Construction and Building Materials 189 (2018) 314–322

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

The influence of different concrete additions on the properties of lightweight concrete evaluated using experimental and numerical approaches

Sang-Yeop Chung [a], Mohamed Abd Elrahman [a,b,*], Dietmar Stephan [a], Paul H. Kamm [c]

[a] Building Materials and Construction Chemistry, Technische Universität Berlin, Gustav-Meyer-Allee 25, 13355 Berlin, Germany
[b] Structural Engineering Department, Mansoura University, Elgomhouria St., Mansoura City 35516, Egypt
[c] Institute of Applied Materials, Helmholtz Centre Berlin, Hahn-Meitner-Platz 1, 14109 Berlin, Germany

HIGHLIGHTS

- The effects of different concrete additions on the performance of lightweight concrete were examined.
- Micro-CT was used to examine microstructural characteristics with the material properties being measured.
- The used supplementary materials can improve the performance of lightweight concrete.

ARTICLE INFO

Article history:
Received 16 May 2018
Received in revised form 24 August 2018
Accepted 28 August 2018

Keywords:
Lightweight concrete
Concrete addition
Filler
μ-CT
Compressive strength
Thermal conductivity

ABSTRACT

Lightweight concrete is a building material used for better insulation and lower energy consumption. The material properties of lightweight concrete, such as compressive strength and thermal conductivity, are strongly affected by the characteristics of its aggregate, binder, and other concrete additions. This study aims to investigate the effects of different concrete additions on the performance of lightweight concrete. Six different materials were used as concrete additions: limestone powder, expanded clay (Liapor®), fine fly ash, fly ash, and fine and normal sand. For lightweight concrete specimens, expanded glass granulate, i.e., Liaver®, was used as a lightweight aggregate to clarify the effects of concrete addition type, with all specimens designed so as to have a density between 800 and 950 kg/m^3. The effects of different concrete additions on the characteristics and properties of lightweight concrete were investigated using several approaches; X-ray micro-computed tomography (μ-CT) was adopted to examine microstructural characteristics, with both the mechanical and thermal properties of the materials being measured using experimental tools. Numerical analysis was also conducted to validate the performance of the materials. The results show that supplementary materials can improve the performance of lightweight concrete with regard to both compressive strength and thermal conductivity.

1. Introduction

Concrete is the most widely used construction materials in the world. There are several types of concrete in use, including structural lightweight concrete, shrinkage-compensating concrete, and heavyweight concrete for radiation shielding [1,2]. Lightweight concrete is widely used as a supplementary building material due to its low density and effective insulation [3–6]. Since environmental matters, such as the recycling of industrial waste and enhancing energy efficiency, have become worldwide issues, sustainable development is desirable in engineering fields, including construction industry. For this purpose, many efforts to reduce energy consumption and save energy in the construction industry and building material field have been undertaken in recent years; lightweight concrete is considered to be one of the most important building materials which can contribute to the development of sustainable materials.

In general, lightweight concrete is produced by using natural or artificial lightweight aggregates instead of normal aggregates. Various materials have been studied and used as lightweight aggregates in developing advanced lightweight concrete with better material properties. For instance, expanded clay [7] or

* Corresponding author at: Building Materials and Construction Chemistry, Technische Universität Berlin, Gustav-Meyer-Allee 25, 13355 Berlin, Germany.
E-mail address: mohattia76@gmail.com (M.A. Elrahman).

https://doi.org/10.1016/j.conbuildmat.2018.08.189
0950-0618/

recycled materials, such as expanded glass [8], masonry rubble [9], and crushed glass [10], have been used as lightweight aggregates, and concrete materials with these lightweight aggregates have shown better insulation performance than conventional concrete. Lightweight aggregates generally occupy more than 50% of the concrete volume; therefore, it is important to use appropriate aggregates to achieve the target performance of concrete materials [11–14].

However, although the rest of the concrete volume is filled with a binder (or matrix) material, relatively less attention has been paid to the binder of lightweight concrete, despite its importance. For concrete binder, ordinary Portland cement (OPC) is the most common and essential material, with more than 4.2 billion tons of OPC being consumed annually in the construction industry; therefore, OPC is an essential element in lightweight concrete. Nevertheless, it is well known that the production of cement is considered to be one of the major sources of CO_2 emissions, and a huge amount of energy is needed to produce OPC, in comparison to the other fundamental components of concrete [15,16]. To reduce the disadvantages of using cement, the use of supplementary cementitious materials (SCM) as concrete addition is considered to be a promising approach, and several studies have been conducted in relation to the SCMs of lightweight concrete. Zhang et al. [17] investigated the sulfate attack resistance of concrete with different binders by using ground granulated blast furnace slag (GGBS), and Diquelou et al. [18] used hemp and lime as a binder to enhance the mechanical performance of lightweight concrete. Real and Bogas [19] evaluated the oxygen permeability of lightweight concrete with fly ash, silica fume, and lime filler, and Real et al. [20] also performed the chloride migration test of lightweight concrete with different binders. Yu et al. [13] used polypropylene fibers to enhance the material properties of lightweight concrete, and Fu et al. [21] demonstrated the effects of different binders using epoxy for porous concrete. Shafigh et al. [22] examined the engineering properties of lightweight aggregates containing limestone powder as well as fly ash and found that the use of limestone powder can improve the compressive strength of lightweight concrete. In particular, Mo et al. [23] and Farahani et al. [24] investigated and summarized the effect of different binder materials on concrete properties. Most of these studies were concerned only with lightweight concrete with a density above 1600 kg/m^3, which is a relatively high density for structural lightweight concrete based on the European standard (EN) [25].

The main objective of this study is to produce and investigate the effects of concrete fillers on the performance of lightweight concrete with a low density. According to EN 206-1 [25], lightweight concrete for use as a structural component should have a density between 800 and 2000 kg/m^3. Here, lightweight concrete specimens with a density less than 1000 kg/m^3 were produced, thus satisfying the standards of structural lightweight concrete. To investigate the effects of filler type on the performance of lightweight concrete, the following supplementary materials were used and compared: limestone powder, Liapor® sand, fine fly ash, fly ash, and fine sand. A lightweight concrete sample with normal sand was also produced as a reference. In all cases, an expanded glass granulate, Liaver®, was used as a lightweight aggregate, only to compare the filler effect on lightweight concrete; the volume of lightweight aggregates was equally fixed in all specimens. Lightweight concrete is generally used for both structural and insulation purposes, and appropriate mechanical and thermal properties are required for the material. Here, the compressive strength and thermal conductivity of the lightweight concrete specimens with different additions were measured using Toni Technik (Germany) and Hot Disk (Sweden) devices, which satisfy European [26] and ISO [27] standards, respectively. The microstructures of the specimens were visualized using micro-level computed tomography (μ-CT). In addition, virtual specimens with the same mix proportions as the real lightweight concrete specimens were generated, and their numerical properties were evaluated using finite element (FE) analysis and compared with the experimental results. With the obtained results, the effectiveness of each supplementary material is discussed, and the proper material is proposed in accordance with the purpose of use.

2. Lightweight concrete specimens with different materials

2.1. Materials

In this study, several concrete mixes with different compositions were prepared and tested. The used cement was CEM III A 42.5 N complying with EN 197-1 which was provided by HeidelbergCement (Germany). Condensed silica fume, provided by Sika Germany which satisfies EN 13263-1, was used to enhance the fresh and the hardened properties of lightweight concrete. To investigate the effects of different additions, several materials, such as limestone powder (sh minerals, Germany), fine fly ash (Baumineral, Germany), class C fly ash, and fine quartz sand (Sand-schulz, Germany), were used for the specimens. In addition, normal sand and lightweight expanded clay (Liapor® sand) were used to compare their performance with other materials. Table 1 presents the physical properties of the used materials, and their particle size distribution is shown in Fig. 1.

To compare the effects of different concrete additions, other conditions besides the concrete additions need to be fixed. For this purpose, Liaver®-expanded glass-was utilized as a lightweight aggregate for all specimens. Liaver® is made of recycled glass, and its granules are sintered in a rotary kiln between 750 and 900 °C [28]. This material has an almost round shape and a smooth surface with numerous closed pores included in the material. Liaver® was used as a coarse aggregate with three different fractions: 0.5–1.0, 1.0–2.0, and 2–4 mm. The measured properties of the used aggregate are presented in Table 2. In this table, the crushing resistance of the material was provided by the manufacturer, while the other properties, such as particle density and water absorption, were measured according to EN 1097-6 [29]; the data in the table was also adopted for the numerical simulation presented in Section 3.

2.2. Design method of the specimens

This study focused on producing lightweight concrete with a density range between 800 and 1000 kg/m^3, which is the lowest dry density (D1, 0) lightweight concrete which can be used in structural elements according to EN 206. The mix design and the grading of aggregate fractions were adopted from [30,31]. Six different mixes of lightweight concrete were manufactured and tested. All mixes had the same composition, and the only difference is the addition type. The volumetric content of the concrete addition was kept constant (57 l/m^3), and the material type was changed only to evaluate its influence on the concrete properties. Table 3 shows the detailed mix composition of all the mixes. The lightweight concrete specimens with different additions (binders) are denoted here as follows: limestone powder mix (LS), Liapor® mix (LP), fine fly ash mix (FFA), fly ash mix (FA), fine sand mix (FS), and normal sand mix (NS). The water/binder was set to 0.4 for all the mixes, and only the cement and silica fume contents were taken into account when calculating the water content. All mixes had a planned consistency class of F4 according to EN 206-1. To achieve this consistency, an ether-based polycarboxylic superplasticizer, provided by Sika Germany (Sika Viscocrete 1051) with a density of 1.04 g/cm^3, was used. One of the main problems of producing lightweight concrete with a low density is the possible segregation resulting from the large difference between the density of lightweight aggregates and cement paste. To avoid this problem, a viscosity modifying admixture provided by Sika was used (Sika stabilizer, type 10160317). The water absorption of lightweight aggregate is also a significant factor which needs to be considered in relation to mix proportions. As can be seen in Table 2, the water absorption of lightweight concrete is about 15% (wt), which is much higher than that of normal aggregates and can affect workability significantly. In general, two different mixing methods are used for taking into account the water absorption of lightweight aggregate: either presoaking of aggregate for a certain period or adding an equal amount of absorbed water to the mixer. In this study, an amount of water, which equals the absorbed water by aggregates in one hour, was added to the mixer with the original mixing water.

2.3. Preparation of lightweight concrete specimens

To produce the lightweight concrete, a mixer with a capacity of 60 l was used to mix the concrete. All mixes were prepared with the same mixing procedure. First, the aggregates and the binder materials were mixed in the mixer for one minute. Water was then added, and stabilizer and superplasticizer were adjusted to achieve the required consistency without segregation or bleeding. After measuring the consistency, cubical molds $100 \times 100 \times 100$ mm^3 were filled with concrete and stored in controlled conditions at a temperature of 21 °C and a humidity of 95%. The samples were demolded after 24 h and cured under water until the testing day. Several