3D PRINTING WITH FOAM CONCRETE

Overview of the ongoing research

The potential use of the foam concrete in 3D printing is a perspective approach, which could generate the synergetic benefits through automation on one hand and superior material properties of the foam concrete on the other. Excellent insulation properties of the foam concrete are able to contribute to the energy efficiency of the structures and eliminate the need of additional insulating layer, which reduces construction time and cost. At the same time, 3D printing process arises challenging requirements on fresh state and hardened state properties of the foam concrete. The article at hand gives a brief overview of the ongoing research at the Institute for Construction Materials at the TU Dresden on the development of the printable load-bearing foam concrete.

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Foam concrete: definition and overview

Foam concrete (FC) can be defined as a lightweight cementitious material with cellular structure, which is produced by incorporating air voids into cement-based matrix. FC can be designed to have any density within the range of 200 to 1900 kg/m^3. FC with densities lower than 400 kg/m^3 are not applicable for structural purposes and mostly used as a filler or insulating material. The origins of the FC going back to the romans time. The Romans accidentally identified that workability of the mixture could be improved by addition of the animal blood to the mortar. At the same time, they observed foaming of the mixture [12]. Developments in the material science and worldwide advancing industrialization in the 1920s encouraged application of FC preferably as insulating material. First comprehensive studies on properties and manufacturing techniques of FC for structural applications appeared only after 1950 [12]. Nowadays, FC is recognized as a versatile construction material, which is environmentally sustainable and at the same time cost efficient.

Generally, there are two mechanisms of introducing air voids into the mixture, namely, with the use of gas-forming chemicals, i.e., aluminum powder, and with the use of the foaming agents. The addition of aluminum powder to the mixture lead to formation of bubbles as a result of a chemical reaction of aluminum powder with calcium hydroxide and other alkalis released during cement hydration. This method is used for production of gas-aerated concrete. In contrast, FC is distinguished from other lightweight concretes by incorporation of the air voids into the cement-based matrix by using foaming agents. However, e.g., ACI terminology does not exactly specify if foaming agents or gas-forming chemicals are used in FC production and defines “foamed concrete” as a “low-density concrete made by the addition of a prepared foam or by generation of gas within the fresh mixture” [1]. In some cases, “foam concrete” or “foamed concrete” is synonymized with “cellular concrete” or “aerated concrete”.

In general, properties of FC are governed by its density. However, they are influenced also by numerous other factors among which are: pore structure, quality of the prefabricated foam, water content, characteristics of the constituent materials in the cement-based matrix, age, curing regime, specimen shape and size, etc.

Production techniques and feeding concepts for continuous 3D printing with foam concrete

Foaming agents, i.e., synthetic or protein-based surfactants, are used to produce FC either by the “pre-foaming method” or the “mixed foaming method”. Figure 1 depicts these two manufacturing approaches schematically. In the pre-foaming method, the cement-based matrix and prefabricated foam are produced separately. In the next step, foam and cement-based matrix mixed together to form the FC. In contrast to the pre-foaming method, the mixed foaming method prerequisites direct addition of the foaming agent to the cement based-matrix followed by a high speed mixing.

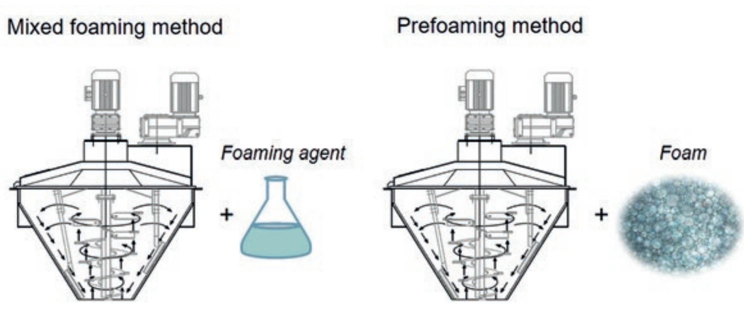

Figure 1: Methods for production of FC.

The quality of the foam is of a great significance while it has a considerable impact on the properties the FC in both fresh and hardened states. Prefabricated foam is produced by diluting a foaming agent in water in specific proportions and passing this solution through a generator or spaying over a mesh. Different types of foaming agents have different foamability characteristics, which can be described as "foaming capacity". Foaming capacity gives a volumetric measure of how much foam can be produced per unit quantity of foaming agent concentrate [13]. The solution for production of the foam has usually a foaming agent to water ratio between 1:5 and 1:40, the optimum performance is commonly achieved at 1:25 ratio [3]. However, the actual dilution ratio depends on the type of foaming agent and foam production techniques. Previous research results of the authors have shown that both types of surfactants along with both types of the production techniques, i.e., mixed foaming method and pre-foaming method, can be applied for the production of both conventional and printable FC [7, 8]. However, to guaranty continuous 3D printing with FC, conventional production techniques must be aligned with specific technical particularities of the machinery used for construction 3D printing. Various concepts for delivering of the FC to the print head are presented in Figure 2. Notably, that presented concepts could be efficiently applied for both production techniques.

In Concept 1 after mixing, FC is placed manually to the reservoir of the print head; see Figure 2a. This concept relies on additional manual work, which is unfavorable in terms of cost and time efficiency. In Concept 2, FC mixer is directly connected to a pump, which continuously delivers FC to the printhead reservoir; see Figure 2b. In Concept 3, the FC mixer is directly connected to a printhead. In Concepts 4 mixer should be installed on the printhead. One of the considerable advantages of Concept 4 is that stability of the FC is not affected by the pumping procedure.

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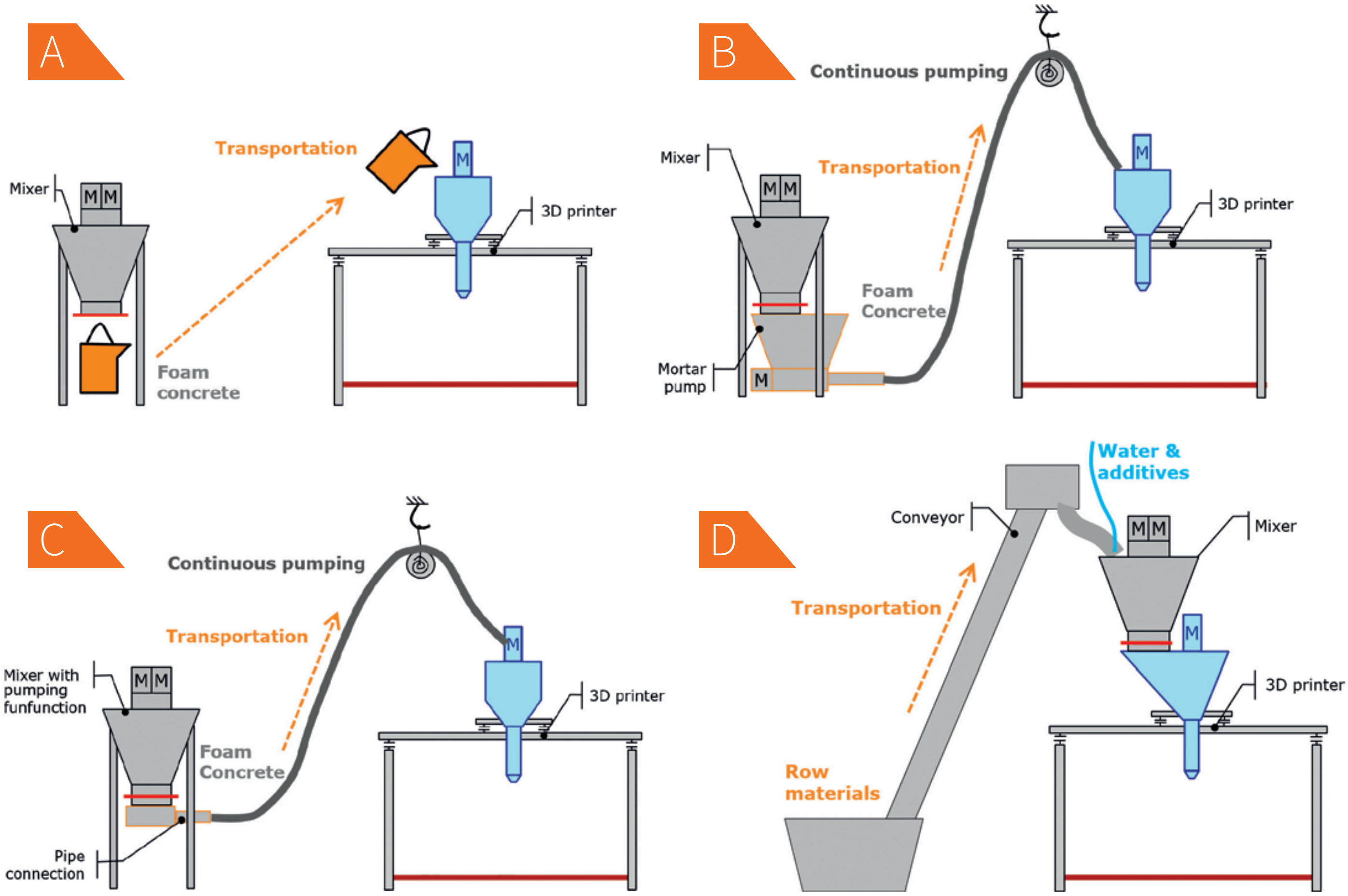

Figure 2: Different concepts of feeding system for continues FC printing: (a) Concept 1: manual filling; (b) Concept 2: mixing and pumping; (c) Concept 3: pumping to integrated mixing system; (d) Concept 4: convening and fully integrated mixing system.

However, technical realization of the Concept 4 is challenging. Existing solutions for inline mixing of dry constituents with water and admixtures must be adopted for mixing of FC on a concrete printhead [14]. It is worth noting that the concepts presented in Figure 2 are also applicable to the normal weight printable concrete and alternative building materials used in construction 3D printing. In such cases, instead of foaming agent, other chemical additives could be added. More details on appropriateness of different mixers for continues manufacturing of FC could be found in [8].

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Properties of the foam concrete in the context of requirements on printable concretes

The use of FC in the 3D printing is a highly perspective concept which will allow to combine the benefits of formwork-free automated construction and specific material properties of FC. However, the implementation of this approach is a challenging, since properties of the conventional FC in fresh state, which are governed by its common applications, differ greatly from the target properties of the printable cementitious materials. In general, printable concretes should have sufficient extrudability and buildability characteristics as well as sufficient interlayer bonding. In addition, printable cementitious materials have to exhibit appropriate mechanical properties, e.g., compressive strength.

Concerning the mechanical characteristics of the FC, it was earlier recognized among research and evidenced in the praxis that it is possible to achieve sufficient strength required for structural applications by simultaneously maintaining the beneficial physical properties such as thermal isolation and sound absorption. Figure 3 illustrates the relationship between density and 28-day compressive strength of the FC based on the data provided in different studies. From this figure, it could be seen, that FC could be produced with various mechanical and physical properties.

FC is characterized by a high flowability, which is advantageous for pumping of the FC in vertical and horizontal directions. However, fresh state properties of FC must be adjusted with regard to the needs of the formwork-free digital fabrication. The perfect coordination of the hydration kinetics and the thixotropic behavior of FC is

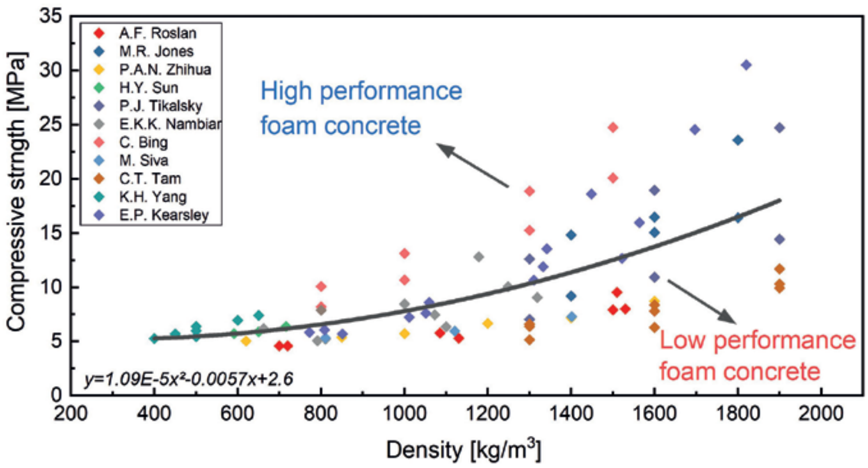

Figure 3: Relationship between density and 28-day compressive strength of FC in various studies.

HGT = 136.5 mm

40 gr per kg cement
HGT = 124.0 mm

60 gr per kg cement
HGT = 112.0 mm

80 gr per kg cement
HGT = 110.0 mm

Figure 4: Effect of the accelerator addition on the consistency of a FC.

clearly the key prerequisite for the successful extrusion and subsequent layer-wise deposition of the filaments. Mix design approach previously published in [7] enables to attain the desired rheological and mechanical properties. Consistency and the setting time of FC can be also adjusted by use of the accelerators. Figure 4 shows the change in the spread diameter of the FC due to addition of the shotcrete accelerator Fluresit-Schnell Plv. (MC-Bauchemie Müller GmbH & Co. KG, Bottrop, Germany). Furthermore, latest research results in [6] show that high structuration rate of 4.9 Pa/min can be achieved even without addition of accelerator. The addition of the high-reactive puzzolans enhance buildability and therefore structural stability of the printed FC elements.

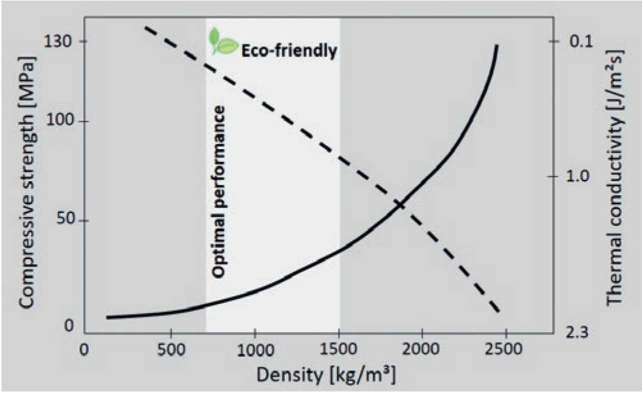

Figure 6: Dependence of the compressive strength and thermal conductivity on the density of the material.

Perspective of the application of the foam concrete in 3D printing

Out from many requirements on construction materials and structures could be outlined three most important aspects: sustainability, efficiency and structural stability. These three areas of engineering interest are constantly driving the material development towards new, better and more efficient materials. Like conventional construction materials, printable cementitious materials are being constantly improved and the variety of the available printable materials is rapidly growing. Figure 5 depicts some of the recently developed printable compositions at the Institute for Construction Materials at the TU Dresden: normal weight concrete with maximum aggregate size of 8 mm, strain-hardening cement-based composite (SHCC), light weight FC, ultra-light weight FC. Each of these four printable compositions has its unique set of properties and is designed for specific application scenario. For instance, the light weight of FC enables to reduce the dead loads, which makes its use beneficial in structural applications by reducing the dimensions of foundations and thus the amount of the required reinforcement. Furthermore, superior insolating characteristics of the FC make possible production of the exterior walls without additional insolation layer. Individual properties of other alternative printable compositions are detailed in [7, 9, 10].

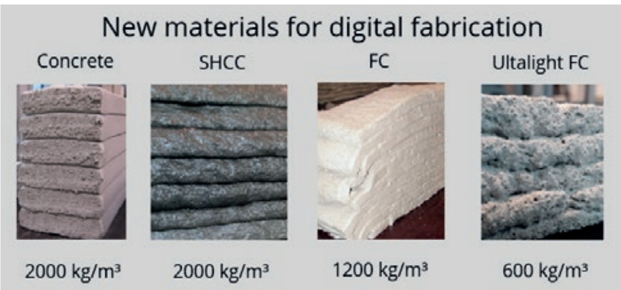

Figure 5: Printable concretes with various properties and different fields of applications.

Most current studies on the cementitious materials for digital fabrication are related to usage of ordinary normal weight concrete or mortar with a bulk density in the range from 2000 to 2500 kg/m^3, while lightweight concrete has been used very rarely. Figure 6 shows the dependence of the concrete's compressive strength on its density and related thermal conductivity. By considering the application field of 3D concrete printing as a construction of residential, low-raise buildings, it is obvious that in most cases high compressive strength is not required and actually superfluous. Sustainability and economic efficiency are some of the primary motives for the development of 3D printing technologies, which also includes reduction of the material consumption. A promising way to achieve this target is the use of the FC in 3D printing. Beneficial material-to-built volume ratio in combination with low thermal conductivity helps to reduce CO_2 footprint and makes concrete environmentally friendly.

Under consideration of above mentioned possible benefits due to application of FC in the digital fabrication, the previously developed CONPrint3D® concept [9] for production of the large scale construction elements and buildings was extended to CONPrint3D-Ultralight [7]. The main purpose of the CONPrint3D-Ultralight is the simplification and optimization of the entire production process due to abolition of the additional insolation layer. Figure 7 shows the typical full-wall cross section printed in accordance with CONPrint3D® concept and printed full-wall cross section by use of a FC. Due to application of the FC, production step needed for montage of the insolation later could be omitted. This logical simplification is combined with reduction of the construction time, which results in reduced construction cost.

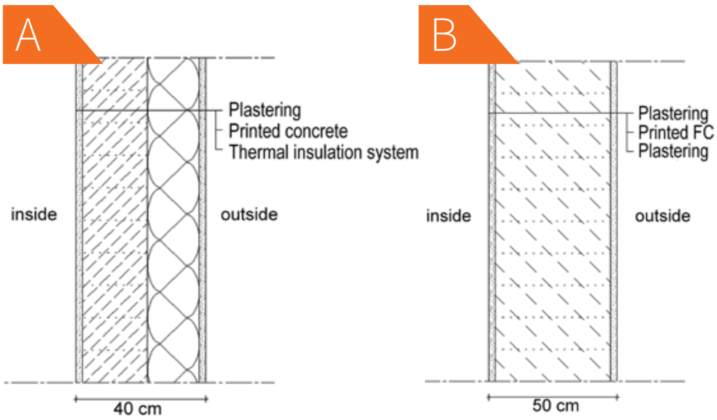

Figure 7: Illustration of the wall cross-sections: (a) wall produced with CONPrint3D® technology, insulation and plastering applied according to conventional methods, (b) entire wall cross section made out of FC using the CONPrint3D-Ultralight approach.

Table 1: Mixture composition in accordance with design guidelines for printable FC in [7].

Constituent	CEM	FA	MS	Water	Foam	SP
Density [kg/m^3]	3120	2220	2295	1000	56	1050
Volumetric por-tion in 1 m^3 FC	0.179	0.130	0.016	0.288	0.383	0.003

Development of the printable foam concretes

Portland composite CEM II / A-M (S-LL) 52.5 R (Opterra Karsdorf GmbH, Werk Karsdorf, Germany) was used for the production of FC. Fly ash (FA) Steament H-4 (STEAG Power Minerals GmbH, Dinslaken, Germany) and microsilica (MS, Grade 971U, Elkem ASA Silicon Materials, Skøyen, Norway) were used as pozzolanic additives. The cement-based matrix for production of the printable FC consisted of 55% cement, 35% fly ash and 5% microsilica. A protein-based foaming agent (Oxal PLB6, MC-Bauchemie GmbH & Co. KG, Bottrop, Germany) was diluted with water in the ratio 1:30 (by volume) and then utilized for production of the foam with an average density of 60 kg/m^3. Technical characteristics of used foam generator and settings for production of foam are detailed in [7]. Polycarboxilate ether-based superplasticizer (SP) MC-PowerFlow 5100 (MC-Bauchemie Müller GmbH & Co. KG, Bottrop, Germany) was used for achieving the required workability and reducing the water content. Table 1 presents composition of one of the FC under investigation.

The mixing of the components took place in the cone mixer KKM 30L (Kniele Baumaschinen GmbH, Germany) [4]. The mixture was designed for a total volume of 30 liters. The mixing process was subdivided into two steps: (1) mixing of the cement-based matrix and (2) intermixing of the prefabricated foam into the cement-based matrix. At first, dry materials were homogenized for 2 min with an engine speed of 3000 rpm. Subsequently, water and superplasticizer were added, and the mixing was resumed for further 2 min at the same speed. In the next step, the speed was reduced to 1500 rpm and the separately prepared foam was gradually added. Figure 8 shows the reduction of the density by gradual addition of the prefabricated foam. The original density of 1890 kg/m^3 of the cement-based matrix was reduced to 1138 kg/m^3. Thus, the deviation between calculated and target density was around 5 %, which is within the range of deviation for conventional concretes [2, 15].

Material characterisation

Figure 9 shows the spread flow of the cement-based matrix before and after addition of the foam. Tested specimens retained their shape stability after removal of the steel ring to a great extent. The strokes lead to some flow of both materials. In comparison to the specimen of the cement-based matrix FC specimens showed only slightly increased in the flow spread diameter after 15 strokes. Thus, low self-weight of the FC contributes to the reduction of the pressure on the bottom layer and thus could improving stability of printed structures in the fresh state.

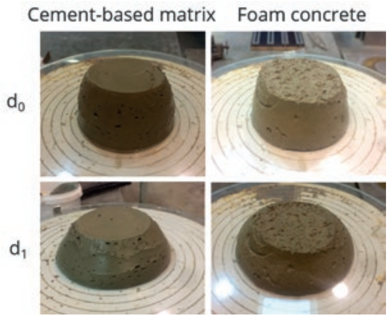

Figure 9: Flow spread: (a) cement-based matrix, (b) foam concrete; d_0 stands for flow spread diameter after removal of the steel ring and d_1 stands for flow spread diameter after 15 strokes.

While low self-weight of the FC contributes to the reduction of the pressure on the bottom layer, it still should yield a sufficient static yield stress to bear the subsequent layers. Within the first 60 min after water addition the developed FC showed linear increase in the static shear limit and yielded the structuration rate Athix of 4.6 Pa/min; see Figure 10. For the higher age of young concrete exponential increase of the strength could be expected [11]. Structuration rate of the FC is an important characteristic, which enables to design the printing regime in the way to avoid a failure due to material overload or the loss of structural stability. Together with the initial static yield stress, this value can be used for identifying the time intervals between the subsequent layers in particular and the most efficient printing strategy in general [5].

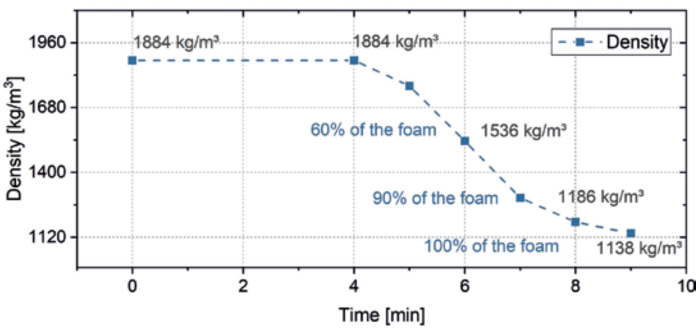

Figure 8: Decrease in the density of the cement-based matrix by gradual addition of the foam.

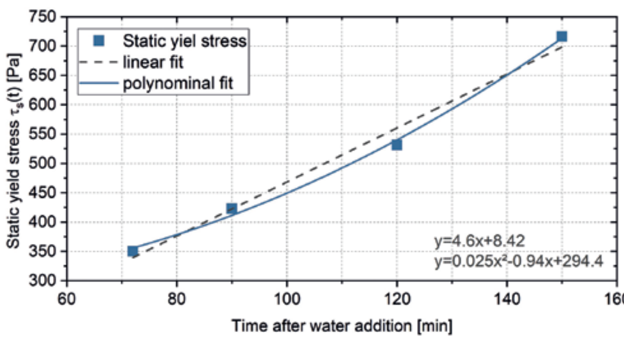

Figure 10: Evolution of the static yield stress of foam concrete in time.

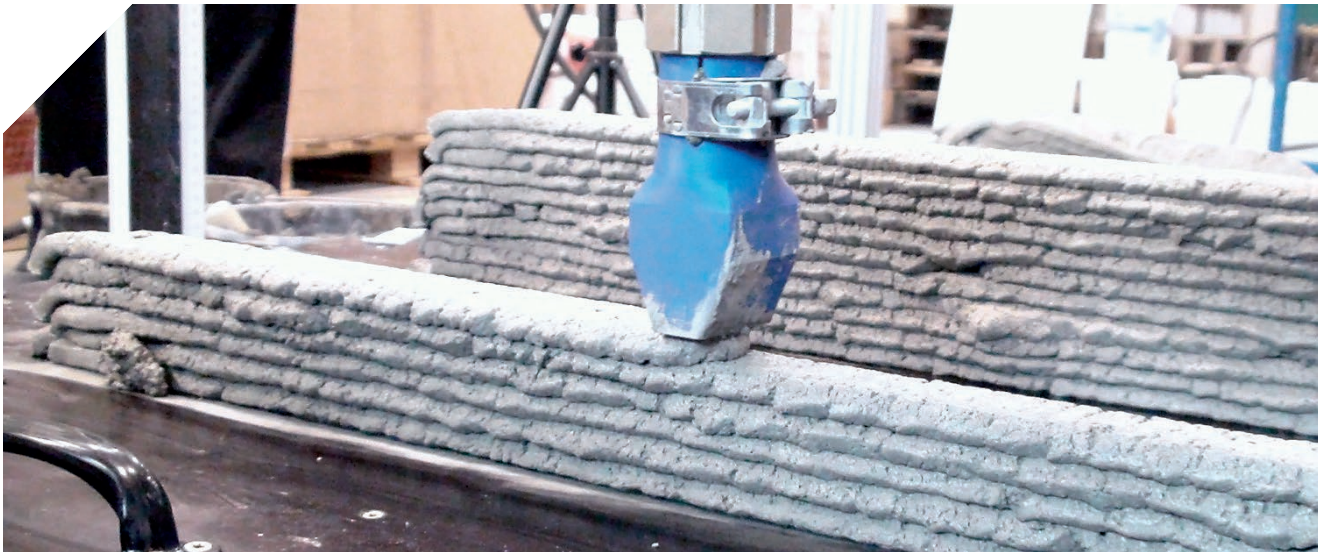

Figure 11: 3D printing with foam concrete

3D printing with the designed FC was conducted using custom developed 3D printing testing device (3DPTD) as described in [11]. 3DPTD was equipped with a progressive cavity screw and a rectangular nozzle with an opening of 33 mm x 14 mm. The printhead was moving at a constant speed of 40 mm/s. Designed FC composition could be extruded and deposited in layers, see Figure 11.

As expected, time interval between deposition of the layers had an influence on the buildability and extrudability of the FC. Thus, with time interval of 2 min approximately 7 layers could be printed before noticeable deformations and final collapse of the wall specimen occurred. With extending of the time interval to 5 min critical number of layers could not been reached because of the overstiffening of the material. It is worth noting that blockage of the nozzle did not occur, but rather the surface quality decreased and certain discontinuities in the printed layers appeared. In total 16 layers could be printed until experiment was stopped.

Table 2 summarizes the results of the compressive and flexural tests. At the age of 14 days the average value of the compressive strength was 3.0 MPa, it increased to 6.9 MPa at the age of 56 days. The flexural strength increased from 1.0 MPa to 1.7 MPa over the same period of time. It should be noted that the FC specimens were not dried before testing; the density at the respective test day ranged for tested specimens between 900 kg/m^3 and 1090 kg/m^3.

The thermal conductivity of the FC was measured using Heat Transfer Analyser ISOMET 2104 (Applied Precision Ltd, Bratislava, Slovakia). Testing procedure was already detailed in [7]. The determined thermal conductivity of 0.21 W/m^{2}K is in line with usual values for conventional FC with similar density.

Conclusions and outlook

The automated manufacturing process by means of 3D concrete printing has already proven its profitability and efficiency. Application of foam concrete (FC) in the construction 3D printing could open new horizons for further reduction of the overall construction cost and lowering of the harmful CO_2 footprint. 3D printing of the full-wall cross-section, as it pursued by a CONPrint3D® concept, with a FC as print material could abolish the need of the additional insulating layer. Thus, manufacturing of the wall will be simplified to the printing of the main core using FC, and completion of inner and outer plastering. Preliminary studies on the printable FC are promising and should be followed by the deeper investiga-

Table 2: Compressive strength of the developed printable FC composition.

Testing age	Compressive strength [MPa]	Standard deviation [MPa]	Flexural strength [MPa]	Standard deviation [MPa]
14 days	3.0	0.3	1.0	0.1
38 days	4.8	0.5	0.0.8	0.3
56 days	6.9	0.9	1.7	0.3

tions of the fresh and hardened state properties. The authors believe that future work will allow to produce printable FC with the density of about 800 kg/m^3 by maintaining mechanical properties and at the same time better insulation capacity in comparison to that determined in this study. In particular, future work needs to be focused on further material development and investigations on the recyclability of the printable FC. A comprehensive comparative study of the construction cost by means of the conventional building materials such as bricks and FC blocks versus novel approach of 3D printing with FC is in process and will be soon released by the authors. This study will give more insides on the economic matters, which are one of the central interests of the industry. The authors trust that in the foreseeable perspective, the application of the printable FC in the large-scale 3D printing will be a feasible option in the practice of construction.

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