# LIGHTWEIGHT AGGREGATE CONCRETE WITH FOAMED BINDER MATRIX FOR SUSTAINABLE APPLICATIONS

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## Abstract

Low density load bearing structural concrete members with improved thermal insulation properties, composed of lightweight aggregate (LWA) and foam concrete is investigated, which expands the application range of lightweight structural materials. This study aims to characterize a lightweight aggregate concrete with a foamed cementitious matrix (LWAFC) through its physical properties (dry bulk density, thermal conductivity, compressive strength, and strain) and possible relationships especially linked to the densities. In the experimental studies, samples are prepared by two kinds of LWA with mineral foam with two differing cement mass contents. The resulting densities of the LWAFC in a dry state after 28 days ranged from 427 kg/m³ to 525 kg/m³. The results show that proper mineral foam content introduced into the LWA can greatly improve the thermal conductivity of the mixture. The compressive strength of the LWA used and the bond strength of the aggregate/cement foam in the interface region are important factors influencing the compressive strength of the LWAFC.
Keywords: Foam Concrete, Lightweight Aggregate, Insulation, Compressive Strength

## 1. INTRODUCTION

In order to reduce heating costs and thus lowering $CO_2$ emissions, the insulation of buildings is of high priority. To achieve an affordable and in terms of both recycling and construction requirements sensible insulant, a combination of construction and insulation material could be key to a long term solution. While due to its low strength, high tendency to shrinkage and very lightweight, pure mineral foam cannot be used as a construction material, lightweight aggregate concrete with a foamed matrix can be used [1]. Whenever combined with a stiff internal lightweight aggregate (LWA) based skeleton it might also have good insulation properties. This would allow for monolithic building techniques, which guarantee easy recycling and high fire safety [2].

Lightweight aggregates are widely used and can be easily incorporated into concrete or mortar to produce lightweight concrete with a wide range of densities [3][4]. Lightweight concrete (LWC) can be obtained by introducing gas or foam into the concrete cement paste, or by totally or partially replacing standard aggregate fractions with low weight components.

Combining the two materials to a lightweight aggregate foamed concrete (LWAFC) can give full advantage to both properties. Adopting cement foam with similar density to the LWA can make the material homogenous and will enhance the mechanical and building physics properties. For strength and strain, this means an even distribution throughout the concrete and

avoids discontinuities in the load transfer. This was also achieved by the backbone of the framework formed by the LWA, which was used as the basis for the mix designs. The density was kept low as this is favorable in general for construction materials. The lower the density, the lower the resulting mass, and therefore, easier transport of prefabricated components. There is also a clear correlation between low densities of construction materials and their corresponding heat transfer coefficient. Because one of the main goals is to achieve low heat transmission coefficients, a low density is of major importance (acc. with DIN EN 1520:2011).

In view of the various advantages mentioned above, in recent years there have been a large number of studies devoted to LWC and LWAFC. Current research mainly shows that the strength of LAC depends on the strength of the lightweight aggregate and the bond strength between the aggregate/cement paste, representing the interface area [6][7]. Furthermore, the interfacial strength of the LAC depends on the porosity of the LAs surface [8][9]. Ünal et al. found that there was a positive correlation between the thermal conductivity of LAC and the cement content [10]. Weighler and Karl produced LWAFC with a density and compressive strength in the range of 1200-1600 kg/m³ and 12-30 MPa, respectively [11]. Jummat et al. produced reinforced oil palm shell foamed concrete with a density of 1600 kg/m³ and compressive strength of about 20 MPa [12]. Hilal et al. compared the failure mechanism of foam concrete with/without LWA. They showed that LWA leads to an improved ductility of foam concrete [13]. Gilka-Bötzow et al. mentioned that the addition of foam will not only reduce the density, but also improve the thermal conductivity of open-structured lightweight aggregate concretes [14].

According to the above references, the reduction in density can improve the thermal insulation property of the material but adversely may affect the compressive strength as well. All studies have focused on materials with densities larger than 1000 kg/m³, however, materials with lower densities have not been studied. Therefore, the aim of this study was to develop a LWAFC with a target density just below 500 kg/m³ while maintaining a reasonable compressive strength and thermal conductivity. The mixtures were designed for two different cement contents and for two types of coarse aggregates. The cement content was varied because this is a practical way to achieve the target density of the foam (300 kg/m³) and slurry mix, while the different aggregates mainly differed in grain size and raw density. The cement content is also a controlling factor for the strength of the respective mix series which is, a major factor for the applicability of this construction material. In this study the concept of filling the voids between the LWA with lightweight foam concrete. The properties of LWA foamed concrete, including the compressive strength, stress-strain curves, and thermal conductivity were investigated.

## 2. MATERIALS AND METHODS

### 2.1 Raw materials

Materials used for this research included Portland cement (CEM I 42.5 R, Heidelberg Zement), hardening accelerator, a stabilizer on basis of melamine resin sulfonate, a shrinkage reducing agent based on a calcium-sulfo-aluminate for the cement paste. The foam was produced with a foaming agent made from hydrolyzed protein. As lightweight aggregate two kinds of expanded aggregate (2B and 2.9E from Liapor) were used, which have grain size range 4/10 and 2/6, respectively (see Figure 1). Fine aggregate (FA) in the form of expanded glass was added with two grain size ranges 0.25/0.5 and 0.5/1.0 (Poraver).

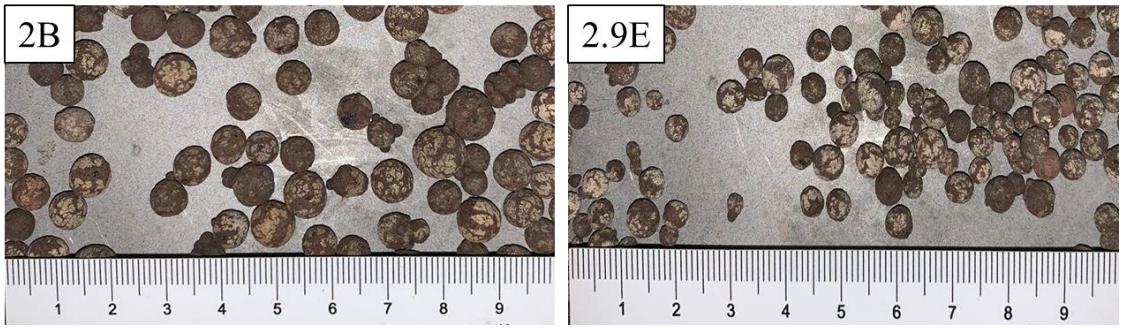


**Figure 1: Lightweight aggregate 2B and 2.9E**

## 2.2 Mix design

The mix design was calculated via volume ratios, depending on the pore space created by the coarse LWAs. In order to ensure good workability of fresh concrete, the water-to-binder-ratio (w/b) is determined to be 0.5. Based on the w/b, the volumetric percentage share for the sum of cement paste and foam was 74 % as a share of the created pore space volume (see Figure 2). The foam volume was oriented on the volume of cement and additives. Cement volume was calculated via known w/b and desired cement amount for 1 m³ of foamed concrete. The pre-foaming method was used to prepare the samples. The compositions of the different mix designs referring to the samples are listed in Table 1.

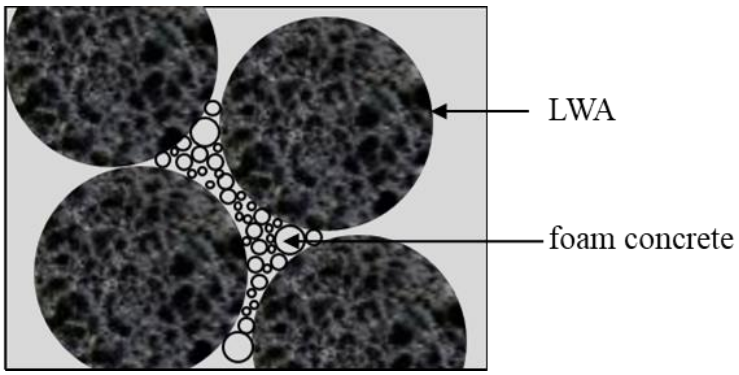


**Figure 2: Concept of mix design**

**Table 1: Mix Design**

| | LWA | FA (0.25/0.5) | FA (0.5/1.0) | water | cement | foam | hardening accelerator | stabilizing agent | shrinkage reducer |
|---|---|---|---|---|---|---|---|---|---|
| 2.9E200 | 290 | 35 | 25 | 100 | 200 | 12 | 2 | 2 | 4 |
| 2B200 | 225 | | | | | | | | |
| 2.9E180 | 290 | 35 | 25 | 90 | 180 | 12.4 | 1.8 | 1.8 | 3.6 |
| 2B180 | 225 | | | | | | | | |

Note: The unit of all values in the table is kg/m³.

### 2.3 Production procedure

The mixing sequence was as follows: Before starting any mixing procedure the aggregates (LWA and FA) were moistened to hinder them from destroying the foam or influencing the actual w/b ratio by absorbing water from the mix. The water and stabilizing agent were poured into a colloidal mixer and mixed at 20 Hz. Over the time of 120 s, the cement and solid additives were added and mixed for 60 s at 20 Hz and for another 90 s at 60 Hz. The cement slurry and fine aggregates were mixed thoroughly and the LWA was added and blended into the mortar. This ensures the wetting of the grains' surface area with slurry. The aqueous foam was produced to an aimed density using a foam generator. With a proportional mixer, the foam generator was adjusted to add 2.5 % foaming agent relative to the water. Compressed air flows into the fluid and the kinetic energy is converted to surface energy and subsequently produces foam. The mortar and foam were mixed until a homogenous mass was achieved. The prepared lightweight aggregate concrete with a foamed matrix was moulded and cured in the moulds for 14 days at 20 °C. After 14 days they were demoulded and wrapped in polyethylene foil and cured for another 14 days to obtain a total curing time of 28 days.

### 2.4 Experimental tests

The experimental program was designed to achieve a better understanding of the relation between compressive strength, density, cement proportion, and thermal conductivity. To be able to examine all the aforementioned parameters the testing program was comprised of compressive strength tests with additional directional recording, heat conductivity tests via transient plane heat source method in accordance with EN ISO 22007-2 and density measurements. The compressive strength tests were conducted with cubic samples with side lengths of 150 mm following the standards from EN 604. The loading rate was set as 20 N/s. The compressive strength tests were conducted for 3 samples per mixture to be able to approach the results statistically. The thermal conductivity tests were performed on samples with 150 mm side length and 80 mm height, which was conducted on a λ-Meter EP500e (guarded hot plate apparatus) in accordance with EN 12667.

## 3. RESULTS AND ANALYSIS

Figure 3 shows the stress-strain curves for the four mixtures and Figure 4 shows the damage of a sample from mix series 2.9E200 at each stage (A-D). Compared to ordinary concrete and foam concrete, it can be found that the stress-strain curve of LWAFC is closer to that of foam concrete. The curve for the compression process can be divided into four stages:

Stage I (O-A, strain approx. 0 % - 0.5 %): a slow increase in stress with the strain, which is caused by the homogeneous surface structure. The foam matrix on the sample surface is mostly composed of open pore (hemispheres). Therefore, the surface of the sample has a lower bearing capacity and is first crushed.

Stage II (A-B, strain approx. 0.5 % - 2.0 %): the strain continues to increase almost linear with the stress. Under the increased stress, the pores in the foam matrix are gradually compacted. The LW aggregates are displaced between layers, and the joint structure is then destroyed.

Stage III (B-C, strain approx. 2.0 % - 2.5 %): the strain increases oscillating with stress. In this stage, the stress reaches the maximum.

Stage IV (C-D, strain approx. > 2.5 %): the stress begins to decrease. The strain increases slightly until reaching a plateau.

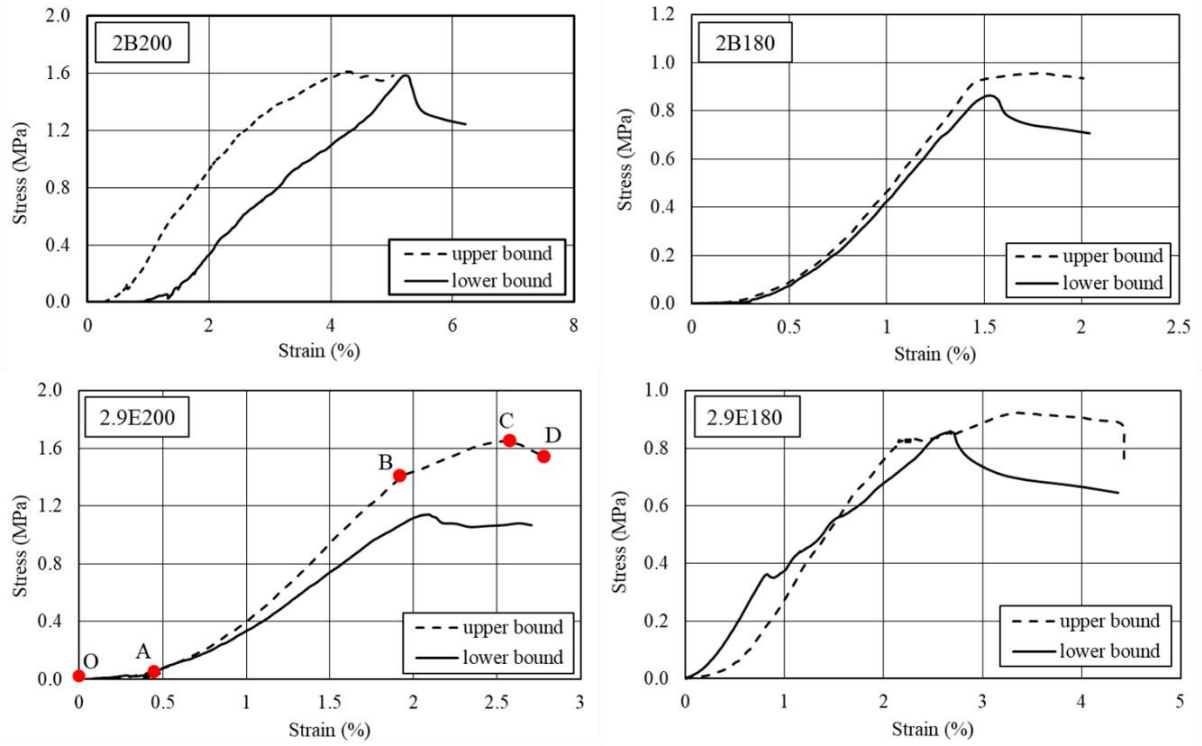


**Figure 3: stress-strain curve of LWAFCs**

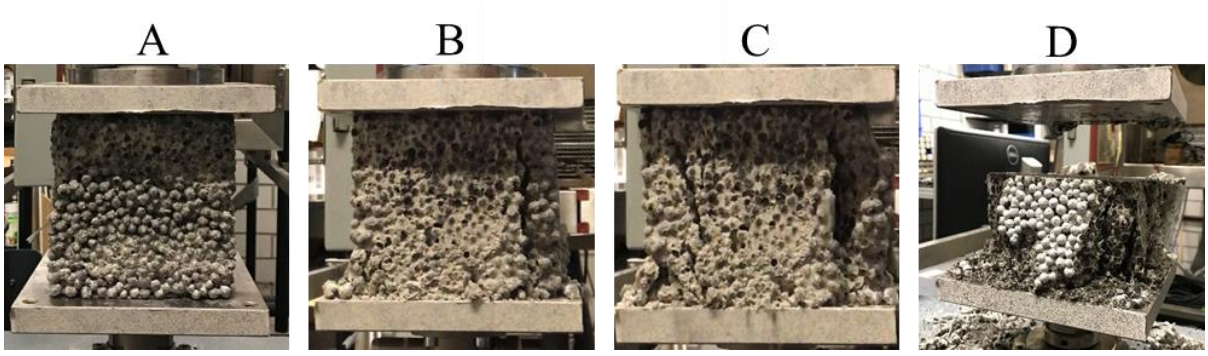


**Figure 4: compression fracture mechanism procedure of 2.9E200**

As can be seen from Figure 5, the dry bulk density of 2B200 and 2.9E200 is larger than 2B180 and 2.9E180, respectively, because the foam matrix of the former two contains more cement. In addition, the dry bulk density of 2B200 and 2B180 is lower than 2.9E200 and 2.9E180, respectively, which is due to the raw density of the given aggregates of 2B is lower at 420 kg/m³ than that of 2.9E with a raw density of 540 kg/m³.

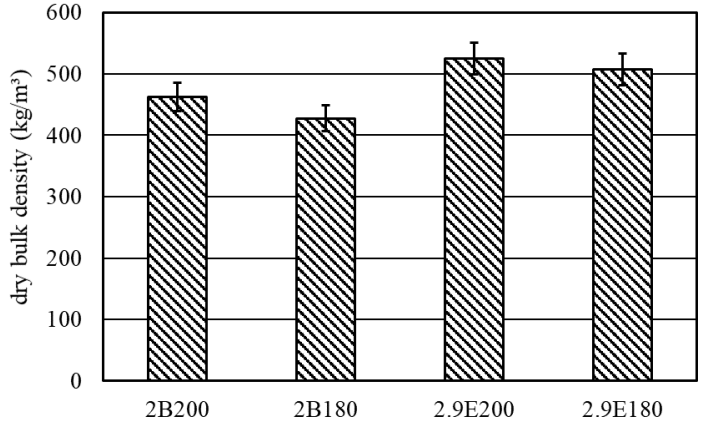


**Figure 5: dry bulk density of LWAFCs**

When comparing the compressive strength and thermal conductivity of the samples, the density of samples is normalized by the following equation, whereby the influence of the density is eliminated.

$$\sigma_i^* = \frac{\sigma_i}{\rho_a}\rho_i \quad (1)$$

In this equation, $\sigma_i^*$ is the density-non-normalized compressive strength of sample i, $\rho_i$ is the bulk dry density of sample i, and $\rho_a$ is the average bulk dry density of all samples. Similarly, the same processing is performed on the thermal conductivity.

$$\lambda_i^* = \frac{\lambda_i}{\rho_a}\rho_i \quad (2)$$

where, $\lambda_i^*$ is the density-non-normalized thermal conductivity of sample i.

From Figure 6, it can be seen that when the density is normalized, 2B200 and 2.9E200 have higher compressive strength, and the values of them are similar. The compressive strength of 2B180 is the lowest, however, it has the best thermal insulation property. In contrast, 2.9E200 and 2.9E180, which have a higher thermal conductivity. The comprehensive comparison of the thermal conductivity and the compressive strength 2B200 was superior to that of the other three.

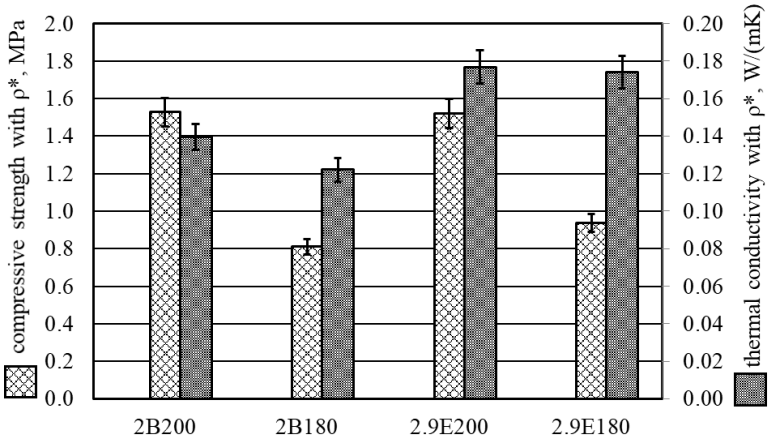


**Figure 6: compressive strength and thermal conductivity of LWAFCs with the same density**

Figure 7 shows the fracture surface of each sample after the compressive strength test. For samples 2B200 and 2.9E200, fractures occur in the LWA. However, for the samples 2B180 and 2.9E180 only a small amount of LWA cracked, which propagated along the weaker interfacial zone in the cement foam matrix. This is because the first two contain 200 kg/m³ cement, while the latter two contain 180 kg/m³ cement. The higher cement content means that the pore walls are firmer and pore structures are denser [14]. When a crack encounters LWAs, it is forced to propagate through them instead of extending around the aggregate-foam matrix interface.

By comparing the 2B200 and the 2.9E200, it can be found that there is more LWAs fracture in the 2B200. Since the interface toughness is lower than the LWAs, the larger the size of LWAs is, the more tortuous is the crack extension path, and the greater the energy is required to overcome the interfacial bonding. Therefore, for the sample containing lager aggregates (2B200), the compressive strength (1.53 MPa) is slightly higher than 2.9E200 (1.52 MPa). However, it is worth noting, that the 2.9E aggregate has a strength of 0.9 N/mm², while the 2B aggregate has strength only of 0.45 N/mm². When the fracture occurs, the strength of the aggregate plays a major role. Therefore, the difference in compressive strength between the two samples is not obvious.

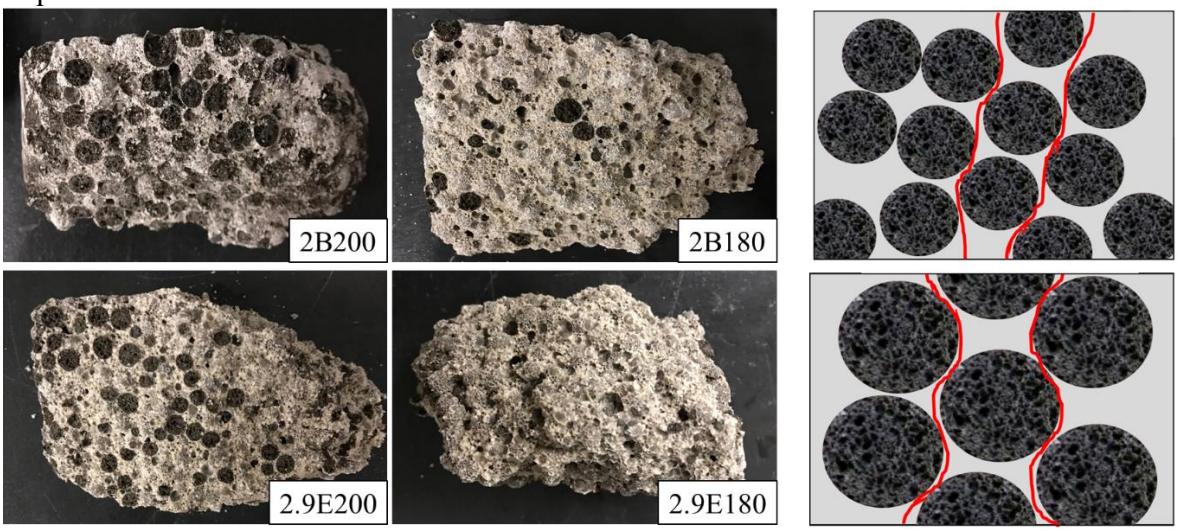


**Figure 7: fracture section of LWAFCs**

## 4. CONCLUSIONS

In this study, four different LWAFC mixes with two kinds of LWA were investigated. Their failure mechanism under compressive loading is evaluated and discussed in this study. The relationship between thermal conductivity and dry bulk density is determined. Based on the results and discussions, the following conclusions are drawn:

- Rather than the compressive strength of LWA, their size has a major role in the overall compressive strength of the tested mixtures;
- For higher cement contents, stronger bond strength of the interface developed. When the samples were subjected to compressive loading, cracks occurred mostly in the LWA;
- The higher the cement content of the mixtures, the stronger the bond strength between the interfaces.
- The LWAFC showed a good thermal insulation property with low thermal conductivity in the range of 0.13 W/(mK)-0.16 W/(mK).

## 5. OUTLOOK

In all the experimental process of this study, the temperature was kept constant (20°C) and the samples were dried for 28 days. However, it would be interesting to examine the weight in the range of temperatures (i.e. 10°C-60°C) and under various humidity conditions. The temperature could influence the thermal conductivity of samples and the stability of the pore structure in the foam matrix. The change in temperature also affects the moisture content in the pores. The optimal balance between these parameters will be the aim of new research in order to effectively improve the performance of the material. This would also mirror more practical orientated conditions and give better insight into actual application possibilities.

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