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Development of High Performance Aerogel Concrete

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Abstract

Current massive wall-building materials can be characterized by having either low thermal conductivities and thus low bulk densities and low compression strength or high compressions strength, high bulk densities and high thermal conductivities. In this paper, the first results of a research project are presented, in which a new aerogel-based construction material is developed that exhibits extra ordinary heat-insulating and load-carrying properties. By embedding silica aerogel granules in a high strength cement matrix "High Performance Aerogel Concrete" is developed, which combines the benefits of conventional concrete (compressive strength, unlimited moldability) with the properties of a heat insulating material. So far, various mixtures were examined in terms of their compressive strength and thermal conductivity. The first results are very promising with compressive strength between 3.0 MPa and 23.6 MPa and thermal conductivities between 0.16 W/(mK) and 0.37 W/(mK).

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1. Introduction

Since the beginning of the millennium the requirements for the thermal insulation of residential and non-residential buildings have led to a number of developments in the field of building materials for massive outer walls. To fulfil the requirements of national regulations resulting from the EU-directive on the energy performance of buildings [1] for the heat transfer coefficient (such as the U-value in the German Energy Saving Ordinance 2014 [2]), only masonry blocks with low bulk density can be used for single-leaf walls. The thermal conductivities of such

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heat insulation masonry are in the range $\lambda = 0.06$ W/(mK) to $\lambda = 0.16$ W/(mK) (Table 1, lines 1-6), so that in general wall thicknesses between 36.5 cm and 49 cm are necessary to achieve the required U-values.

Table 1. Bulk densities, thermal conductivities and compressive strength of selected massive wall-building materials.

	Material	ρ (kg/m³)	f_k / $f_{(l)ck}$ (MPa)	λ (W/(mK))
1	Light-weight Concrete Block Bisomark Hbn [3]	315-335	0.8	0.06
2	Aerated Cement Block Ytong PP 1,6-0,25 [4]	250	0.8	0.07
3	Poroton Brick S9-MW [5]	810-900	4.2	0.09
4	Aerated Cement Block Ytong PP 2-0,40 [4]	400	1.8	0.10
5	Light-weight Concrete Block Bisoplan 14 [3]	600	2.5	0.14
6	Poroton Plane Brick T16 [5]	710-800	4.7	0.16
7	Sand-lime Brick Silka KS L-R P 12-1,4 [6]	1210-1400	5.6	0.56-0.70
8	Light-weight Aggregate Concrete LC35/38 [6]	1500-1600	35.0	0.89-1.00
9	Sand-lime Brick Silka KS-R P 20-2,0 [6]	1810-2000	10.5	0.99-1.10
10	Normalweight Concrete C12/15 [7]	2200-2400	12.0	1.65-2.0
11	Reinforced Concrete C30/37 [7]	2300-2400	30.0	2.3-2.5

As it is apparent from Table 1, the characteristic compressive strength of these materials, which are optimized in respect of a low thermal conductivity, is in the range $f_k \leq 4.7$ MPa. Therefore multi-storey buildings cannot be erected with these materials even if the wall thickness is high. Thus, if a higher compressive strength is required (Table 1, lines 7-11), typically an exterior wall construction without additional insulation is no longer feasible due to the higher densities and the associated higher thermal conductivities. In most cases, a load bearing layer of normal weight concrete, lightweight aggregate concrete or sand-lime bricks with an external thermal insulation system or with core insulation and facing layer (cavity wall) is implemented in this case.

In this paper, the first results of a research project are presented, in which “High Performance Aerogel Concrete” is developed by embedding silica aerogel granules in a high-strength cement matrix, which combines the benefits of conventional concrete (high compressive strength, any formability) and the properties of a thermal insulation material. The aim is to develop a building material, which exceeds significantly at comparable thermal conductivities, the compressive strength of conventional insulation masonry and thus is suitable for the construction of single-leaf exterior walls of multi-storey buildings without any further thermal insulation.

2. State of research

The idea of embedding silica aerogel granules in a cement matrix was first reported in [8]. Here, mainly superhydrophobic silica aerogel granule with a particle size from 0.01 mm to 4.0 mm, a porosity > 90% and a particle density 120 kg/m³ to 150 kg/m³ was used, which was added to normal-strength mixtures of CEM II 32.5 R, CEM I 42.5R and CEM I 52.5R. The amount of aerogel was varied between 50 and 75 percent by volume so that aerogel concretes with densities $580 \text{ kg/m}^3 \leq \rho \leq 1050 \text{ kg/m}^3$ were produced. The results of the experiments show the excellent physical properties of this new construction material. With an uniform distribution of 70 percent by volume of aerogel a thermal conductivity of $\lambda = 0.10$ W/(mK) was measured. Thus, the aerogel concrete has a thermal conductivity that is comparable to that of heat insulation masonry (Table 1, lines 1-6). The compressive strength determined on prisms with 50 mm edge length were in the range $0.6 \leq f_{cm} \leq 1.5$ MPa, well below the compressive strength of the building materials listed in Table 1. The modulus of elasticity deduced from the results of the compressive strength tests were between 52 MPa and 127 MPa.

In [9] silica aerogel was embedded in a matrix of Ultra High Performance Concrete (UHPC), which is not described in more detail, in order to increase the compression strength of aerogel concrete. The measured thermal conductivity varied between $\lambda = 0.06$ W/(mK) for mixtures with a bulk density $\rho \leq 400$ kg/m³ and $\lambda = 0.10$ W/(mK) for mixtures with a bulk density of 570 kg/m³. The compressive strength were ascertained to $1.4 \leq f_{cm} \leq 2.5$ MPa for mixtures with bulk densities in the range $500 \text{ kg/m}^3 \leq \rho \leq 620 \text{ kg/m}^3$, so that in principle the intended positive effect of an UHPC matrix on the compressive strength could be observed. The compressive strength of aerogel concrete with $\rho \leq 400$ kg/m³ was not investigated. The further results of the investigations in [9] showed that aerogel concrete has a low modulus of elasticity (E_{cm} = 1100 MPa), a high frost resistance, low coefficient of thermal expansion ($5.3 \cdot 10^{-6}$ 1/K), a high tendency to shrink (2.2 mm/m) and a very low bond stress (0.95 N/mm at a slip of 0.02 mm at a rebar diameter of 8 mm).

The compressive strength, the flexural tensile strength and the thermal conductivity of aerogel concrete were also investigated in [10]. For the mixtures investigated hydrophobic aerogel granules with a particle size of 2-4 mm, CEM I 52,5R, silica fume, superplasticizer, natural sand and distilled water were used. The aerogel fraction varied between 0 and 60 percent by volume, which lead to bulk densities in the range $1000 \text{ kg/m}^3 \leq \rho \leq 2300 \text{ kg/m}^3$. For the most interesting mixture with an amount of 60 percent by volume of aerogel granules, the results were $\lambda = 0.26$ W/(mK), f_c = 8.3 MPa (prisms with 40 mm edge length) and $f_{c,fl}$ = 1.2 MPa. Similar numerical relations were found between thermal conductivity and density as well as compression strength and density (see par. 3.4).

Thus far, aerogel concrete shows extraordinary physical properties, but the low modulus of elasticity, the high tendency to shrink, the low bond stress and particularly the compressive strength, which still is below the compressive strength of brick or lightweight concrete masonry with similar thermal conductivities (Table 1 = characteristic values), preclude the application of aerogel concrete for load-bearing walls of multi storey buildings.

3. Development of an High Performance Aerogel Concrete

Based on the concrete mixtures of High Performance Concrete (HPC), Ultra-high Performance Concrete (UHPC) and Lightweight Concrete (LC) mixtures for aerogel concrete are developed in this research project. The developed aerogel concrete should provide an extraordinary heat-insulating property while showing a sufficient load bearing capacity similar to a conventional concrete. By embedding at least 60 Vol.-% of silica aerogel granules the aerogel concrete exhibits the required extraordinary thermal insulation properties.

The composition of the individual components of the aerogel concrete is influenced by the known mixtures of HPC, UHPC and LC. The components which are investigated are shown in the following list:

- Portland cement
- Microsilica (suspension and powder)
- Different aggregates
- Quartz sand
- Concrete liquefier
- Stabilizer
- Aerogel
- Water

The investigated mixtures out of these components are illustrated in the following chapter 3.1.

3.1. Optimizing mixtures for aerogel concrete

The first mixtures were based on HPC concrete formulas [11]. The focus of this investigation lied on the cement matrix influenced by silica aerogel granules. An uniform distribution of between 60 and 70 percent by volume of silica aerogel granules was chosen. By embedding 70 percent by volume of silica aerogel granules in a cement matrix the bulk density and the tested compressive strength were minor compared to conventional concrete. The compressive strength could be increased by reducing the percentage of silica aerogel granules to the chosen minimum 60 percent of volume of silica aerogel granules.

Subsequently the influence of the above mentioned additives has been investigated. Therefore 25 mixtures (prismatic test specimen) were analysed with the aim to improve the compressive strength. The concentrations of additives, concrete liquefier, microsilica and Portland cement were varied. Hereafter the most suitable mixtures were optimized further on. For this purpose concrete cubes with an edge length of 15 cm according to German standards [12] were tested. The following chapters refer to the optimized mixtures which are named M1 up to M13.

3.2. Storage of aerogel concrete

Another important aspect for the development of the compressive strength of an aerogel concrete is the type of storage. In the scope of testing three types of storage have been used. The first is dry storage at an ambient air temperature of 20 °C±2 °C, the second one is a mixed storage consisting of six days storage in a water bath at a water temperature of 20 °C±2 °C and a dry storage at an ambient air temperature of 20 °C±2 °C for the following 12 days according to EN 12390-2 [13]. In [14] the positive effects on the compressive strength of heat treatment of HPC are discussed. Therefore the concrete cubes were also stored in the drying cabinet for 24 hours at a concrete age of 24 hours as recommended in [14]. All concrete cubes have been stripped at a concrete age of 24 hours before using the three different types of storage (heat treatment, dry storage, mix storage).

The investigation of three concrete cubes was necessary for each mixture and each kind of storage. Furthermore the specimens have been tested at a concrete age of seven days and 28 days according to [12]. Thus, 18 concrete cubes have been manufactured for each mixture in total.

3.3. Investigation of the concrete temperature during hydration

To investigate the heat treatment as well as the hydration heat of the aerogel concrete, the temperature was measured during the hydration process by placing a temperature sensor in the core of a concrete cube. For each mixture three temperatures have been measured in view of the used three types of storage (Fig. 1).

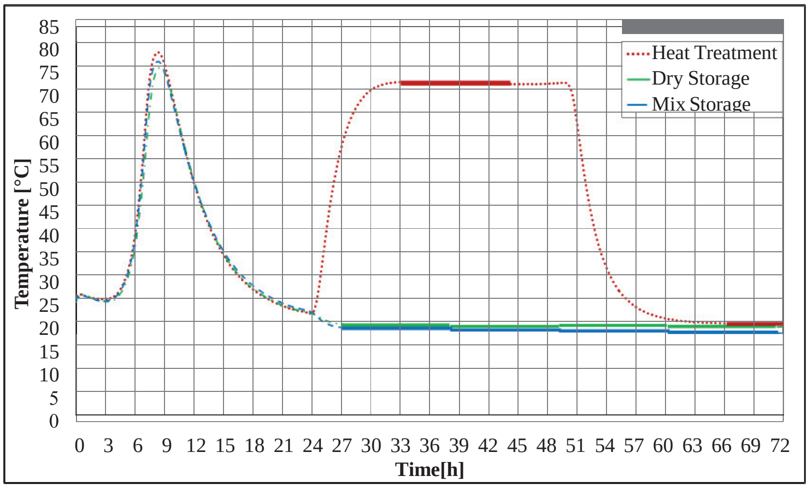

Fig. 1. Temperature curve of mixture M10

During the first hours a significant rise in the core temperature could be observed. After five to eight hours the maximum temperature was achieved. The high core temperature depends on the high cement content and the addition of silica fume (i.e. [15]). The three temperature curves drop not as rapidly as they rise. The core temperature was between 20 °C and 25 °C after 26 h for the mixtures M1 to M13 regardless their maximum temperature. During this period, the ambient air temperature and the water temperature was kept between 20 °C and 25 °C. Thus it can be assumed that the hydration process has completed after approximately 26 hours.

The heat treatment of the concrete cubes is also shown in Fig. 1. The drying cabinet provides an ambient temperature between 84 °C and 93 °C. The core temperature of the concrete cubes reached a maximum of 75 °C. The influence on the compressive strength by the chosen heat treatment can be estimated as negligible (see par. 3.4).

3.4. Compressive strength of the developed mixtures

The results of the strength tests and the related dry bulk densities are shown table 2.

Table 2. Compressive strength ($f_{cm,cube,150}$) of the optimized mixtures after 28 days (7 days)

Mixture	M8	M5	M7	M1	M10	M9	M6	M12	M2	M11	M3	M4	M13
Dry bulk density ρ [kg/m³]	730	750	810	850	860	880	940	1010	1015	1050	1070	1130	1170
Dry Storage: f_{cm} [MPa]	3.1	6.2	7.9	7.4	8.9	9.9	9.8	13.0	11.5	15.3	13.8	17.1	21.1
Heat Treatment: f_{cm} [MPa]	3.0	6.6	7.2	7.8	10.0	9.5	9.2	12.0	12.7	16.3	12.8	12.7	23.6
Mix Storage: f_{cm} [MPa]	3.7	7.3	7.9	8.4	9.3	9.2	10.1	11.7	13.9	16.5	12.7	15.8	23.1
Mix Storage: $f_{cm,7\ Days}$ [MPa]	3.7	5.6	7.4	8.1	8.9	6.6	7.7	11.6	10.3	14.5	10.9	16.2	19.2

Most of the mixtures achieved the highest compressive strength by using the mix type of storage. The early heat treatment did not lead to a significantly higher compressive strength. Regarding the relation between the compressive strength at concrete ages of seven days and 28 days no clear trend could be observed.

A further important aspect, which has been discovered in the scope of testing, is the correlation between the dry bulk density and the compressive strength. The compressive strength for the 13 mixtures by using mix storage is shown in Fig. 2. For this purpose, a linear regression analysis was performed. The coefficient of determination was calculated to a value of 0.93 which shows a high correlation between the bulk density and the compressive strength. In [16] the compressive strength of porous bodies can be calculated as a function of the bulk density. In this case the values ρ_0 and σ_{cr}^0 of the employed Portland Cement have been used.

$$\sigma_{cr} = 0{,}2 \cdot \sigma_{cr}^0 \cdot (\rho / \rho_0)^{(3/2)} \qquad (1)$$

Regarding the investigations of aerogel concrete in [8] the factor 3/2 in the equation should be replaced by 0.75. Both functions are represented in Fig. 2. In the experimental investigations of the Institute of Structural Concrete (ISC) most of the optimized mixtures achieved a higher compressive strength than expected according to equation (1) regarding [8] and [10].

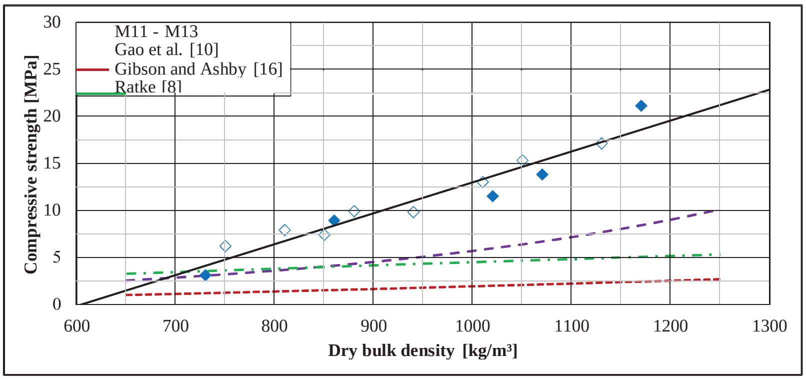

Fig. 2. Compressive strength at a concrete age of 28 days of 13 mixtures in relation to the dry bulk density

3.5. Investigation of the thermal conductivity of selected mixtures

The thermal conductivity was determined for some of the mixtures (M5, M8, M9-M13) with the Transient Hot Bridge (THB) measurement principle. The results of the ISC and the results of [10] are shown in Fig. 3. A correlation between thermal conductivity and compressive strength becomes obvious. For both studies the thermal conductivity rises with an increase of the compressive strength (as well as the dry bulk density). The test results represented in [10] stretch across compressive strength between 8 MPa and 62 MPa with corresponding thermal conductivities between 0.26 W/(mK) and 1.9 W/(mK) while the currently determined values for compressive strength and thermal conductivity are located in a range between 6 MPa and 23 MPa as well as 0.17 W/(mK) to 0.37 W/(mK). This means that the scope of testing at the ISC delivered smaller values for the thermal conductivity – which imply a better heat insulating property – at a comparable compressive strength.

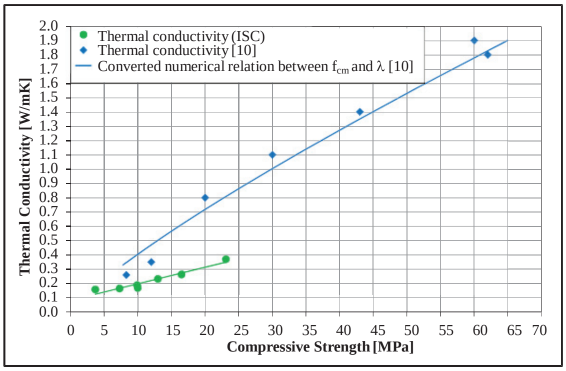

Fig. 3. Correlation between compressive strength and thermal conductivity

4. Conclusions

Based on concrete formulas of HPC, UHPC and LC an aerogel concrete was optimized at the ISC with the goal to increase the compressive strength while maintaining good heat insulating properties.

Three types of storage have been investigated. The influence of a heat treatment on the compressive strength is negligible. The concrete core reached up to 80 °C during the hydration process depending on the cement and silica fume content. The hydration process was completed after approximately 26 hours.

The compressive strength reached values up to 23.6 MPa and increased with bulk density. No trend can be identified for the difference of compressive strength between seven and 28 days. The thermal conductivities are in the range $0.16 \leq \lambda \leq 0.37$ W/(mK) representing good insulating properties. The most suitable mixture achieved a compressive strength of 10 MPa, a density of 860 kg/m³ and a thermal conductivity of 0.17 W/(mK). Compared to heat insulation masonry, the developed High Performance Aerogel Concrete achieves higher compressive strength at comparable thermal conductivities.

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