens up new ways of retrofitting. The low thermal conductivity of the material combined with the optimization-possibilities of the additive manufacturing process will enable simple, robust and easy to recycle, monolithic buildings or building parts without the necessity of further insulation.

For an industrial application of the process further material development must be undertake to identify formulations which combine extrudability and rapid curing of the fresh concrete while retaining good hardened concrete strength properties. Furthermore, the extruder has to be perfected to a continuously working, combined mixer-extruder-unit. Finally, it seems worth investigating how by deliberately orienting the chips, material strength can be enhanced and how by varying the wood-concrete ratio during the printing process a grading inside the workpiece can be realised.

ACKNOWLEDGEMENTS

The project was funded by Zukunft Bau research initiative, Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety, Federal Republic of Germany. It was supported by RoboDK offline programming and simulation, www.robodk.com and ViscoTec Pumpen- u. Dosiertechnik GmbH, www.viscotec.de.

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