Development of High Performance Aerogel Concrete (HPAC) and statistical evaluation of compressive strength for practical use in construction

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Abstract. The Institute for Structural Concrete (ISC) at the University of Duisburg-Essen and the Institute of Materials Research of the German Aerospace Center (DLR) developed a new lightweight concrete, called “High Performance Aerogel Concrete” (HPAC). HPAC is made by embedding of silica aerogel granules in a high strength cement matrix. It exhibits a remarkable relation between compressive strength and thermal conductivity. HPAC for the load bearing layer of double-leaf external walls contains approx. 50 vol% aerogel and has a compressive strength in the range of normal concrete (20 MPa – 30 MPa). Up to now, the compressive strength of each mixture was determined on three to six cubes or cylinders. The scattering of the results has not been investigated yet. For this reason, 30 test specimens of a 50 vol%-mixture have been produced in two batches. The results of the compressive strength tests were then statistically evaluated. The underlying statistical distribution was determined by the Anderson-Darling-Test. Subsequently the 5 % fractile values of the mixtures, which represent the characteristic concrete compressive strength, were determined.

1. Cause and purpose
Single-leaf exterior walls must fulfill the requirements of both load-bearing capacity (a compressive strength as high as possible) as well as sound and heat insulation. Normal concrete (NC) meets the requirements for the load-bearing capacity, but due to its density of 2.4 kg/dm³, it has a very high thermal conductivity of λ ≈ 2.5 W/(mK). Therefore, single-leaf external walls made of reinforced normal concrete cannot be constructed without further measures, e.g., the application of a thermal insulation composite system (ETICS) or the design as a double-leaf wall with core insulation. Due to disadvantages regarding design and construction associated with ETICS, conventional structural lightweight aggregate concretes (LWAC) were discussed as an alternative in the past. The thermal conductivities of LWAC are in the range of 0.40 ≤ λ ≤ 1.35 W/(mK), resulting in required wall thicknesses of ≥ 0.50 m. Thus, the aim of the research project was to develop an optimized high-performance aerogel concrete with a significantly more favorable ratio between compressive strength and thermal conductivity.

2. Development of High-Performance Aerogel Concrete (HPAC)
The first investigations on the suitability of silica aerogel granules as an aggregate for concrete were conducted by Ratke [1]. The noteworthy properties of the developed aerogel concrete are the low thermal conductivity, the high sound absorption, and the fulfillment of the fire protection requirements (fire resistance class > R120). However, the corresponding compressive strength and modulus of elasticity were too low for the use as an exterior wall construction material. For this reason, in [2 - 4] silica aerogel granules were embedded in a high strength matrix to achieve a higher compressive strength.
with limited success. At the ISC, many investigations have been undertaken to develop a HPAC with a significantly favorable relation between compressive strength and thermal conductivity. For this purpose, different aggregates, cements, additives, and admixtures were investigated. Thus, a HPAC with 50 vol% aerogel, 13% silica content, 3.5% superplasticizer content, 0.5% stabilizer and a w/c ratio of 0.24 was developed.

2.1. Building physical properties of HPAC
For the determination of the thermal conductivity, a heat flow meter (NETZSCH HFM 436 Lambda) was used. The thermal conductivity of a LWAC, a HPAC and a NC mixture was investigated. Comparing the LWAC and the HPAC, the HPAC achieved a thermal conductivity of $\lambda = 0.26$ that is approx. 25.7% lower as the LWAC’s thermal conductivity by the same density. The material-specific absorption coefficient $\mu$ was selected to evaluate the sound absorption capacity of the aerogel concretes. Thereby $\mu$ was determined by a test setup, which is based on a tube of impedance, specially developed by the DLR. HPAC with 50 vol% aerogel content showed a sound absorption capacity of $\mu = 0.309$, which was about 38% better than normal-weight concrete (cf. [5]). In addition, the water absorption of HPAC was determined according to [6] as well as the water vapor permeability according to [7]. The concrete mixtures investigated showed a very low capillary water absorption capacity. All three HPAC mixtures investigated were classified as water repellent ($W_w = 0.02-0.1 \leq 0.5$ [kg/m²·h⁰.⁵]) in contrast to NC or LWAC. The investigations on the water vapor diffusion showed that HPAC can be classified as vapor retarder ($S_v = 0.25$ m – 2 m) (cf. [8]). To investigate the durability, the carbonation depth was determined on concrete prisms. After 267 days, a carbonation depth of 1 mm was measured (see [5]).  

2.2. Mechanical Properties of HPAC
The Young's modulus is determined in accordance with [9] using cylindrical specimens. The resulting fracture pattern at the end of the Young's modulus test shows agreement with the fracture pattern from [10]. The modulus of elasticity of the mixture with 50 vol% aerogel content was about 8000-10,000 MPa and is comparable to LWAC with the same bulk density. To classify the tensile strength, the flexural tensile strength was determined in experimental investigations and converted into a centric tensile strength in the same way as for LWAC. The centric tensile strength determined in this way is approximately 5-10% of the compressive strength. The compressive strength tests were carried out on a 3 MN two-column compression testing machine according to [9]. For this purpose, cubes with an edge length of 150 mm were produced as test specimens. The results have shown a correlation of bulk density and compressive strength which can be described in an exponential function (cf. [11]).

\[ f_{lcm,cube150} = 0.37 \cdot e^{0.0034\rho} \]  

(1)

3. Statistical Evaluation of HPAC with 50 vol% aerogel content

3.1. Experimental Evaluation of HPAC
Compressive strength is one of the most important properties for materials used in exterior walls. For the practical use of HPAC in construction, the compressive strength must therefore be evaluated statistically. For this reason, 30 test specimens have been produced in two batches. Subsequently, the compressive strength tests of the 30 specimens were carried out as mentioned in par. 2.2.

3.2. Results of the experimental evaluations
The mean value of the determined compressive strength is 25.1 MPa as well as 27.0 MPa for batch 1 and 23.2 MPa for batch 2, respectively. The mean value of the corresponding dry bulk density of all specimens is 1440 kg/m³ as well as 1400 kg/m³ for batch 1 and 1440 kg/m³ for batch 2.

3.3. Statistical evaluation of HPAC
The Anderson-Darling test was used to check whether the data are normally distributed. The statistical program R [12] was applied for this purpose. Subsequently, the data was tested for a Weibull
distribution, and the Akaike information criterion (AIC) value for both distributions was ascertained (Weibull: 160.3 normal: 164.5). The lower AIC value shows that the Weibull distribution fits better than the Normal distribution. Hereafter, the 5% fractile was determined considering the Weibull distribution, resulting in a value of 19.2 MPa. The following graph shows the test data and the Normal and the Weibull distribution, as well.

![Graph showing test data and Normal and Weibull distribution](https://example.com/graph.png)

**Figure 1.** Compressive Strength, Normal distribution, and Weibull distribution.

### 4. Conclusion

Compressive strength is the most important property for the characterization of as a construction material. For practical building applications, the data from experimental tests were statistically evaluated and the 5% fractile value was ascertained. The average compressive strength of the investigated mixture is 25.1 MPa and the corresponding characteristic compressive strength is 19.2 MPa.

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