Production of monolithic, load-bearing wall constructions with very high thermal insulation through formwork-free deposition of foam concrete

The aim of the research project CONPrint3D® Ultralight was to develop the fundamentals of a 3D-concrete-printing process for the construction of load-bearing walls of foam concrete using the CONPrint3D® technology. Building material, construction machine, process engineering, and construction management aspects were dealt with.

3D-concrete-printing using the CONPrint3D® process is a continuous, formwork-free construction technology that works according to the principle of additive manufacturing. It enables the cost-efficient construction of concrete structures and components under *on-site* construction conditions. The CONPrint3D® process utilizes conventional machinery and concrete technology to the maximum extent possible, by adopting them for the specific requirements of 3D-printing. The basis for the development of the CONPrint3D® process had been the "Zukunft Bau" research project "Feasibility study on continuous and formwork-free construction process with 3D-printing of fresh concrete" (AZ: SWD-10.08.18.7-14.07). The present project dealt with the extension of this CONPrint3D® process to use of foam concrete instead of ordinary density concrete.

Foam concrete is characterized by low bulk density and good thermal insulation properties and therefore should offer the following significant advantages with respect to the construction of walls by 3D-printing:

- Continuous and formwork-free production with low personnel costs, fast execution times, and low construction costs (directly on the construction site or in the precast plant);
- Relatively low dead-weight input into the building structure, while a sufficient static load-bearing capacity of the foamed concrete walls is attained;
- Compliance with legal regulations of thermal insulation: When the monolithic foam concrete walls of sufficient thickness are produced, the additional thermal insulation layer could be avoided;
- Consequently, recycling of construction elements after the end of their use would be simplified.

The scientific and technical objectives of the CONPrint3D® Ultralight were:

- Development of foam concrete, which 1) is pumpable or can be produced directly on the printhead, 2) has sufficient very early strength development (tens of minutes to few hours from production) upon formwork-free forming or 3) can be stimulated to set rapidly, 4) hardens without considerable volumetric changes (shrinkage), 5) possesses sufficient load bearing capacity for structural applications in multi-storey new residential constructions, and 6) has a low thermal conductivity;
- Development of a print head for 3D-printing of foam concrete;

- Demonstrating the economic viability and sustainability of foam concrete 3D-printing technology.

The above stated objectives were attained in the following steps:

- Development of printable foam concretes:
  - By developing 1) high-strength fine mortar as mineral base for foam concrete by means of granulometric optimization of solid constituents and adaptation of the water demand, and 2) appropriate foams made with synthetic surfactant-based or a protein-based foaming agent;
  - By producing foam concrete by means of 1) direct foaming of mortar, and 2) separate foam production and mortar production;
  - By controlling the stiffening and hydration kinetics of foam concrete;
- Design and implementation of a printhead for foam concrete;
- 3D-printing of foam concretes with the developed laboratory printing device according to the CONPrint3D® technology;
- Investigations on the foaming of the fine mortar directly at the print head, using a fundamentally different mixing technique;
- Rheological characterization of fresh foam concrete and testing of the geometrical stability of 3D-printed foam concrete elements as well as characterization of physical and mechanical properties of hardened foam concrete;
- Life cycle cost (LCC) analysis to assess the cost-effectiveness, and life cycle analysis (LCA) to assess environmental and sociological aspects of foam concrete 3D-printing for residential construction applications.

Two methods were used for the production of the printable foam concretes: pre-foaming and mixed-foaming. The pre-foaming method, in which a pre-mixed cement matrix and separately pre-produced foam are eventually mixed together, proved to be the best option. Through iterative mixture optimization, for example, the foam concrete labelled A3-CN with a density of approx. 980 kg/m^3 was produced. The dimensional stability of this foam concrete enabled a rapid subsequent deposition of multiple filaments through 3D-printing. The hardened printed foam concrete featured a compressive strength of 8.3 MPa and a flexural strength of 1.35 MPa. Thus, it can be used for construction of load bearing structures. The developed 3D-printable foam concretes exhibited, depending on their bulk density, thermal conductivities of 0.17 to 0.35 W/mK, indicating their good thermal insulating properties.

The developed materials, technological and analytical processes and procedures, as well as the machine elements including their integration establish necessary foundations for a large-scale or industrial implementation of formwork-free construction processes with foam concrete. The project results can be used by producers of building materials and construction chemicals as well as by construction machinery manufacturers and construction companies to further develop marketable products and technologies with a strong and unique selling proposition. This can be done with limited effort by using the prototypically proven 3D-printing of foam concrete as a basis. The positive evaluation of the cost-effectiveness of the developed construction process provides an excellent argument in favour of its transfer into the construction practice.

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- BAM Deutschland AG, Dresden: Application scenarios in multi-storey residential construction;
- Kniele GmbH, Bad Buchau: Mixing technology, provision of concrete mixer for the experimental program;
- MC-Bauchemie Müller GmbH & Co. KG, Bottrop: Foaming agent, foaming machinery;
- Opterra Zement GmbH, Werk Karsdorf: Concrete technology, cement and other mineral binders.

Based on the results of the project at hand, following publications appeared or are in preparation:

1. Viktor Mechtcherine, Frank Will, Jens Otto, Viacheslav Markin, Mathias Näther, Martin Krause, Venkatesh Naidu Nerella, Christof Schröfl: „CONPrint3D-Ultralight – Herstellung monolithischer, tragender Wandkonstruktionen mit sehr hoher Wärmedämmung durch schalungsfreie Formung von Schaumbeton", Deutsches Architektenblatt, 2019, accepted (in German);
2. Viktor Mechtcherine, Frank Will, Jens Otto, Viacheslav Markin, Mathias Näther, Martin Krause, Venkatesh Naidu Nerella, Christof Schröfl: „CONPrint3D-Ultralight – Herstellung monolithischer, tragender, wärmedämmender Wandkonstruktionen durch 3D-Druck mit Schaumbeton", Beton- und Stahlbetonbau, 2019, submitted (in German);
3. Viacheslav Markin, Genady Sakhmenko, Venkatesh Naidu Nerella, Mathias Näther, Viktor Mechtcherine: "Investigations on the foam concrete production techniques suitable for 3D-printing with foam concrete", 4th International Conference "Innovative Materials, Structures and Technologies" (IMST 2019), 2019, accepted;
4. Viacheslav Markin, Venkatesh Naidu Nerella, Christof Schröfl, Gyunay Guseynova and Viktor Mechtcherine: "Material Design and Performance Evaluation of Foam Concrete for Digital Fabrication", Materials, 2019, 12, 2433; doi:10.3390/ma12152433;
5. Christof Schröfl: „CONPrint3D-Ultralight", 10. Projektetage der Bauforschung, Bonn, 06.11.2018 (in German);
6. Jens Otto: „CONPrint3D-Ultralight", 7. Projektetage der Bauforschung, Bonn, 08.11.2017 (in German).