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Three-phase-foams for foam concrete application

Christina Krämer, Matthias Schauerte, Torsten L. Kowald, Reinhard H.F. Trettin

Universität Siegen, Institut für Bau- und Werkstoffchemie, Paul-Bonatz-Str. 9-11, Siegen, Germany

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ABSTRACT

Minerally bound foams are used throughout in the building industry for their combination of load bearing capacity and thermal insulation. Nowadays this can be achieved by lightweight concretes, especially with aerated and foam concretes. Blocks made of aerated concrete as well as prefabricated components are well-known. Typically the mechanical properties are enhanced by autoclaved treatment and thus result in high energy consumption. Also, the production of aerated concretes is factory based due to stationary autoclaves and the components are limited in their dimensions. Another category of mineral foams are foam concretes. They are produced by mixing a mortar and aqueous tensides or protein foam. The problem in production is to get a controlled and homogeneous air entry and thin, high strength borders surrounding the air pores. The latter has to be achieved on the basis of a dense packing of the materials within the borders. On a laboratory scale, significantly enhanced foam stability could be achieved and the most stable samples showed no destabilizing effects. The improved handling, workability and reproducibility of the modified foam are also leading to an increased reproducibility of the foam concrete quality. The study of the influence of three-phase-foams on microstructure, phase development and mechanical properties of lightweight concrete will be shown and explained.

1. Introduction

Over the last years lightweight materials play an ever increasing role and are no longer considered as niche products. They can be found in all material classes like metals, ceramics, plastics or composite materials. Natural or industrial lightweight aggregates in inorganic binding materials like concrete lead to a reduced density [1]. Other concepts for lightweight materials are a variation of production or inclusion of cavities. Creating cavities can be carried out by stabilization of air pores within the materials. Thereby the density of the materials will be reduced. Examples for these materials are lightweight concretes with densities between 800 kg/m^3 and 2000 kg/m^3 [2]. But also densities below 800 kg/m^3 down to 500 kg/m^3 are possible [3].

Two types of lightweight concretes are known in the building industry. The low density of aerated concrete is achieved chemically and foamed concrete is produced by physical foaming [4]. In the case of aerated concrete cavities are formed by the formation of hydrogen, resulting from the reaction of aluminum powder to aluminum hydroxide due to the high pH value of cement paste. In a second step an energy-intensive autoclaving process is necessary for strength-increasing. This type of production is suitable for prefabrication only and impedes on-site usage. In the case of foam concrete foaming agents are used for the preparation of foams that are mixed with the fresh concrete. By using superplasticizer and UHPC (ultra-high performance concrete) formulations the performance of foam concrete can be increased such that they are comparable or even better than aerated concrete. Because no special curing is needed a cheaper, more flexible and location-independent production is possible [5].

The challenges for foam concrete are not only the low density and weight, but also the ratio of the density to the needed mechanical properties, e.g., compressive strength. In addition, the pore structure has to be homogeneous with respect to the pore sizes to avoid the formation of gradients. Therefore, the setting time of the binding material and the stability of the incorporated foam must be considered. Also, particle sizes of the used binding materials and aggregates need to be small enough to reduce sedimentation and prevent the foam from destabilizing effects. These effects strongly influence the materials properties of the resulting foam concrete.

Typical targets of material developments are material and cost savings with respect to the production and energy saving through low weight. Of special interest are the advantageous properties of lightweight concretes. Material- and cost saving, high strength combined with low weight, and thermal or noise insulation are some examples of these. One main focus is placed on the reduction of CO$_2$ emission and high costs due to air conditioning of buildings. 40% of the European energy consumption belongs to the climate control of buildings [6]. The main goal for the development of construction materials must be the reduction of energy in the material production process, the ease of use in the construction itself, as well as in the use of buildings. An increased porosity of concrete leads to substantial material savings and decreased thermal- and noise conductivity. The adaption of the material properties to the demands of buildings can prevent a substantial loss of heat [6].

The new approach is to use three-phase-foams instead of wet foams based on surfactants or proteins and water for the production of foam

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E-mail address: kraemer@chemie.uni-siegen.de (C. Krämer).

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concrete. Gonzenbach et al. were the first group, which reported a simple method for the preparation of high-volume particle-stabilized foams with low densities. Thereby, metalloid or metal based nanoparticles are introduced in the water–air-interface (continuous–disperse-interface) caused by sorption of surfactants on the particle surface which results in partial hydrophobation. Functionalizing the surface groups of the solid oxides and functional groups of the surfactants at a specific pH value leads to van der Waals interaction between the surfactants and solid surfaces. This interaction increases foam stability due to reduced destabilizing effects like Ostwald-ripening, coalescence and drainage [7–10]. Three-phase-foams are made with a concentrated water-based dispersion that has to be prepared first. Therefore, the measurement of the isoelectric point (IEP) and adaption of the individual components are essential. The sorption of protonated or deprotonated agent and particle dispersion takes place after mixing. The air entrainment is done by a mechanical foaming process using a continuous dynamic stirrer which disperses gas in the fluid [11].

One advantage of three-phase-foams is the reduction of destabilizing effects compared to two-phase-foams. Previous investigations showed that three-phase-foams were always more stable than foams without nanoparticles using the same surfactant concentrations. The loss of continuous phase after 30 min was more than two times higher in case of two-phase-foams. A further advantage is the possibility to incorporate pozzolanic active nanomaterials into the borders. In this way, nanosilica can lead to a strengthening of the borders in foam concrete by a reaction with $Ca(OH)_2$ formed during the cement hydration. The so-called pozzolanic reaction leads to the formation of mostly X-ray amorphous calcium silicate hydrates (C–S–H) with the general formula $(CaO)_x{\cdot}SiO_2{\cdot}(H_2O)_y$ [12]. Since the pozzolanic reactivity of SiO_2 strongly depends on the specific surface area nanostructured SiO_2 shows higher reactivity compared to coarser SiO_2-based materials [13]. Also, the incorporation of three-phase-foams in cement paste to produce foam concrete shows a method to stabilize the pores and control the pore size distribution in the achieved lightweight concrete.

2. Experimental section

2.1. Materials

2.1.1. Cement

The cement used, CEM I 52.5 R, has a low C_3A content, low water demand and moderate heat development. It also has a high sulfate resistance and low alkali content (HS/NA cement).

2.1.2. Nanoparticles

The nanoparticles used were AEROSIL® 90 (NS) and AEROSIL® MOX 80 (MO) (Evonik). NS is a hydrophilic fumed silica with a specific surface area of 104 ± 10 m^2/g determined by gas adsorption and MO is a co-fumed oxide consisting of silicon dioxide and approximately 1% aluminum oxide with 88 ± 9 m^2/g. The particle size of NS is 20 nm and MO has a particle size of 30 nm as specified by the manufacturer.

2.1.3. Surface active agents

As surfactant TEGO Betain F 50 (Evonik) was used. According to IUPAC cocamidopropyl betaine is also known as *N*-(carboxymethyl)-*N*,*N*-dimethyl-3-[(1-oxododecyl)amino]-1-propanaminium ($C_{19}H_{38}N_2O_3$).

2.2. Specimen preparation

2.2.1. Water-based dispersions

Dispersions containing 30% w/w MO or 35% w/w NS were prepared considering the minimum of zeta potential at pH 10. At this pH level, the zeta potential is far away from the isoelectric point (IEP) and the highest repulsion of the particles is reached to avoid agglomeration. The MO, respectively NS powder was successively added to deionized water, continuously stirred and dispersed by an ultrasonic finger (Dr. Hielscher GmbH, UP 200 s, sonotrode diameter 2.5 mm, cycle: 0.5; amplitude: 90%). Every 10 min the pH was controlled with a pH-meter and adjusted by 2 M NaOH.

2.2.2. Foaming of nano-stabilized foams

The surface active agents were added to the dispersions, homogenized for 30–90 s and foamed simultaneously. The foaming was induced with a continuous dynamic stirrer (Hobart).

2.2.3. Production of foam concrete

For the production of foam concrete the most stable three-phase-foams consisting of NS and 60 mmol/L betaine (NS B) or MO and 10 mmol/L betaine (MO B) were used. NS B and MO B were chosen because of the assumption that these foams will also lead to the most stable pore system in the foam concrete. At first, betaine was added to the dispersions, 30–90 s homogenized and foamed simultaneously. While foaming the dispersions, cement paste was mixed followed by stirring in the prepared foam into the cement paste. A W/C-ratio of 0.5 was chosen to ensure good workability of the mix given that the nanoparticles have a high water demand. A foam content of 45% v/v and superplasticizer content of 0.25% w/w was used for foam concrete preparation. For further investigations three prisms (40 mm · 40 mm · 160 mm) were produced for performance evaluation based on curing time. The resulting six samples for each mixture were mechanically tested.

2.2.4. Storage and shaping of foam concrete

The norm prisms were stored at 20 °C and 98% relative air humidity for 7 and 28 d (days). De-molding of the prisms took place after 1 d. Finally, the mechanical properties were examined and the tested samples were taken for studies of microstructure and phase development.

3. Results

3.1. Study of microstructure

3.1.1. Pore size distribution

With the help of light microscopy, the pore size distribution of the respective foams was determined immediately after foaming. For the measurement of the foam concrete samples, polished sections were prepared. A comparison of the results of the incorporated three-phase-foams and the resulting foam concretes was done to determine the influence of the air pore size distribution of the foams on the produced foam concretes. The incorporated three-phase-foam NS B had air pore radii between 50 and 500 μm in which 70% had pore radii of 50–300 μm. The foam MO B showed a more narrow size distribution with 98% of the air pore radii in a range of 30–300 μm. The averages of pore radii of the foams were 234 μm for NS B and 118 μm for MO B. The air pore radii of the foam concretes based on NS B (FC NS B) were between 60 and 250 μm and those of the foam concretes based on MO B (FC MO B) were between 75 and 220 μm. Averages of pore radii were 172 μm for FC NS B and 152 μm for FC MO B. Thus, the air pore radii of the foams NS B were 26% bigger and the MO B foams were 29% smaller compared to the resulting foam concretes.

3.1.2. Morphology and pore structure

The investigations by scanning electron microscopy provided results of the microstructure with respect to the homogeneity of the pore size distribution, pore constitution and morphology of hydration products. The examination was done at the fracture mirror of the samples. The foam concretes based on NS B had a very inhomogeneous pore structure with respect to the pore size distribution (Fig. 1, upper left). The pore surfaces are mainly intact but some pores were destroyed due to the thin lamellae and destabilizing effects like Ostwald-ripening which can be seen as small cracks in the pore surface. At the inner pore surface, a layer can be seen which was built during hydration (Fig. 1, upper right). The borders showed a dense structure caused by the formation of hydration products with low porosity (Fig. 1, bottom left and right). The hydration