Thermal behaviour of autoclaved aerated concrete exposed to fire

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ABSTRACT

The reaction to fire of autoclaved aerated concrete (AAC) has been investigated at multiple dimensional scales. Changes in the chemical composition were detected and analysed by means of thermal analysis methods. Then, the thermal conductivity after different heat treatments was measured at different temperatures ranging from 120 °C to 720 °C. Finally, the evolution of temperature in an AAC wall exposed to the standard fire of ISO 834 has been monitored by built-in temperature sensors. The results hereof were used as input for a transient and non-linear numerical model which has been set up to predict temperatures at different depths of the wall. Measured and calculated results have been compared and discussed.

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1. Introduction

Autoclaved aerated concrete (AAC) is a load bearing building material with a low density due to its higher porosity compared to other load bearing building materials. By varying production parameters, AAC can be produced in a wide variety of densities in the range of 93–1800 kg/m^3 [1,2] whereas its constituent particle density is around 2600 kg/m^3. In other words 30–90% of its volume consists of pores [3]. Consequently, at low densities AAC reaches a low thermal conductivity that is an advantage in terms of thermal insulation at ambient temperatures as well as an asset for resistance against fire. The lighter weight implies a better sustainability too assuming the benefit for less material outweighs potentially higher energy costs for production, which together with non-combustibility [4] represent additional assets of this material in the building industry. Since the mechanical strength of this material decreases as the density decreases, optimisation for the intended application is required. A recent review of AAC [1] gives only a short account of the fire-resisting properties of this material and refers to a study made half a century ago [5]. Most of the published studies deal with the mechanical performance of different type of AAC and investigate methods to enhance it [4–7]. Recently, Andreini et al. [8] have investigated the mechanical behaviour of masonry materials including AAC at fire temperatures without going into the details of the thermo-physical properties and their change with temperature. The constituent materials of AAC are lime, gypsum, finely dispersed aluminium, cement and sand (SiO$_2$). Its structure is similar to that of Tobermorite with water molecules absorbed between crystallographic planes [9]. For an ACC of 530 kg/m^3 a typical raw composition of 67% sand, 19% cement, 10% hydrated lime and finally 4% gypsum (anhydrite) has been reported [8]. The present research investigates the thermo-physical properties of AAC subjected to fire at different dimensional scales. Hereby, thermal analysis methods, fire tests and transient numerical simulations complemented each other in enabling a general view and providing a plausible explanation of the observed behaviour.

2. Experimental

2.1. Material

About 60 AAC bricks with dimensions 125 × 250 × 625 mm and an initial density of 600 kg/m^3 were supplied by the producer. After drying for 33 days at 110 °C the resulting dry density was about 480 kg/m^3. Out of these bricks, a wall was made for investigating fire resistance. Some of the remaining bricks were further kept in a climatic chamber at 25 °C and 50% rel. humidity for a period of several years. From these bricks, powder samples were extracted for the X-ray diffraction (XRD), Differential Scanning Calorimetry (DSC) and Thermogravimetric Analysis (TGA) measurements. Sample blocks of dimensions 250 × 250 × 40 mm were also cut for thermal conductivity measurements after having them exposed to heat treatments at different temperatures. The pore

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structure of the investigated material, seen by naked eye and by microscopy, is shown in Fig. 1. According to the above-mentioned recent review [1], the pore structure of AAC comprises at least two types of pores. The large ones are visible by naked eye and known as "air pores" with radii between 0.1 and 1.5 mm, depending on the pore-forming agent, but undetectable by mercury intrusion porosimetry. The smaller ones are integrated in the skeletal material with radii in the region of 5–80 nm [10]. For an apparent density of ρ_a = 480 kg/m³, a volume fraction of air pores of around 58% of the total volume has been reported by Schober [10]. Laurent and Guerre-Chaley [11] mention a total porosity φ_{total} = 83% for an AAC of 425 kg/m³, where 58% has been attributed to the air pores. Yet another similar value has been reported by Kadashevic et al. [3], with a 53% air-pore fraction and an apparent density of 485 kg/m³, and the pure (particle) density of AAC ρ_p = 2632 kg/m³ resulting in a total porosity of 82%.

For the material investigated here, with ρ_a = 480 kg/m³, the total porosity is estimated as P = 81% according to Eq. (1) (ignoring the mass of air in the pores).

$$\varphi_{total} = \left(1 - \frac{\rho_a}{\rho_p}\right) \cdot 100\% \tag{1}$$

2.2. X-ray diffraction XRD

The crystalline phase assemblage was determined by qualitative X-ray diffraction analysis (XRD). About 4 g of the sample were ground by hand to a particle size of below 63 μm using an agate mortar. X-ray diffraction was performed using a PANalytical X'Pert Pro MPD diffractometer in a θ–2θ configuration using Cobalt Kα radiation with a fixed divergence slit size of 0.5° and a rotating sample stage. The samples were scanned between 5° and 90° 2θ with the X'Celerator detector.

2.3. Thermal analysis

The heat-absorption/desorption behaviour due to the heat capacity $C_{p,sam}(T)$ [J/(g K)] and the transition enthalpies $\Delta H_p(T_o)$ (J/mol) of pulverized AAC sample with respect to the temperature was monitored using a Netzsch DSC 404 C Pegasus differential scanning calorimeter (DSC). Initially a 62.060 mg of pristine pulverized AAC sample was heated under a synthetic air atmosphere (50 ml/min) in a covered Pt crucible at a rate of 15 °C/min from 30 °C up to 900 °C. The run was repeated three times for the same sample body, the weight change of which was monitored using an external balance after each measurement.

The measurement signal recorded in the DSC is the voltage difference between two thermocouples, one being placed under the sample crucible and the other under an identical but empty reference crucible under the same temperature and atmospheric conditions. The observable $C_{p,sam}(T)$ and $\Delta H(T_o)$ can then be calculated using the raw data recorded from a sample (sam) material, standard (std) material with known $C_p(T)$ (sapphire) and an empty sample crucible (base) applying the ratio method as stated in Eq. (2) according to ASTME 1269:

$$C_{p,sam} = C_{p,std} * [(DSC_{sam} - DSC_{base}) * m_{std}]/[(DSC_{std} - DSC_{base}) * m_{sam}], \tag{2}$$

where $C_{p,i}$ = heat capacities and m_i = masses of sample and standard. The DSC_i = recorded voltage signals of the measurements from empty sample crucible, sample and standard.

To complement the DSC observations, the mass-loss behaviour was monitored by TGA using a Netzsch STA 409 CD thermobalance. A 109.17 mg sample of pulverized AAC was heated under a synthetic air atmosphere (50 ml/min) in an Al₂O₃ crucible at a rate of 15 °C/min from 40 °C up to 1000 °C. The described approach enables us to distinguish between the physical and chemical transitions (reactions), as the DSC peaks produced by the changes in the chemical composition are typically accompanied by a weight gain or loss – due to absorption or desorption of volatile species – while the purely physical transitions are visible only in the DSC signal.

2.4. Thermal conductivity measurements

The thermal conductivities measured at ambient temperature were obtained using a Heat Flow Meter (HFM) apparatus with a single sample configuration in a stable chamber. The temperature gradient over the sample was 10 K with an average temperature around 20 °C and the sample dimensions being 250 × 250 × 40 mm. The first measurement was carried out on the sample taken from the chamber at 25 °C and 50% rel. humidity. For further measurements the sample was treated successively at 120 °C, 320 °C, 420 °C, 620 °C and 720 °C for 4 h at each step. In between the treatments, the sample was taken out and cooled down in the chamber where its thermal conductivity was determined at 20 °C. For measurements at elevated temperatures, a special Guarded Hot Plate GHP TITAN has been used with a symmetric sample configuration. This apparatus was able to go up to 400 °C to determine the thermal conductivity under an air atmosphere. These measurements were carried out at ZAE (Bavarian Centre for Energy Research) in Würzburg Germany.

2.5. Fire testing

Experiments were carried out on a vertical oil fired furnace at Empa (Swiss Federal Laboratories for Materials Science and Technology). The interior dimensions of the furnace were 3.0 × 3.0 × 1.5 m and the internal volume was 13.5 m³. The furnace temperature was computer controlled by furnace
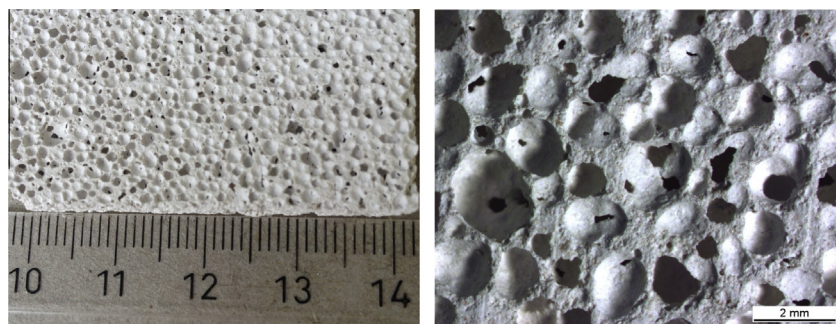

Fig. 1. The pore structure of the investigated AAC samples, seen by naked eye (left) and microscopy (right).