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Selective Cement Activation (SCA) – new possibilities for additive manufacturing in construction

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Abstract

This article presents research on the additive manufacturing of concrete elements using selective binding of cement. In the process referred to as selective cement activation, fine layers of a dry cement-sand mixture are solidified locally by applying water. This way, layer by layer, complex 3D objects can be created with a high degree of geometric freedom. Initial tests with a prototype 3D printer have demonstrated the potential of the manufacturing method for applications in construction. An updated prototype printer is presented which enables further exploration of the process and its future applications.

Keywords: selective binding, 3D printing, additive manufacturing, free form construction, concrete

1. Introduction

Recent developments in additive manufacturing methods for the construction industry have opened up new possibilities for the design and production of building elements. Various additive manufacturing methods have been developed to create concrete structural components which can be optimized regarding load bearing capability or building physics while at the same time reducing the amount of waste produced.

2. Additive manufacturing in construction

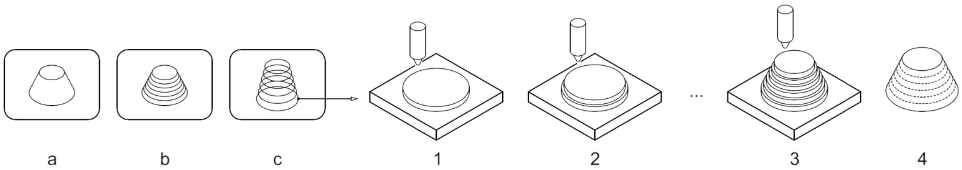

Figure 1: Extrusion process: digital pre-process (a -c) and physical manufacturing (1 -4) [1]

The majority of the research worldwide focus on variations of extrusion-based 3D printing. In general, these methods use pre-mixed concrete which is deposited onto a build platform according to a processed digital 3D model of the desired element. By adding subsequent layers, the complete object can be manufactured without the use of formwork (see figure 1). However, these manufacturing methods are limited in regard to their geometric freedom.

Well known examples for this manufacturing method can be seen in [2] and [3].

Alternatively, in the process known as selective binding thin layers of particles can be selectively solidified to create a 3D concrete object. Figure 2 shows the general process. As before, a 3D model is processed and translated into machine instructions (figure 2, a-c). However, instead of mixing the material and depositing it, an entire layer of bulk material is spread out onto a build platform and then selectively solidified by applying a fluid component. Layer by layer a 3D object is thus created, entirely encased in surrounding bulk material, which acts as support (figure 2, 1-3). In a final step, the unbound material is removed and could be reused for following prints. Using this method objects with a high degree of geometric freedom can be created.

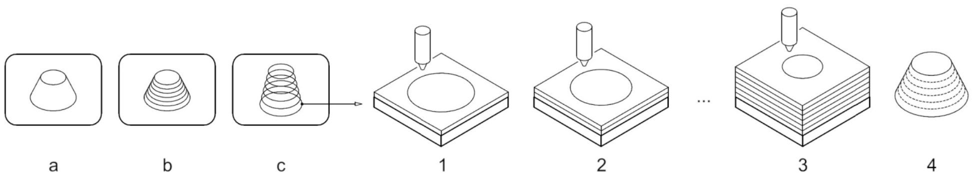

Figure 2: Selective binding process: digital pre-process (a -c) and physical manufacturing (1 -4) [1]

Two main variants of this method are currently being researched at the Technical University of Munich. In the first, referred to as selective paste intrusion, layers of coarse sand (grain size < 3 mm, layer height 3 mm) are selectively bound by depositing a fluid cement paste which infiltrates the voids between the particles. Experiments using this method have proven successful with achieved compressive strengths above 70 MPa after 7 days and good durability against freeze-thaw and carbonation attacks. [4] [5]

The second variant of the selective binding method, and the focus of this article, is the so-called Selective Cement Activation (SCA). Here, the bulk material consists of a dry cement and sand mixture. The hydration process of the cement is then activated by applying water to the layer. Since this method only uses water as an activator the print head can be outfitted with much finer nozzles which allows for a high print resolution. In addition, by using very fine quartz sand (d_{max} = 0.5 mm) as an aggregate, the layer height can be significantly reduced. Put together, the selective cement activation method enables the manufacture of objects with a high resolution in all 3 dimensions. First experiments conducted using a prototype 3D printer achieved material strengths above 16 MPa after 7 days [6]. However, form fidelity and layer cohesion still proved to be problematic. Furthermore, the prototype printer proved difficult to work with, as its print head, build chamber dimensions and particle dispenser volume were insufficient for extensive testing. In order to continue the research on selective cement activation, it was necessary to develop an improved 3D printer.

3. Prototype SCA printer and process description

3.1. Overview of the prototype printer

The first prototype printer for selective cement activation was developed in a recent research project within the DFG (German Research Foundation) priority program 1542 'Light Construction with Concrete'. Aim of the project, in part, was to explore the possibilities of selective cement activation for the use in construction and to determine suitable process parameters and materials. For this, a first prototype printer was developed which allowed the manufacture of specimens for material and contour precision testing. [7]

Due to the promising results of the previous research an improved version of the prototype printer was developed as part of an ongoing DFG transfer project. With its larger build chamber and increased print speed and reliability, the new machine enables the next steps to be taken in material development and research into real-world applications.

The prototype printer (seen in figure 3) is made up of multiple distinct components. Most noticeable is the outer frame with its linear bearing units (a) which are used to raise a three axis CNC portal (b). The build chamber (c) which holds the bulk material consists of a base platform and boundary walls. The print head (d) as well as the bulk material dispenser (e) and the compaction roller (f) are also mounted on the CNC portal which ensures that their distance from the bulk material remains constant for each layer. Fluid is supplied by a pressurized water tank (g) and fed through a series of filters before reaching the print head.

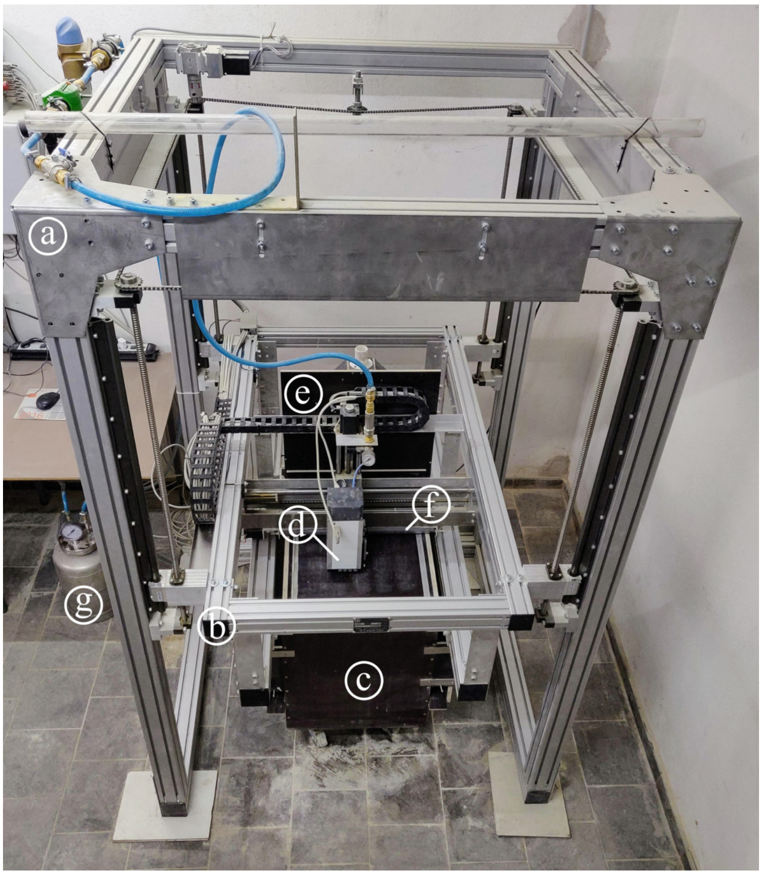

Figure 3: Prototype printer for selective cement activation (a: printer frame, b: CNC portal, c: build chamber, d: print head, e: bulk material dispenser, f: compaction roller, g: pressurized fluid supply)

3.2. Creating the bulk material layer

Before printing, a layer of bulk material must be laid down. For this, the walls of the build chamber with an internal area of 450 mm x 600 mm are raised slightly above the level of the desired layer height. The dispenser, which consists of a hopper with a motorized roller with flexible ridges at its bottom, is filled with the sand-cement mixture. While moving across the build chamber the roller inside the dispenser rotates and forces the bulk material through a sieve. This ensures that agglomerates are broken up and a loose powder layer with a thickness slightly above that of the desired layer height is dispensed onto the build platform (see figure 4).

Figure 4: Freshly dispensed bulk material onto a previous layer. Top left: bulk dispenser unit, right: bulk overflow container.

Since the cement-sand mixture cannot be mixed with water in a conventional way to form concrete, the final strength properties depend heavily on the density of the particles and thus on the packing density of the dry bulk material. In order to create a homogenous layer with a high packing density, the dispenser unit has a compaction roller attached to it. While the dispenser moves across the build chamber, in a first step, the freshly dispensed powder is smoothed by the counter rotating roller and excess material is pushed into an overflow container for reuse. Then, the compaction roller is moved back down again to obtain the desired layer height. Finally, the compaction roller is moved back across the bulk layer with a forward rotation corresponding to its linear velocity, thus compacting the bulk material.

Typically, the machine is set to create layers with a thickness of 1 mm by compacting 1.5 mm of loosely smoothed bulk material. Depending on the cement/sand ratio this results in a packing density between 1.3 and 1.7 g/cm^3.

3.3. Printing

Once the layer of cement and sand is laid down and compacted, water is locally applied by the print head to those areas of the layer that are to be solidified. The previous version of the printer was outfitted with a single flat fan nozzle. Apart from limiting the possible geometry of printed objects, the fine water mist which was sprayed onto the surface could not fully penetrate the particle layer, resulting in less cohesion between layers and lower material strength. [6]

In contrast to the previous printhead, the new version consists of 32 individual nozzles. Each nozzle creates a fine water jet which penetrates the layer surface, enabling a better hydration of the particle layer. The deionized water is provided by a pressurized tank and fed through multiple filters before entering the print head. The water pressure is regulated depending on the desired water/cement ratio and penetration depth.

Printing takes place in a two pass system by moving the print head across the build chamber, shifting it by 1 mm and moving it back to its original position, thereby covering 64 mm of the build chamber width. In order to print the entirety of the build chamber this must be repeated for a total of seven times. This is also one of the main factors in determining the print speed of the system, the other being the chosen federate of the CNC portal in accordance with the water pressure to set a specific water/cement ratio. The current setup allows for a print speed of up to 40 layers per hour. A close up of a single printed layer can be seen in figure 5.

Figure 5: Close up of a printed layer with visible individual printed lines.
Printed image dimensions: 68 mm x 35 mm

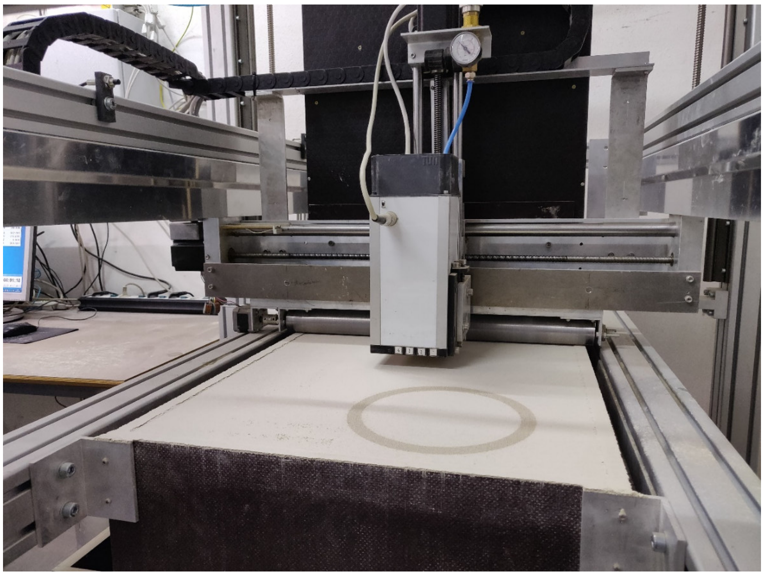

Figure 6: Print head and compacted cement-sand layer during print of a tubular test geometry

3.4. Excavation

Once the last layer is completed (see figure 6), the print is left to rest until the cement has developed enough initial strength for excavation. Depending on the type of cement/sand ratio used, this period can last from a few minutes to multiple hours. Due to the shape of the fine aggregate and cement, as well as the high packing density, the printed objects cannot simply be taken out of the surrounding dry material without risking damage to the objects. Therefore, in a first step, large portions of dry material must be removed with the use of shovels, spatulas and brushes. This material can be reused for subsequent prints. Figure 7 shows the build chamber and printed objects with most of the bulk material removed.

At this point, the printed objects still have an outer coating of cement and sand about 3 mm thick which must be discarded, as it may be contaminated by moisture from the print. This material can be removed by either scraping and brushing the parts clean, where possible, or by spraying the parts with water, thereby washing away the excess material. This latter approach may also function as a form of post-treatment of the parts the effect of which must still be examined.

Figure 7: Printed parts during excavation

A 3D-printed object fabricated by this method can be seen in figure 8. The pipe segment with a length and diameter of 200 mm is an example of an object that is nearly impossible to manufacture using typical concrete formwork.

Figure 8: 3D-printed pipe segment with internal trusses

4. Further research and conclusion

The new prototype printer enables the production of concrete objects with a high level of geometric freedom and detail. In addition to test specimens for material testing, e.g. test prisms for 3 point bending tests, current research is focusing on the possible geometric freedom and shape accuracy that can be achieved using different material and manufacturing combinations. Test objects as seen in figure 9 (left) are used to gauge limits in geometric elements such as minimum shaft and hole diameter or tongue and groove thickness that can be manufactured. The printed specimens are also analyzed using a 3D scanner and evaluation software to determine their deviation from the original cad model (see figure 9, right).

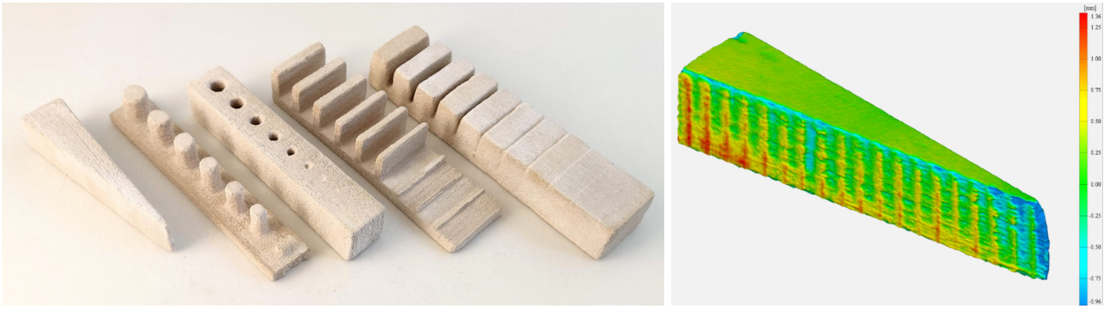

Figure 9: Printed geometric test specimens (left) and comparison of geometric fidelity via 3D scan and evaluation software (right)

First results of examined test specimens show deviations within a range of ± 3 mm of the original cad model. Also, a noticeable increase in deviation is noticeable towards the bottom of the test specimens. This is likely the result of a combination of water dissipating into the surrounding material and further compression of the layers caused by the additional weight.

However, the resulting geometric fidelity and minimal geometric elements are not only limited by the material and print process parameters, but also largely depend on the ability to remove the excess material after printing. For example, even though holes with a diameter as little as 8 mm can be printed, excavating them proves to be difficult after a certain depth. In order to develop design rules for applications in construction, further research and standardized excavation methods are required.

In conclusion, the new prototype printer for selective cement activation provides new possibilities for the manufacturing of concrete elements with a high degree of geometric freedom with material strengths suitable for applications in construction. Further research, especially in regard to material composition, packing density, excavation methods, post-treatment and concepts for upscaling of the process are needed in order to transfer this technology from prototype to real-world applications.

5. Acknowledgements

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6. References

[1] K. Henke, Additive Baufertigung durch Extrusion von Holzleichtbeton. Dissertation. Technical University of Munich, 2016

[2] B. Khoshnevis, Contour Crafting - State of Development. Proceedings of the 10th Solid Freeform Fabrication (SFF) Symposium, Austin, Texas, 1999

[3] N. Cheniuntai, Apis Cor. [Online] Available: https://www.apis-cor.com/. Accessed on: May 27 2019

[4] D. Weger, D. Lowke, C. Gehlen, D. Talke, and K. Henke, “Additive manufacturing of concrete elements using selective cement paste intrusion - effect of layer orientation on strength and

durability," in First RILEM International Conference on Concrete and Digital Fabrication - Digital Concrete 2018, 2019

[5] D. Weger, C. Gehlen, and D. Lowke, "Additive Fertigung von Betonbauteilen durch selektive Zementleim-Intrusion," in Tagungsbericht / Ibausil, 20. Internationale Baustofftagung, Weimar, 2018

[6] D. Lowke et al., "Particle-bed 3D printing in concrete construction – Possibilities and challenges," Cement and Concrete Research, vol. 112, 2018

[7] D. Lowke et al., "3D-Drucken von Betonbauteilen durch selektives Binden mit calciumsilikatbasierten Zementen – Erste Ergebnisse zu betontechnologischen und verfahrenstechnischen Einflüssen," in Tagungsbericht / Ibausil, 19. Internationale Baustofftagung, 2015.