Anisotropic properties of additively manufactured lightweight concrete elements

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Abstract

Robotic concrete extrusion is a novel additive manufacturing process (3D concrete printing) and is part of a continuously digitally controlled value chain. According to the state of the art, concrete is considered to be an isotropic material due to the manufacturing process. However, for the additive manufacturing process, the isotropic approach hast to be reconsidered due to the layered structure. It can be assumed that due to the layered structure, the material properties vary depending on the deposition direction and the geometry of the layers. The aim of the work was to record the material-technical characteristics of extruded elements manufactured according to standards in comparison with concrete recipes. Process-related influences on the mechanical parameters of additively manufactured concrete elements were examined and evaluated in more detail. Based on the findings obtained, the dimensioning, design and measurement of components can be carried out and thus guidelines for components can be derived. With these derived guidelines, the material utilization and economic efficiency can be improved.

Anisotropic properties of additively manufactured lightweight concrete elements

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Robotic concrete extrusion is a novel additive manufacturing process (3D concrete printing) and is part of a continuously digitally controlled value chain. According to the state of the art, concrete is considered to be an isotropic material due to the manufacturing process. However, for the additive manufacturing process, the isotropic approach hast to be reconsidered due to the layered structure. It can be assumed that due to the layered structure, the material properties vary depending on the deposition direction and the geometry of the layers. The aim of the work was to record the material-technical characteristics of extruded elements manufactured according to standards in comparison with concrete recipes. Process-related influences on the mechanical parameters of additively manufactured concrete elements were examined and evaluated in more detail. Based on the findings obtained, the dimensioning, design and measurement of components can be carried out and thus guidelines for components can be derived. With these derived guidelines, the material utilization and economic efficiency can be improved.

1. Introduction

Rapidity, precision, economics and resource saving are the most important requirements of the construction industry of the future. Modern lightweight construction technologies can implement these requirements and add the aspects of design freedom, efficiency, and sustainability. Therefore, the development of new manufacturing technologies for highly stressable, durable and free-forming prefabricated concrete components with low material and energy input is the focus of the research group “Lightweight Constructions in Civil Engineering” (LBW) at the Chemnitz University of Technology. In general, the well-known building material concrete is considered isotropic due to the material properties and classical processing methods (casting, laminating e.g.). In contrast, the application of additive manufacturing processes result in anisotropic material properties because of the layered structure of the concrete elements by means of extrusion.

The aim of the work was to determine and compare the material properties of test specimens produced by casting (in accordance with standards DIN EN 12390) and by means of extrusion technology to be able to draw conclusions about anisotropic material behavior because of the extrusion process.

In addition, numerical investigations were conducted to reproduce the results of the mechanical tests. As a part of the investigation, process-related influences on the mechanical parameters of additively manufactured concrete elements were examined and evaluated in more detail. Based on the findings obtained, design and dimensioning of components can be conducted and thus guidelines for components can be achieved. With these derived guidelines, material utilization and economic efficiency can be improved and the lightweight construction principles can be implemented.

2. Material and methods

2.1. Experimental procedure

Additive manufacturing with mineral materials, in particular robot-assisted concrete extrusion, is a new manufacturing technology in construction and offers architects and civil engineers a variety of options for implementing lightweight construction concepts. At the same time, it requires great care in selecting the correct manufacturing parameters and material composition. The development was executed at the research facility "LBW RoboArena" (**Table 1** .) at Chemnitz University of Technology [1, 2, 3, 4, 5, and 6].

Table 1. Research facility "LBW RoboArena" at research group LBW

research facility	research facility
robot system	KUKA KR 90 R2700 pro
conveyor system	PFT BOLERO FC-230V
max. rate of delivery Q_{max}	2.5 l/min
control technology	KUKA KR C4
control technology	SPS Siemens S7
hose type	RSI 40 BD

The extrusion technology, consisting of a conveyor system (screw conveyor on the mixer) and a robot-guided tool head, generate the concrete layers. A spray-extrusion multi-tool nozzle (SEMT) was developed and implemented for the production of the concrete modules in the robot-supported flow production process in order to avoid a changing of tools in the production process while changing from the spray to the extrusion technology. This allows a thin additive application of material by spraying concrete and then the application of an adapted concrete extrudate. For example, facade modules consist of a fibre-reinforced shotcrete surface with a high surface quality and a support structure made of extruded thin concrete, which is applied directly to the shotcrete in the green state. On the one hand, the new type of nozzle allows the concentric, fibre-reinforced extrusion of a concrete layer and, on the other hand, the generation of a spray mist through the controlled activation of compressed air and thus the shaping by means of concrete spraying. The SEMT is attached to the robot arm, using a quick coupling. The following table 2 summarizes the tool parameters for testing.

Table 2. Tool parameters

technical parameters of the experiment	technical parameters of the experiment	technical parameters of the experimen
nozzle diameter spraying	[mm]	10
air pressure spraying	[bar]	5

technical parameters of the experiment	technical parameters of the experiment	technical parameters of the experimen
nozzle diameter extrusion	[mm]	20
rate of delivery	[l/min]	1.3
feed nozzle speed	[m/s]	0.06
endless fibre	[-]	non

As a result, several process steps (spraying, extrusion, endless fibre reinforcement) can be implemented in an automated process with the spray-extrusion multi-tool nozzle without changing the tool or position of the component. In this publication, reinforcement with endless fibres for better comparability was not used.

2.2. Materials

The material composition bases on a complex of technological restrictions and requirements of the precast concrete element. For example, a high-strength and durable fine-grained concrete with short-fibre reinforcement was developed, so these could be processed using spraying and extrusion. When characterizing the material, the green strength as well as the material and component-related strength and failure behaviour under compressive and flexural stress were of particular interest. In addition to high strength in the use state, the concrete for this process combination of spraying and extrusion also requires application-specific properties in the uncured state, such as high green strength, thixotropy, low shrinkage, adjusted processing time and good bonding behaviour of the individual layers as well as the contact zone between the sprayed and extruded layers.

To evaluate the durability, crack and failure behaviour of the reference components, climate change tests and angle-dependent insert pull-out tests were also carried out. Furthermore, the influence of the recipe and the process parameters on the material characteristics in the fresh and hardened state was examined and described.

Another focus was on the exposed concrete properties of the sprayed concrete shell for facade elements. For this purpose, the air void content in the fresh concrete, the exposed concrete surface according to the DBV/VDZ data sheet in porosity class and deviations from evenness and colour requirements according to DIN 18202 were determined and evaluated [7, 8].

The concrete recipe was determined empirically with constant testing of the consistency and is summarized in table 3. The mixing process was using an Eirich R05T.

Table 3. Concrete mixture

concrete mixture kg/m^3	concrete mixture kg/m^3
cement	620
silica fume	120
Dolomite filler	300
dispersible AR–glass fibre 12 mm	0.75
PCE superplasticizer	8.6
stabilizer	1.5
retarder	6,2
W/B	0.34

2.3. Proof of usability

Concrete is regarded as a homogeneous, joint-free material in the construction industry. However, this cannot be assumed for additive manufacturing, since several layers of concrete are build up. Due to the production-related anisotropy, the compressive strength was determined in three load directions. Figure 1 serves to clarify the load directions and the designation. Here, the placement direction is in the X-direction. The installation height in the Z-direction is based on the number and dimensions of the layers. The width of the component in the Y-direction is depending on the width and number of the extrudate. Furthermore, samples were produced in two ways: the concrete was injected directly and extruded into the moulds.

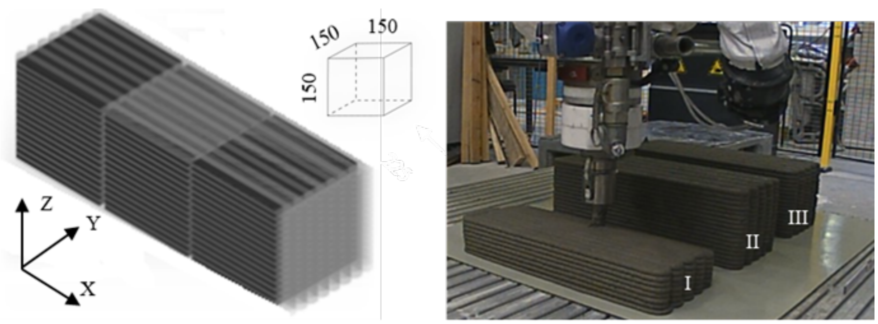

Figure 1. Extrusion test specimen: CAD (left) and physical while production (right)

To determine the compressive strength (f_{ck}, cube, 28 d), cube-shaped specimens with an edge length of 150 mm were produced and stored under water for 28 days (according to DIN EN 12390-2 [11]). The compressive strength was determined in accordance with DIN EN 12390-3 [12]. Table 4 summarizes the test parameters.

Table 4. Test parameters

test parameters on the basis DIN EN 12390-3 (n=3) [12]	test parameters on the basis DIN EN 12390-3 (n=3) [12]	tes
testing machine		To
sample dimension	[mm]	15
testing age	[d]	28
speed	[MPa]	0.5
test temperature	[°C]	20

Due to the spatial orientation of additively manufactured specimens, the flexural strength is also dependent on the direction of loading (Figure 2).

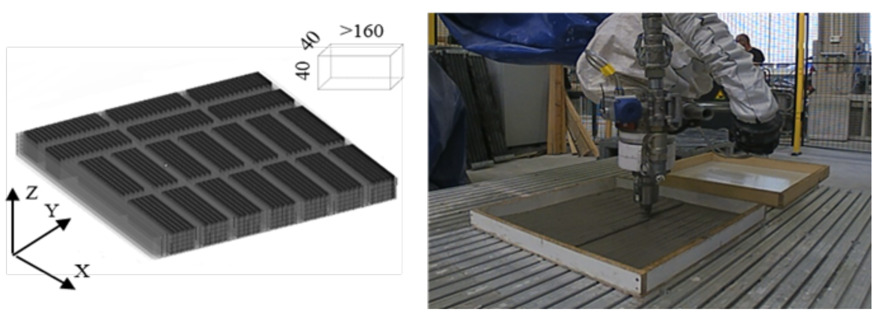

Figure 2. Extrusion

A four-point bending tensile test was chosen to determine the load properties, because in contrast to the three-point flexural test, there is a constant bending moment between the upper force application points. In this way, the material parameters are determined more realistically, especially in the case of plate-shaped samples, and these are less influenced by possible inhomogeneities in the sample. For the determination of the four-point bending tensile strength, based on DIN EN 12390-5 [13], were prismatic specimens (extrudate) manufactured and stored under water. The Test parameters are summarized in table 5.

Table 5. Test parameters 4-point bending tensile test

test parameters on the basis DIN EN 12390-5 (n=6) [13]	test parameters on the basis DIN EN 12390-5 (n=6) [13]	tes
testing machine		To
sample dimension	[mm]	40
testing age	[d]	28
speed	[N/mm²s]	0.0
test temperature	[°C]	20

In addition to the classic parameters, there is a focus on the bond between the sprayed and extruded layer (Figure 3). For assessment, a 15 mm thin layer was sprayed and a 40 mm thick layer of extrudate was built up on top of this.

Figure 3. Spraying (left) and extrusion (right)

After the 28 days of hardening, the samples were prepared in such a way that this contact zone could be subjected to tensile loads. Here drill cores were created with a depth of 5 mm protruding into the sprayed layer (Figure 4).

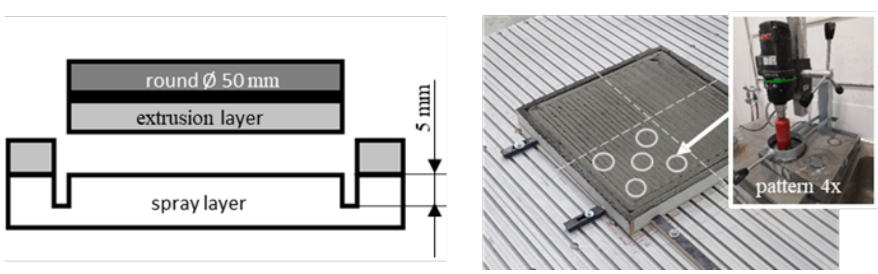

Figure 4. Set-up test specimen

A defined test specimen (round) is glued to the surface of the drill core with epoxy resin adhesive. The tensile force is now initiated into the construction via the test plate until a fracture occurs. The test parameters are summarized in table 6.

Table 6. Compilation of test parameters

test parameters on the basis DIN 18555-6 [14]	test parameters on the basis DIN 18555-6 [14]	test parameters on the b
testing machine		Form+Test ComTest
sample dimension	[mm]	Ø = 50
testing age	[d]	28
speed	[N/mm²s]	0.05
test temperature	[°C]	20
adhesive		Silikal RI/21

3. Results

The practical proof of the suitability of the newly developed nozzle tool for the production of reinforced and non-reinforced extrudates and sprayed layers is based on pressure, flexural and tensile adhesion tests. The samples with the designation "M" are characterized by the fact, that the concrete was taken directly from the concrete mixer. The samples with "S" and "E" were *s* prayed or *e* xtruded directly into the corresponding mould. The samples marked "X", "Y", "Z" depict the direction of loading in the coordinate space. The following figure 5 summarizes the compressive strength results.

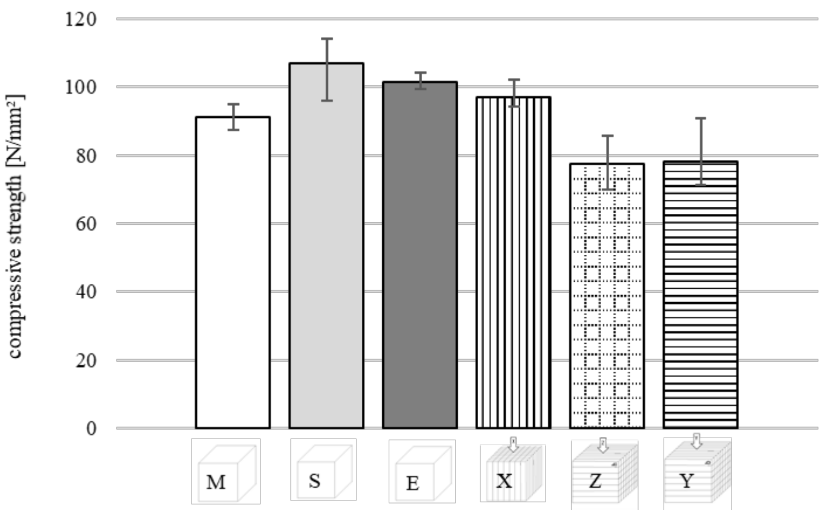

Figure 5. Summary of compressive strength results

In comparison to the compressive strengths, the sprayed "S" and the extruded "E" samples characterize significantly high values. It is assumed that the particle acceleration minimizes the defects. The samples with "X" are loaded in the direction of feed, which means that the front sides of the layers are subjected to pressure. It can be assumed that the layer geometry has less influence since the layers support each other against buckling. It is assumed that the layer geometry has an influence on the two sample batches "Z" and "Y". The cross-section of the extrudate is not rectangular with sharp edges, but rounded, so that defects accumulate.

A comparison of the bending tensile strengths of the individual batches shows figure 6.

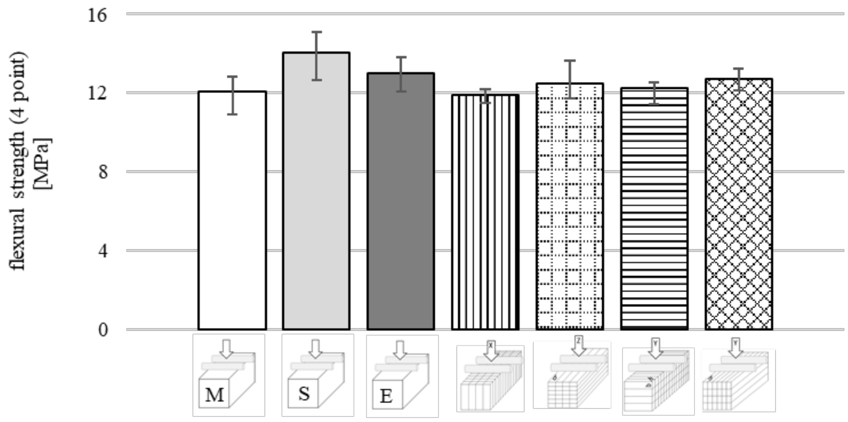

Figure 6. Summary of the flexural strength results

Because of the compilation, it can be stated that all sample batches produced with the new tool can generate high flexural strengths with little deviation. Similar to the pressure tests, the sprayed samples also showed the highest strength.

To assess the bond between the sprayed layer and the extruded layer, the area was subjected to a tensile test. The mean value is 2 MPa (Min. 1.9 MPa Max. 2.2 MPa). The fracture took place in the extrudate. According to DIN 18555-6 it is a cohesive fracture. This means that the contact zone is more resilient than the joining partners are.

Overall, it can be stated that the extrudates produced with the new tool achieve a very high level in terms of strength and deviations.

4. Conclusions

The aim of the work was to determine and compare the material properties of test specimens produced by casting (in accordance with standards) and by means of extrusion technology to be able to draw conclusions about anisotropic material behaviour caused by the extrusion process. As a part of the investigation, process-related influences on the mechanical parameters of additively manufactured concrete elements were examined and evaluated in more details. Based on the findings obtained, design and dimensioning of components can be conducted and thus guidelines for components can be achieved. With the guidelines derived from this, material utilization and economic efficiency can be improved and the principles of lightweight construction can be implemented.

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