Investigations on the foam concrete production techniques suitable for 3D-printing with foam concrete

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Abstract. With high thermal insulating property and low density, foam concrete has high potential in 3D-printing applications such as residential buildings. The synergy of the foam concrete and 3D-printing process pre-requisites research and optimization of foam concrete production. This paper presents investigations on the appropriateness of two different methods for production of foam concrete: 1) mixed foaming method in turbulence (colloidal) mixer and 2) mixed foaming method in cavitation disintegrator. Performance of synthetic and protein based foaming agents were examined. The dosage of the foaming agent was varied from 0.7% to 1.2% by weight of cement to produce foam concretes with densities ranging between 800 kg/m³ and 1500 kg/m³. The study shows that foaming ability of the designed concrete compositions depends primarily on their w-b ratio. Moreover, foaming with lesser dosage of foaming agent is possible when turbulence mixer is used. Furthermore, mechanical and physical properties of foam concrete, including compressive strength, bending strength, and water absorption were reported.

1. Introduction

Developments in the application of the 3D-concrete-printing (3DCP) technology in the construction industry over the past few years are providing the construction industry a chance to increase their productivity and cost efficiency [1, 2]. In the recent years sophisticated methods and theoretical approaches in conjunction with material development were proposed [3–5]. Nevertheless, the development of the 3DCP for construction industry is in the early stage. The high degree of automation with utilization of robotics impose new requirements concerning quality control, safety, and compliance with building standards [6]. In addition, the rheological requirements on the concretes suitable for the placement and extrusion during printing are primary challenges associated with implementation of 3DPC. Due to the complex requirements and novel nature of printable concretes, their optimal production techniques are still to be developed and adopted for on-site application. The research at the hand investigates methods of the foam concrete (FC) production and assesses their applicability for the 3D-foam-concrete-printing (3DFCP).

Initial studies and practical use of cement based materials for digital concrete construction are mostly related to usage of ordinary normal weight concrete or mortar (bulk density 2000-2500 kg/m³) [1, 2]. Although, the normal weight concrete is irreplaceable for the construction of numerous infrastructural
projects, there is a significant subdivision of applications where novel materials could be used. In recent years, various non-traditional building materials, such as clay (also with addition of straw as fibre reinforcement) and geopolymers were applied in 3DPC [7–10]. Sustainability and efficiency are some of the primary motives for the development of 3D-printing technologies, this also includes reduction of material consumption. Therefore, it is necessary to develop economical and sustainable concrete compositions for 3D-printing. A promising way to achieve this target is the use of foam concrete in 3D-printing. The significantly lower density of foam concrete allows to decrease construction self-weight and improve thermal insulation properties. In the context of 3D-printing, lower self-weight makes it possible to decrease pressure on the bottom layers thus improving stability of printed structures in the fresh state. Upon this background, 3D-printable foam concrete was recently introduced as a versatile material with excellent physical and sufficient mechanical properties [7, 11, 12].

The primary reason to regard foam concretes as economical and ecological materials is the presence of air cells up to 80% of their total volume. The large volume of air cells in foam concrete are often introduced by mechanical aeration of cement mortar using foaming agents [13]. Two primary methods of foam concrete production are: pre-foaming and mixed-foaming [14]. In the former, separately generated/prepared foam and cement matrix (paste/mortar) are mixed together to form foam concrete. In mixed-foaming method, foaming agent is added directly to the cement matrix mixer; this means cement matrix, foam, and subsequently foam concrete are generated in one mixer. The research at hand focuses on mixed-foaming method using intensive turbulence mixer, and cavitation disintegrator. It is known that intensive mixing improves dispersion of agglomerated cement and micro-filler particles and promotes accelerated hydration processes in foam [15]. Various concepts for delivering of the foam concrete to the print head are presented in Figure 1. All presented concepts presume mixed-foaming production method. In the Concept 1 after mixing, foam concrete is placed manually to the reservoir of the print head; see Figure 1a.

This concept prerequisite additional labour involvement and slows down construction rate. In Concept 2 foam concrete mixer is directly connected to a pump, which continuously delivers the foam
concrete to the print head reservoir; see Figure 1b. In comparison to the Concept 1, the Concept 2 eliminates time required for manual transportation and refilling of the print head reservoir.

In the Concept 3, the foam concrete mixer is directly connected to a print head. Technical particularities of the mixer used in Concept 3 allows delivery of the foam concrete to the print head reservoir. The Concept 3 appears as very suitable for 3DFCP and the technical particularities of chosen mixers in this study match overall technical requirements of this concept; see Section 2.2. In Concepts 4 mixer should be installed on the print head. The Concept 4 is similar to Concept 3, except position of the mixer and that supply of raw materials is automated. Raw materials in predefined quantities are transported and mixed on the printhead. One of the considerable advantages of Concepts 4 is that stability of the foam concrete is not effected by the pumping procedure. However, technical realisation of the Concept 4 is challenging. Existing solutions for inline mixing of dry constituents with water and admixtures must be adopted for mixing of the foam concrete on a concrete printhead [16]. It is worth noting that presented concepts in Figure 1 are also applicable to the normal weight printable concretes and alternative building materials used in 3DPC [8–10]. In such cases, instead of foaming agent, other chemical additives could be added.

2. Materials and methods

2.1. Materials

This study was conducted with a type II Portland composite cement CEM II/ A-M (S-LL) 52.5 R (OPTERRA Zement GmbH, Werk Karsdorf, Germany). Hard coal fly ash Steament H-4 (STEAG Power Minerals GmbH, Dinslaken, Germany) was chosen as a secondary cementitious material. Details of chemical composition are provided in Table 1. A polycarboxylate ether (PCE) based Superplasticizer (SP) (MasterGlenium SKY 593, BASF Construction Solutions GmbH, Trostberg, Germany) was used in the cement-based matrix to adjust the workability at reduced water contents. The SP is characterized by density of 1050 kg/m³ and water content of 77% by mass. A tenside based foaming agent (Centripor SK155, MC-Bauchemie GmbH & Co. KG, Bottrop, Germany) and a protein based foaming agent (Oxal PLB6, MC-Bauchemie GmbH & Co. KG, Bottrop, Germany) were used for production of the FC.

| Material | Density (kg/m³) | Residue | SiO₂ | Al₂O₃ | Fe₂O₃ | CaO | MgO | SO₃ | K₂O | Na₂O | Loss on ign | CO₂ | CL |
|----------|----------------|---------|------|-------|-------|-----|-----|-----|-----|------|-------------|-----|-----|
| CEM II/ A-M (S-LL) 52.5 R | 3.120 | 0.74 | 20.63 | 5.35 | 2.82 | 60.94 | 2.14 | 3.52 | 1.05 | 0.22 | 3.47 | 2.87 | 0.07 |
| Fly ash H4 | 2.220 | | | | | | | | | | | | |

2.2. Overview of the mixers used

The details of two different mixers used for production of the foam concrete in this study are presented below:

(a) Cavitation disintegrator (CD). Initially CD was designed for production of the stable fuel mixtures and water-fuel emulsions; to improve heavy fuel oil by dispersing asphalt-resin components and to increase the efficiency of input additives. In addition, CD may be applied for preparation and activation of other emulsion and dispersion systems [17]. A novel hydrodynamic dispersion method for fine particles was developed and patented by Polakovs et al. [18]. Mechanical activation is associated with cavitation effect, which is achieved by high-speed rotation of toothed disks (up to 7000 rpm); see Figure 2. It must be noted that the application of CD for the preparation of FC is an innovative idea [15]. Since usage of CD is neither well known nor widespread in the construction industry, its technical components are worth noting. In CD, a set of toothed disks and impeller, fixed on a motorized shaft, form the rotor with frustoconical shape. The fixed body of the disintegrator is made of a conical lid and rectangular
grooves corresponding to toothed disks of the rotor. The body contains an inlet branch pipe and an outlet branch pipe. The electric motor is protected from liquid by a ferrule, installed in the intermediate disk, fastened together with the body on the motor flange. If the ferrule leaks, the liquid flows out on the leakage opening (ferrule operating monitoring). To discharge air from system, a plug is set in the upper part of the body. At first cement-based matrix with addition of the foaming agent are filled in the supply reservoir. During operation of the CD, the mixture cycles numerous times from supply reservoir through the tube to the disintegrator. CD used in this study had an output capacity of 10 m³/h, power 5.5 kW and was equipped with a frequency converter to control the rotational speed of the mixer working shaft in the range of 50 rpm to 7000 rpm.

(b) Laboratory turbulence mixer (TM). The TM used in this study allows to produce foam concrete in both techniques: mixed-foaming and pre-foaming method. Additionally, cement based slurries could be also produced and pumped under application of the air pressure. The mixer consists of conical mixing tank, electrical motor, bearing, pressure compensated coupling and vertical shaft, see Figure 2. The mixer enables mixing under pressure (up to 0.7 bar), which allows producing low density FC as well as unloading and pumping of the foam concrete mixture through excess pressure. The mixer is equipped with a frequency converter to control the rotational speed of the mixer working shaft in the range of 20 rpm up to 1000 rpm. Particular advantage by application of this type of the mixer in conjunction with 3DPC is integrated possibility of pumping of the foam concrete. Consequently, foam concrete could be pumped directly to the print head eliminating necessity of a separate screw pump. According to the technical data sheet of the TM-Mixer, the produced foam concrete under applied air pressure could be pumped up to 100 m distance. However, the producer doesn’t specify spatial arrangement of the pipe by the given distance.

![Figure 2](image_url)

**Figure 2.** Overview of used mixers: (a) cavitation disintegrator (CD): 1. body; 2. conical lid; 3. toothed disks; 4. rectangular recess; 5. impeller; 6. shaft; 7. inlet branch pipe; 8. outlet branch pipe; 9. electric motor; 10. ferrule; 11. plug; 12. leakage opening, and (b) laboratory turbulence mixer (TM): 1. electrical engine; 2. bearing; 3. pressure compensated coupling; 4. vertical shaft.

2.3. Experimental procedures

The concrete mixing procedure was organized in the following way: all dry materials were premixed with addition of water and SP for approximately 2 min using brick trowel. At the end of premixing, foaming agent was added and mixed for additional 15 s. Then the mixture was filled into reservoir of cavitation disintegrator or turbulence mixer, respectively. In total, six foam concrete compositions were designed, see Table 2. Operating principles as well as technical procedures of used mixers are different, therefore different mixing protocols were used for the mixers; see Table 3.

In the fresh state, the plastic density of the mixtures was measured right after foam concrete production. The workability of the samples was assessed by visual observation of the homogeneity of performed FC. The compressive and flexural strength of foam concrete mixture was measured by casting
of prism specimens with dimensions 160x40x40 mm³ following the procedure provided by DIN EN 1015-11 (2007-05) [19]. At an age of 24 hours, produced specimens were wrapped into the polyethylene foil and stored under approx. constant temperature until testing day. Water absorption of the designed foam concrete compositions was measured in accordance with DIN EN 772-11 [20].

Table 2. Mixture compositions per m³.

| Constituents               | Designed composition of mixture (per m³) |
|----------------------------|-----------------------------------------|
|                            | M-1  | M-2  | M-3  | M-4  | M-5  | M-6  |
| Cement (kg)                | 405  | 405  | 405  | 405  | 405  | 405  |
| Fly ash (H-4) (kg)         | 192  | 192  | 192  | 192  | 192  | 192  |
| Tap water (kg)             | 189  | 189  | 243  | 189  | 189  | 192  |
| SP SKY 593 (%)*            | 0.5  | 0.7  | 0.1  | 0.5  | 0.5  | 0.6  |
| FA SK-155 (%)**            | 1.2  | 1.2  | 1.2  | -    | 0.7  | 0.7  |
| FA Oxal PLB6 (%)**         | -    | -    | -    | 1.2  | -    | -    |
| (w/c)_{eq}                 | 0.39 | 0.39 | 0.5  | 0.39 | 0.39 | 0.4  |
| Used Mixer                 | CD   | CD   | CD   | CD   | TM   | TM   |

* in the mass percentage of the binder, i.e. the total amount of cement and fly ash
** in the mass percentage of the cement

Table 3. Foam concrete mixing procedure.

| Cavitation disintegrator   | Turbulence mixer               |
|----------------------------|--------------------------------|
| (CD)                       | (TM)                           |
| 0 min-2.0 min: 2100 rpm    | 0 min-2.0 min: 1500 rpm        |
| 2.0 min-4.0 min: 2400 rpm  | 2.0 min-4.5 min: 3000 rpm      |
| 4.0 min-6.0 min: 3600 rpm  | 4.5 min-6.0 min: 4800 rpm      |
| 6.0 min: Conveying of the FC | 6.0 min: Setting of 1 bar air pressure for conveying of the foam concrete |

3. Results and discussion

3.1. Verification of the density

Figure 3 gives an overview of measured plastic (fresh state) densities of all tested mixers and corresponding drying loss after accelerated drying in a drying chamber at a temperature of 105 ± 5 °C until no change of mass is identified. As shown in the Figure 3, it was possible to achieve different densities of the foam concrete by varying of the constituencies and mixing methods. Drying loss is corresponding to the achieved plastic density and increases with reduction of the density [21]. Considering plastic density of 1712 kg/m³ of composition M-4-CD it could be concluded that addition of protein based foaming agent didn’t reveal sufficient foaming by mixed-foaming technique using CD-mixer. Based on performance of protein based foaming agent using CD-Mixer it could be expected that similar inadequate performance would be achieved by use of TM-Mixer.
Figure 3. Drying loss depending on density of the foam concrete.

3.2. Effectiveness of the dosage of the foaming agent

Figure 4 presents the relationship between dosage of foaming agent and plastic density of foam concrete. Major factor influencing plastic density are dosage of the foaming agent and initial followability of the cement-based matrix that is influenced by w-b ratio and amount of the SP.

Figure 4. Effectiveness of the dosage of the foaming agent SK155 in different mixture compositions.

In case of CD-Mixer, increase of the flowability of the cement-based matrix by increasing the SP dosage from 0.5% to 0.7% (in the percent by mass of the binder, %bmob) yielded in achieving lower density. Reduction of the amount of SP while increasing w-b ratio in the composition M-3-CD yielded in achieving lower density in comparison to the compositions M-1-CD and M-2-CD. The influence of the flowability of the cement-based matrix on the foam concrete density is also evident in compositions M-5-TM and M-6-TM. Similar to the CD-Mixer, increase of SP-dosage yielded in reduction of plastic density when TM-Mixer was used.

Since compositions M-1-CD and M-5-TM distinguish only amount of foaming agent and type of used mixer, the results of these mixtures could be used to compare the performance of tested mixers. Using TM-Mixer with 0.7 %bmob of the foaming agent, foam concrete with plastic density of 1100 kg/m³ could be produced. In contrast, using CD-Mixer with a higher (1.2 %bmob) dosage of the foaming agent foam concrete with plastic density of 1382 kg/m³ could be produced. It is remarkable that, in case
of TM-Mixer, higher foam volume i.e. lower foam concrete density could be achieved even with lower dosage of foaming agent.

3.3. Hardened state Properties of the foam concrete

The compressive and flexural strengths of tested foam concretes at various ages are presented in Table 4. Mechanical properties of the foam concretes correlated with their density at the particular age. As shown in Figure 5, density at the testing age could vary from measured plastic density. The plastic density of the composition M-6-TM was 1100 kg/m³ and 28-day density was ca. 1230 kg/m³. This discrepancy can be imposed by pressure applied on the foam concrete during the pumping through the extruder and pipe (approx. 1.5 m with bend) to the casting molds. Presented results in the Figure 5 underline significant influence of the density of the foam concretes on their mechanical properties.

### Table 4. Mechanical properties of the foam concrete.

| Mix    | Mixer                        | Plastic density [kg/m³] | Compressive strength [N/mm²] | Flexural strength [N/mm²] |
|--------|------------------------------|-------------------------|-----------------------------|---------------------------|
|        |                              |                         | 7d | 28d | >120d | 7d | 28d | >120d |
| M-1-CD |                              | 1383                    | 20.2 | 25.3 | 30.0  | 3.3 | 3.2 | 3.2   |
| M-2-CD | Cavitation disintegrator     | 1367                    | 20.2 | 28.0 | 31.0  | 2.9 | 1.7 | 3.3   |
| M-3-CD |                              | 1008                    | 6.1  | 9.4  | 10.9  | 1.9 | 1.2 | 1.4   |
| M-4-CD |                              | 1712                    | 35.0 | 47.4 | 53.0  | 4.1 | 1.3 | 3.0   |
| M-5-TM | Turbulence mixer             | 1070                    | 14.2 | 17.4 | 19.3  | 2.4 | 1.6 | 1.4   |
| M-6-TM |                              | 1100                    | 4.4  | 5.8  | 4.9   | 1.7 | 1.3 | 0.9   |

**Figure 5.** Relationship density – 28 d compressive strength for foam concretes prepared in 2 types of the mixers.

The results of the compressive tests show that, all tested foam concrete compositions increased their compressive strength with age; see Figure 6. Similar to normal weight concrete, the rate of the strength development was greater within first 7 days and decreases gradually afterwards; see Figure 6. Foaming of the composition M-4-CD was affected by ineffectiveness of the protein based agent, and as result of that, volumetric proportion of the cement was considerably higher than other compositions. This resulted in higher rate of the strength development compared to other compositions containing more entrapped air and corresponding lower volumetric proportion of the cements.

In contrast to compressive strengths, certain rate of the degradation of the flexural strength of all tested specimens over age is evident; see Table 5. In the course of aging over time, the water in the foam
concrete evaporates due to drying. This leads to drying shrinkage among other adverse effects. Due to these and the highly porous structure of foam concrete, cracks may form in the inner pore microstructure [22, 23]. As a consequence, tensile and flexural behavior of foam concrete decreases, as confirmed by the advancement of flexural strengths of the measured foam concretes. It must be noted here that, all tested specimens have identical storing conditions, and density on the testing day vary in admissible deviation of 2-5 %.

Figure 6. Long term compressive strength development.

3.4 Water absorption

Density of the foam concrete influence rate of the water absorption, which is evident in Figure 7. For instance, composition M-3-CD with the lowest dry density exhibited highest water absorption of ca. 27% by volume. Results of the composition M-4-CD shows that decrease of the porosity and corresponding increase of the density implies reduction of the water absorption. This results underlines that production technique has also influence on the rate of the water absorption. It could be seen that the composition M-7-TM with lower density than compositions M-1-CD and M-2-CD has lower water absorption. These results are based on quality of pores effected by the production of the foam concrete using two different types of mixers. Thus, formation of pores by use of TM-Mixer has better influence on resistance against water absorption and associated durability of produced foam concrete.

Figure 7. Relationship dry density – water absorption, for foam concretes prepared in 2 types of mixers.

Conclusion
This study has shown that turbulence (colloidal) mixer and cavitation disintegrator can be applied for the production of the foam concretes with varying mechanical and physical properties. Obtained range
of the densities – 800 kg/m³ to 1500 kg/m³ – correspond to the 28 day compressive strength from 5 MPa to 45 MPa. The flexural strength of tested foam concretes tends to decrease with their age, potentially due to effects of drying shrinkage. This finding needs to be further examined by microscopic investigations with aim to describe and prevent the origins. The successful production of foam concrete following mixed-foaming method using CD- and TM-Mixer made it feasible to deliver foam concrete directly to the printhead of a 3D-printer. In addition, analyses of the achieved densities revealed beneficial influence of the flowability of the cement-based matrix on foam concrete properties. Considering this fact, subsequent addition of the accelerator after foaming of a flowable cement-based matrix need to be explored to meet requirement on the consistency of printable foam concretes presented in [7]. Water absorption measurements revealed the influence of used mixers and corresponding different foaming techniques on microstructure and pore distribution of foam concretes.

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