Impact of the pumping process on the properties of lightweight concrete

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Abstract. The distinctive characteristic of lightweight concrete lies in its combination of load-bearing and insulating properties. In order to produce this material using modern manufacturing processes such as spraying or printing, certain hurdles must be overcome. For example, a multi-component concrete has to be developed that is not only optimized concerning its rheological properties, but also takes into account the influence of the pumping process on its characteristics. Especially concerning the objective of a heat-insulating concrete, the pumping process has a decisive influence on the range of properties. For pumping applications, the system technology limits the largest grain size of the concrete mixture. This leads to very fine concretes or mortars, which react sensitively to the applied pressure. The occurring pressure-induced compaction leads to an increase in strength due to an increment in bulk density and the damage of lightweight aggregates. This, in turn, affects the thermal conductivity of the material. Based on a lightweight concrete developed at the Institute of Construction Materials at the University of Stuttgart, these challenges are highlighted and discussed in the following paper. The concrete was utilized for pumping and spraying experiments at a testing facility in collaboration with the Institute for System Dynamics, and the resulting thermal properties were examined at the Material Testing Institute, University of Stuttgart. Furthermore, the interaction between the employed system technology and the properties of the pumped lightweight concrete, such as consistency, strength, bulk density, and thermal conductivity was examined and analyzed. Results showed that the concrete properties reacted sensitively to different configuration setups of the pumping system and the conveyance line. Hence, a clear interdependency between the mix design and the employed machinery could be observed and has to be considered in future endeavours.

1. Introduction
Lightweight concrete has been utilized for construction worldwide since the early 1920s [1]. The peak for research and application in Germany was reached in the 1970s with gradual loss of importance due to the oil crisis and the associated price increases for energy, which is crucial for the production of lightweight aggregates [1]. In recent years, the material is experiencing a revival due to new development in concrete technology, which resulted in reduced weight and lowered thermal conductivity. The recently developed infra-lightweight concrete [2], [3] has a bulk density below 800 kg/m³ in contrast to ordinary lightweight concrete (between 800-2000 kg/m³ according to DIN EN 206).
At the Institute of Construction Materials, University of Stuttgart, lightweight concrete was developed for the so-called functionally graded concrete (FGC) technology [4]. Using concrete mixtures with different properties and arranging them in an optimized way to build up the inner structure of concrete components, results in fully stressed components with significantly reduced weight without loss of bearing capacity [4]. One possible execution of FGC is the placement of highly porous concrete in regions of low stress. The Institute for System Dynamics set up a prototype platform for automated construction of such FGC components [5]. However, the employed manufacturing techniques require pumping of the concrete mixtures either in a dry state or as wet-mix. This imposes additional challenges onto the development of the concrete mixtures.

Some aspects of pumping wet-mix concrete have already been investigated in scientific literature such as effects of mix design, modelling of the pressure distribution and particle velocity distribution during pumping [6], [7], dynamic segregation of concrete particles [8] and the build-up of a lubrication layer in the vicinity of the pipe’s wall [9]. Relations between the tribology of fresh concrete and pumpability [10] as well as its linkage to rheological properties are examined in [11].

In the scope of the FGC research, a pumpable concrete with a bulk density and thermal conductivity as close as possible to infra-lightweight concrete was pursued. Thus, a dry density of $\lambda_{\text{dry}} < 800 \text{ kg/m}^3$ combined with thermal conductivity of $\lambda_{\text{dry,10}} < 0.2 \text{ W/(m·K)}$ was the set target. A possible application for the developed concrete could be as an insulating layer in a multifunctional wall with a heat transfer coefficient below 0.21 W/(m²·K) in accordance with the German Energy Saving Ordinance EnEV [12]. To ensure that all the requirements were fulfilled, a thorough evaluation of all components had to be conducted. Especially the aggregates that were expected to be mainly affected by the pumping process due to their low compressive resistance were examined closely.

In section 2, the equipment for the pumping process is detailed. The design of a suitable lightweight concrete mixture in a laboratory environment is explained, followed by the challenging transfer to the experimental stage. A thorough analysis of the correlation between different pumping settings and the resulting concrete properties, such as bulk density, thermal conductivity, and compressive strength, is given in section 3. Section 4 contains the conclusion of the research.

2. Pumping of lightweight concrete

2.1. Experimental setup for pumping

Different types of pumps are available for wet-mix concrete. The most common type is the double cylinder concrete pump providing a large throughput. However, for small line pumping eccentric worm pumps can be employed. A coupled motor drives a single helix rotor element, which revolves eccentrically within a double helix stator element. Thereby, a continuous cavity is formed progressing towards the discharge end. The ascending slope of the helix in combination with other geometric design parameters determine the achievable throughput and maximum grain size for concrete pumping. An advantageous feature of these worm pumps is their continuous non-pulsing flow. For a given pressure and speed of rotation, accurate dosing of the concrete volume flow rate is achieved.

The employed eccentric worm pump for our experiments is depicted in figure 1 along with an illustration of its principle of operation. For this pump, WM Variojet FU produced by the Werner Mader GmbH, three different rotor/stator combinations are available (figure 1). The KP45 has a rotor diameter of 45 mm revolving inside a rubber stator with additional clamps for adjustable pre-load moments. The KP20+ has a rotor diameter of 20 mm and a different stator with a more wear resistant rubber material. A second version is called KP20w providing a water cooling system for the stator element to conduct upcoming heat due to friction. Different sized rubber hoses can be attached to the worm pump depending on the rotor size. We employed a Ø35 mm hose and a Ø50 mm hose for the 20 mm rotor and the 45 mm rotor respectively. Both hoses had a length of 10 m.
2.2. Design of lightweight concrete in a laboratory setup

For the first test phase, the primary aim was to use the highest possible volume-specific quantity of light aggregates. Different concrete compositions based on perlite, pumice, expanded glass and aerogel were investigated. Concrete mixtures with pumice resulted in the worst density of around 750 kg/m³ because pumice has a higher density compared to other used aggregate. Perlite and aerogel have a low compression strength due to low density, thus, making their application for pumpable concrete rather unlikely. Hence, combinations of different aggregates were experimented with next. The properties of the resulting mixtures are listed in table 1, and their structure is visualized in figure 2. A combination of aerogel and perlite achieved the lowest bulk density, followed closely by a mixture with aerogel and expanded glass. However, both mixtures provided such a low compressive strength that resulted in the destruction of their granular structure during pumping. The third mixture combining perlite with expanded glass could also be applied through pouring only. Solely, mixture MII_L,4 was suitable for pumping.

To ensure good pumpability, all cement-reduced lightweight concrete mixes were produced with a high fly ash content. Fly ash contributes to a constant increase in strength of concrete during curing due to the pozzolanic reaction. Its almost perfectly round shape and high fineness are also of benefit for higher packing density and smoother pumping.

Table 1. Lightweight concrete mixtures and their properties developed in the laboratory.

| Unit                          | MII_L,1 | MII_L,2 | MII_L,3 | MII_L,4 |
|-------------------------------|---------|---------|---------|---------|
| Aerogel V-%                   | -       | 45.0    | 53.0    | -       |
| Expended glass V-%            | 45.0    | -       | 15.0    | 65.0    |
| Perlite V-%                   | 22.0    | 22.0    | 32.0    | 35.0    |
| Binder V-%                    | 33.0    | 33.0    | 33.0    | 33.0    |
| Water-binder ratio -          | 0.650   | 0.720   | 0.660   | 0.650   |
| Air entrainment agent M-%     | 0.600   | 1.000   | 1.000   | -       |
| Bulk density kg/m³            | 596.0   | 475.0   | 481.0   | 618.0   |
| Thermal conductivity W/(m-K)  | 0.158   | 0.090   | 0.098   | 0.168   |
| Compressive strength N/mm²    | -       | 2.0     | 1.7     | 9.7     |
| Workability                   | Pouring | Pouring | Pouring | Pouring, pumping |

a related to binder
b oven-dry
2.3. Transfer from laboratory to experimental setup and challenges for pumping

The intended scope of application for our lightweight mixture imposes challenging demands on the concrete properties. Pumpability needs to be assured while dynamical segregation and bleeding have to be minimized. The smallest rotor/stator setup employed limits the maximum grain size to 4 mm. In the preliminary studies, starting from the lab developed lightweight concrete mixture MII L,4 different variations were studied in order to fulfil pumping demands. A stabilization agent was added for better flowability and reduced segregation. The proportions of other ingredients such as cement, fly ash, silica, superplasticizer, air entrainment agent, and water content, were varied. Moreover, different proportions of expanded glass with grain size ranging from 0.25 mm up to 4 mm were assessed. The different stages of the concrete mixture and the corresponding actions taken are illustrated in figure 3.

The final mixture v4.2 is composed of 62 V-% expanded glass and 38 V-% binder. It has a water binder ratio of 0.65 and contains 0.4 M-% air entrainment agent.

3. Evaluation

3.1. Bulk density

As specified in [13], bulk density, moisture content and temperature have a decisive influence on thermal conductivity. Moreover, materials with higher bulk density have generally higher compressive strength. Thus, bulk density proves to be a vital link for the assessment of pumped concrete. As observed in the preliminary pumping tests, lightweight aggregates are damaged during the conveying process. The components are compacted and the cement paste ingresses into the aggregates, which can impact the bulk density significantly. Thus, in-depth testing was conducted to analyze the influence of pumping equipment on concrete properties. Fresh lightweight concrete was pumped with all three available rotor/stator combinations (KP20+, KP20w, KP45) in two stages. First, no hose was attached in order to analyze the impact of the rotor/stator element on the fresh concrete. Second, matching
hoses were attached, and the pumping was repeated. After every step of conveying, specimens were fabricated. Subsequently, the samples were weighted directly after casting (table 2), as well as after stripping the forms, after the water bath and finally in the oven-dry state.

Utilizing the Ø35 hose, the largest contribution to the concrete’s compression could be attributed to the hose itself. In contrast, using the Ø50 hose, the rotor/stator element had a larger contribution to the compression. The KP20w had the least impact on grain fracturing compared to the other rotor/stator setups, leaving most of the largest grains undamaged (table 2).

| Table 2. Bulk density of fresh concrete during different stages of the conveying process and for different setups (percentage density increase in comparison to pre-pumping density). |
|-------------------------------------------------|
| **Bulk density pre-pumping [kg/m³]** | KP20+ & Ø35 | KP45 & Ø50 | KP20w & Ø35 |
|---------------------------------|-------------|-------------|-------------|
| Bulk density post-rotor [kg/m³] | 932 (+10.9%) | 924 (+15.4%) | 924 (+6.4%) |
| Bulk density post-hose [kg/m³]  | 1034 (+10.9%) | 1066 (+15.4%) | 983 (+6.4%) |
| Damage post-hose                |             |             |             |

3.2. Thermal conductivity

The main specification for the lightweight concrete mixture in the FGC project was low thermal conductivity as the material should perform as an insulating layer.

Thermal conductivity measurements were performed with a Transient Hot Bridge device (hereinafter THB device), which determines thermal transport properties of a material through the heating bridge method. Cube-shaped specimens with an edge length of 10 cm were produced, which were halved with a circular saw. The sensor of the THB device was placed for measurement between two specimen halves. Based on measured values for various lightweight concretes from [14] and [15], an approximate function was used to estimate the thermal conductivity of the material. The comparison between approximate and measured results can be found in table 3. It can be observed that the values for the post-pumping specimens are higher than for the pre-pumping ones. Hence, due to the correlation with bulk density, the main factor for the increase can be attributed to the pumping process.

| Table 3. Thermal conductivity for three specimens of different age and processing (increase in thermal conductivity compared to pre-pumping). |
|-------------------------------------------------|
| Specimen & age | Weight [-] | Bulk density, oven-dry [kg/m³] | Thermal conductivity, approximated [W/(m·K)] | Thermal conductivity, measured [W/(m·K)] |
|----------------|------------|----------------------------------|---------------------------------|----------------------------------|
| C1, pre-pumping, 7 days | 0.709 | 730.41 | 0.249 | 0.207 |
| C2, post-pumping, 7 days | 0.909 | 918.18 | 0.312 | 0.256 (+23%) |
| C3, post-pumping, 28 days | 0.919 | 947.53 | 0.324 | 0.274 (+32%) |

Additionally, testing was conducted at the Material Testing Institute University of Stuttgart. All specimens were older than 28 days at the time of measurements. Here, not only lightweight concrete
elements were examined but also scaled wall elements for a functional gradient wall (FCG). The FCG elements had an area of 200x200 mm and consisted of three layers 9 mm – 21 mm – 9 mm (see figure 4) with lightweight concrete being in the middle while normal concrete was used for outer shells. Thermal conductivity was measured in two-plates apparatus with a guarded hot plate at the average temperature of 10 °C. The tests were performed at dry specimens according to standard EN 12664. The results of thermal conductivity measurements are listed in table 4. Thermal conductivity of post-pumping specimens is almost 40 % higher than for the pre-pumping specimens. Moreover, the thermal conductivity of the FCG elements is 25 % lower than the estimated value (based on the calculation of thermal resistance). This may be attributed to the slight merging of both mixtures between the layers.

![Figure 4. Scaled sandwich wall element for testing of thermal conductivity properties.](image)

### Table 4. Thermal conductivity for scaled concrete elements.

| Element | Structure               | Thickness (specimen no.1 / no.2) [cm] | Density [kg/m³] | Thermal conductivity, measured [W/(m·K)] |
|---------|-------------------------|---------------------------------------|-----------------|----------------------------------------|
| W1      | MI-MII-MI               | 3.95 / 3.45                           | 1488            | 0.351                                  |
| W2      | MI                      | 2.85 / 2.83                           | 2030            | 1.045                                  |
| W3      | MII, post-pumping       | 2.71 / 2.71                           | 1021            | 0.247                                  |
| W4      | MII, pre-pumping        | 1.74 / 1.73                           | 758             | 0.177                                  |

### 3.3. Mechanical properties

Besides thermal conductivity, the increase in bulk density can also influence the mechanical properties of concrete. The specimens used for assessment of the bulk density were further investigated for mechanical properties. Flexural and compressive strength were determined according to DIN EN 12390-3 and DIN EN 12390-5 respectively.

Figure 5 shows a clear relation between compressive strength and bulk density due to the pumping process. While the rotor/stator element had a moderate effect on the compression strength resulting in an average increase of values by 20 %, the pumping through the hose nearly doubled them. For flexural strength, a similar effect can be observed.

### 3.4. Scope of application

For a theoretical application in a wall element with three layers of thickness 6 cm – 14 cm – 6 cm with lightweight concrete being in the centre, the following calculation was conducted to obtain the U-value with the values from table 4.

\[
U_{GrB} = \frac{1}{\frac{d_1}{\lambda_1} + \frac{d_2}{\lambda_2} + \frac{d_3}{\lambda_3} + R_{se}} = \frac{1}{0.13 + \frac{0.14}{0.247} + \frac{0.06}{1.045} + 0.04} = 1.17 \frac{W}{m^2\cdot K} \gg 0.21 \frac{W}{m^2\cdot K} = U_{EnEV} \tag{1}
\]
In order to achieve the required $U$-value of $U_{\text{EnEV}} = 0.21 \text{ W/(m}^2\cdot\text{K)}$ according to EnEV [12], the thermal conductivity coefficient for lightweight concrete using the same standard mix should not exceed $0.031 \text{ W/(m} \cdot \text{K)}$. This results from the following consideration:

\[ U = \frac{1}{R_T} \rightarrow R_{T,\text{EnEV}} = \frac{1}{U_{\text{EnEV}}} = 4.76, \tag{2} \]

\[ R_{T,\text{EnEV}} = R_{si} + \frac{d_1}{\lambda_1} + \frac{d_2}{\lambda_2} + R_{sc} \rightarrow \lambda_{1,\text{EnEV}} = \frac{d_1}{\lambda_{T,\text{EnEV}} - R_{si} - R_{sc}} \frac{d_2}{\lambda_2} = 0.031 \text{ W/m}\cdot\text{K}. \tag{3} \]

Equivalently, to reach the EnEV value $U_{\text{EnEV}} = 0.21 \text{ W/(m}^2\cdot\text{K)}$ with the tested materials, an increase in layer thickness could be considered. If the ratio between the layers is to stay the same, the following results can be expected:

\[ d_2 = \frac{3}{7} d_1 \tag{4} \]

\[ R_T = R_{si} + \frac{d_1}{\lambda_1} + 2 \frac{3}{7} \frac{d_1}{\lambda_2} + R_{sc} \tag{5} \]

\[ \rightarrow d_{1,\text{new}} = \frac{\lambda_1 \lambda_2 (R_T - R_{si} - R_{sc})}{6 \lambda_1 + \lambda_2} = 95 \text{ cm}, \quad d_{2,\text{new}} = 40 \text{ cm}, \tag{6} \]

\[ d_{T,\text{new}} = d_{1,\text{new}} + 2 d_{2,\text{new}} = 175 \text{ cm}. \tag{7} \]

However, more reasonable dimensions can be achieved only if the lightweight concrete is used for wall structures (compare table 5).
Table 5. Possible wall thicknesses in correlation with targeted U-values for outer walls constructed from lightweight concrete (*EnEV 2016; **EnEV 2014).

| Thermal conductivity | Target U-value | Wall thickness |
|----------------------|----------------|---------------|
| [W/(m·K)]            | [W/(m²·K)]     | [cm]          |
| 0.177 (pre-pumping)  | 0.21*          | 81            |
|                      | 0.28**         | 60            |
| 0.247 (post-pumping) | 0.21*          | 113           |
|                      | 0.28**         | 84            |

4. Conclusion
While lightweight concrete offers a range of challenges in the application through pumping, valuable knowledge could be obtained through development and examination of the material. More recent publications on lightweight concrete and pumping usually do not contain a range of bulk densities lower than 1500 kg/m³ [16], [17]. In that instance, a significant step in lowering bulk density could be obtained. Further improvement is to be expected by optimizing the utilized machinery like a specifically designed rotor/stator for lightweight concrete in combination with a suitably sized hose.

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