Construction and Building Materials 116 (2016) 422–430

Contents lists available at ScienceDirect

Construction and Building Materials

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

Green lightweight cementitious composite incorporating aerogels and fly ash cenospheres – Mechanical and thermal insulating properties

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HIGHLIGHTS

- Ultra-lightweight cementitious composite was developed using aerogel and FAC.
- Both aerogel and FAC significantly reduce the density of resulting composites.
- Excellent thermal insulation properties and specific strength values are achieved.

ARTICLE INFO

Article history:
Received 28 November 2015
Received in revised form 10 April 2016
Accepted 26 April 2016
Available online 9 May 2016

Keywords:
Aerogel
Fly ash cenosphere
Lightweight
Cementitious composite
Thermal conductivity
Sustainable development

ABSTRACT

The research focused on the development of an ultra-lightweight cementitious composite with both excellent mechanical and thermal insulating properties. Fly ash cenosphere (FAC), and aerogel, a nano-structured highly porous material made of silica, were used as lightweight aggregates. Polyvinyl alcohol fibers were used to improve the mechanical behavior of the cementitious composite. The experimental results showed higher specific strength (up to 18 kPa/kg m^{-3}) of the resulting composites as compared to conventional lightweight materials. Depending on the amount of FAC and aerogel, the compressive and flexural strengths of the cementitious composite were found as 23.54–18.63 MPa and 4.94–3.66 MPa, respectively, while the thermal conductivity was reduced to 0.3197 W/m-K. Moreover, the hydration products and microstructures of the FAC/aerogel modified cementitious composite were investigated by the Scanning Electron Microscopy and Energy Dispersive X-ray Spectroscopy (EDS). Thermal stability of the hardened matrix was studied by using thermo-gravimetric analyses and it was revealed that the composites were fairly stable at a high temperature range. The weight loss varied with increasing aerogel content. In conclusion, both FAC and aerogel are excellent candidates for producing mechanically strong as well as thermally insulated composites which have great potential to be used in buildings for energy conservation.

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1. Introduction

Lightweight concrete (LWC) is advantageous over normal weight concrete because of the reduction of dead loads, ease of handling, and better durability. LWC has been widely used in long-span bridges and floating marine structures [1,2]. Moreover, the better fire resistance [3] and thermal insulation properties [1] of the LWC further encourage its use in building structures such as roof coverings and facades, to improve the fire safety and thermal insulation properties of infrastructures. In the past decades, LWC has been developed using various kinds of lightweight aggregates (LWA) such as expanded perlite [4–9], hollow glass beads [8,10–13], expanded clay [8,14] and expanded polystyrene beads [13,15–19]. However, the conventionally used LWA requires various processing steps before utilizing in the cementitious composite, which not only increases their production cost but also releases the high amount of carbon dioxide emission associated with the processes which further raises concerns for the sustainable development. Furthermore, although the resulting composites have better thermal insulation properties, the poor mechanical properties hinder the use of such composites in load-bearing structures. Sengul et al. [5] experimentally investigated the effect of perlite aggregate on the mechanical and thermal properties of LWC and found that by replacing 60 vol.% of natural sand with expanded perlite, the strength reduction is about 84% which discourages its use in structural members. Nemes and Jozsa [12]

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http://dx.doi.org/10.1016/j.conbuildmat.2016.04.134
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also demonstrated that compressive strength of the cementitious composites incorporating expanded glass as lightweight fillers drastically decreased with the increasing volume fraction of the expanded glass, and the optimal amount of filler was found to be 48%. It was found by them that at 48% volume fraction of expanded glass aggregates, the strength was adequate (35 MPa) but the density was not low enough (1550 kg m^{-3}).

Recently, fly ash cenosphere (FAC) [2,20–25] and aerogel [26] have been studied for producing LWC. FAC is a byproduct of coal burning during electricity production process [27], which is lightweight (bulk density up to 800 kg m^{-3}) and cost effective. Wu et al. [28] conducted a series of experiments with various fractions of FAC and found that FAC is an excellent filler material for producing LWC which reduces the density of resulting concrete but the corresponding strength decrease is not substantial. They could produce lightweight composite having 28-day compressive strength of 49 MPa with density of 1240 kg m^{-3}. Also, Demirboga [29,30] showed that the thermal conductivity is affected due to the nature of the FAC which makes them a very reasonable choice for thermally insulated concrete as well. Moreover, aerogel is an extremely light (density 100 kg m^{-3}) nano-porous material composed of silica having a major volume (94–95%) being the air voids [31]. Gao et al. tried to produce LWC by using aerogel and found that using 60% of aerogel (by volume) the strength could reach only 8.3 MPa with the density being 1000 kg m^{-3}; which might be attributed to the low mechanical strength of the aerogel particles [32].

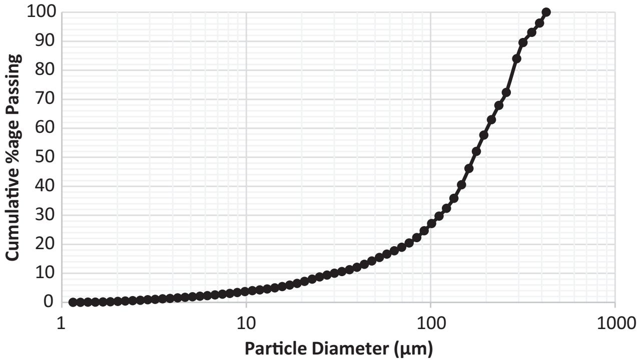

Fig. 1. Particle size analysis (by weight) of fly ash cenospheres.

Table 1
Physical properties of aerogels.

Density	Specific surface area	Particle size range	Porosity	Pore diameter	Hydrophobicity
40–150 kg m^{-3}	366.52 m^2/g	0.1–5 mm	>90%	20–100 nm	Super hydrophobic

Although the effects of FAC and aerogels on the cementitious composite were widely investigated, the co-effects of FAC/aerogels composites on the mechanical and thermal insulating properties of cementitious composite have not been conducted. The aim of current research is to develop an ultra-lightweight cement-based composite by incorporating FAC and aerogels that possesses not only excellent thermal insulation properties but also superior mechanical properties so that it can be efficiently used in building structures for energy conservation.

2. Experimental procedures

2.1. Materials

Ordinary Portland cement (OPC) type 52.5 was from Green Island, HK. Cement and silica fume were used to fabricate the binder. Fly Ash Cenospheres (FAC) were obtained from Zhen Yang Mineral Powder Processing Plant, Hebei China. The bulk density of the FAC particles was 720 kg m^{-3} and the particle sizes ranges from 60 to 360 μm, as shown in Fig. 1. The aerogel were obtained from Guangdong Alison Hi-Tech Co., Ltd (China). The physical properties of the aerogel are shown in Table 1. The specific surface area was measured by using Brunauer–Emmett–Teller (BET, Coulter SA 3100) analysis. The pore size distribution in aerogel is shown in Fig. 2. The PVA fiber (KURALON K-II REC15) used was 39 μm in diameter and 12 mm in length. The chemical composition of the raw materials analyzed by X-ray fluorescence spectrometer (XRF, JSX-3201Z) are listed in Table 2.

2.2. Mix design and specimen preparation

Table 3 enlists the six mix proportions of the cementitious composite with different FAC/aerogel composite contents. The water to binder ratio of all the mixes was set as 0.70 while the amount of FAC was 70% by weight of the binder. FAC and aerogel were used as the filler materials. A poly-carboxylate based admixture/super-plasticizer (ADVA 105 by Grace Inc. Canada) was used to maintain the homogeneity and consistency of the mixture.

The mixing procedure consisted of dry mixing of all the powders for one and a half minute followed by addition of 50% water while continuously mixing for another one and a half minute. Then the remaining water and super plasticizer were added and subjected to mixing of one minute. Finally the PVA fibers were gradually dispersed in the mix while continuously mixing which was continued for another four to five minutes until a homogeneous and consistent matrix was achieved. The mixing of fibers was done at a slow speed followed by high speed of the mixer thus maximizing the extent of uniformity of the mix.

The mixed slurry was cast into the molds and compacted for a small duration on a vibrating table to enable removal of entrapped air. Specimen of size 40 mm × 40 mm × 160 mm (for flexural strength testing), 40 mm × 40 mm × 40 mm (for compressive strength testing) and 350 mm × 350 mm × 20 mm (for evaluating thermal conductivity behavior) were cast for each mix. The specimens were kept sealed after casting at room temperature for 24 h and then de-molded.

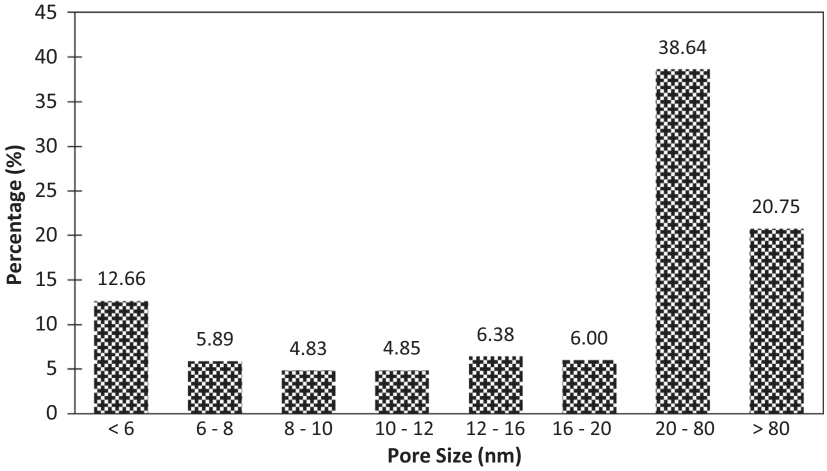

Fig. 2. Pore size distribution in aerogel particles.

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