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Proportioning and characterization of Portland cement-based ultra-lightweight foam concretes

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HIGHLIGHTS

- Ultra-lightweight Portland cement-based foam concretes were successfully prepared.
- Collapse and air-void escape can be avoided by adding thickening agent and stabilizing emulsion.
- The optimal foaming temperature and W/CM ratio were 45 °C and 0.55, respectively.
- Most pores in ultra-lightweight foam concretes were non-connected pores with size of 2.0–4.0 mm.
- Ultra-lightweight foam concretes showed lower thermal conductivity, desirable mechanical properties.

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ABSTRACT

Due to desirable thermal insulation properties, superior fire-resistant and higher durability, ultra-lightweight foam concretes are recommended to achieve energy efficiency in buildings. Generally, aluminate cement, sulphoaluminate cement and other quick hardening cementitious materials are used to control the stability of air-voids in foam concretes. These special cementitious materials are relatively expensive and not universally available, retarding the application and popularization of foam concretes. In the present study, the proportioning and properties of Portland cement-based ultra-lightweight foam concrete were investigated. The results show that ultra-lightweight foam concretes with apparent density of 100–300 kg/m^3 can be prepared using Portland cement, fly ash, hydrogen peroxide and chemical admixtures. Collapse and air-voids escape can be avoided by adding thickening agent and foam stabilizing emulsion into foam concretes. Most of pores in ultra-lightweight foam concretes were non-connected pores with size of 2.0–4.0 mm, resulting in a lower thermal conductivity, desirable compressive and tensile strengths.

1. Introduction

Since the widespread adoption of ‘sustainability’ as a key criterion for the assessment of materials and buildings, energy efficiency and CO_2 emissions reduction during the construction and the whole service life of buildings are more and more focused on. As a result, thermal insulation materials are widely used in buildings. Compared with organic thermal insulation materials, such as polystyrene board and expanded polystyrene (EPS) lightweight concrete, foam concrete has advantages of desirable thermal insulation properties, superior fire-resistant and durability [1–4].

Foam concretes are manufactured by adding foaming agent into cement paste or cement mortar [5]. The key of the preparation process is the matching of the foaming process and the hardening process of foam concrete, thus aluminate cement, sulphoaluminate cement and other quick hardening cementitious materials are generally used to control the stability of bubbles in foam concrete [6]. However, these foam concretes present poor durability and high cost, and the availability of special cements is relatively difficult, all of which lead to limitations in the application and popularization of foam concretes. In addition, many investigations have been conducted on the composition, physical properties and application of foam concretes with density of 600–1500 kg/m^3 [7–11], while few studies have been done on the composition and properties of ultra-lightweight foam concretes (<300 kg/m^3), which show superior thermal insulation properties than the former [12].

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Table 1
Chemical compositions of Portland cement and fly ash used in the experiment.

Material	Density (g/cm^3)	Chemical composition (%)								
		SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	SO_3	LOI
Portland cement	3.14	21.68	4.35	2.95	63.81	1.76	0.51	0.16	0.36	1.19
Low calcium fly ash	2.56	45.43	25.36	4.70	9.53	1.51	1.23	0.36	1.03	7.88

Note: LOI, loss on ignition.

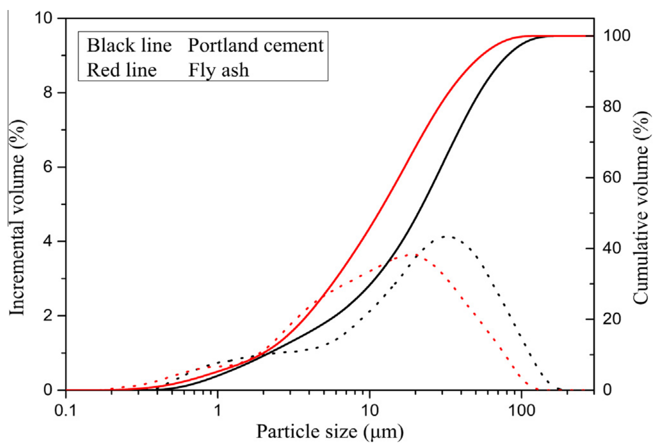

Fig. 1. Particle size distributions of Portland cement and fly ash used.

Fig. 2. Photograph of polypropylene fiber used in ultra-lightweight foam concretes.

In this paper, ultra-lightweight foam concrete was prepared using Portland cement, fly ash, hydrogen peroxide and chemical admixtures. Factors influencing the properties of ultra-lightweight foam concrete were investigated, and the relationships between compressive strength, thermal conductivity and apparent density of foam concretes were evaluated. The results will be very useful to the preparation and application of Portland cement-based ultra-lightweight foam concrete, and thus to the energy efficiency in buildings.

2. Experimental producers

2.1. Raw materials

A Portland cement and a low calcium fly ash (a Class F fly ash according to ASTM C 618 [13]) were used in the experiment, their chemical compositions and particle size distributions are given in Table 1 and Fig. 1, respectively. The fundamental properties of the Portland cement are listed in Table 2. Industrial hydrogen peroxide solution with concentration of 27.5% by mass was selected as the foaming agent. Polypropylene fiber with size of φ 30 μm × 9 mm was added to improve the cracking resistance of foam concretes (see Fig. 2). Thickening agent (a mixture of xanthan gum, cellulose ether and re-dispersible emulsion powder) was used to increase the consistence of paste and the shell thickness of air-voids in the foam concretes. Foam stabilizing emulsion (synthesized by stearic acid ($CH_3(CH_2)_{16}COOH$), NaOH, KOH and ammonia) was also used to form electrical double layer at the liquid–vapor interface and to accelerate the setting of cement paste.

2.2. Preparation of foam concretes

The foam concretes were prepared according to the proportions listed in Table 3 in an environmental chamber at 20 ± 1 °C. The process is shown in Fig. 3 and specified as follows: Firstly, a certain amount of tap water was poured into agitation vat after being heated to a desirable temperature (35, 40, 45, 50, 55 °C), and then Portland cement, fly ash, polypropylene fiber, foam stabilizing emulsion and thickening agent were added into the agitation vat gradually. After stirring for 210 s, hydrogen peroxide was poured into the agitation vat followed by another 11 s stirring. Then the foaming paste was immediately casted into 36 × 36 × 46 cm^3 molds until about 30% depth was filled (2 cm plastic sheets were placed at the internal sides of steel molds to keep the temperature of the foam concretes, and the internal side of plastic sheets was also covered with polyethylene film to avoid leakage). When the foaming process finished (about 18 min), the exposed top surface was covered with polyethylene film to avoid water evaporation, and then sealed with a 2 cm plastic sheet. Demoulding process was conducted after 6 days curing at 20 ± 1 °C, then each specimen was fully covered with polyethylene film and cured for another 28 days at 20 ± 1 °C. Lastly, the specimens were incised for plate thermal conductivity test and compressive strength test respectively, and all specimens were dried at 60 °C until constant weight was achieved.

2.3. Testing methods

2.3.1. Apparent density measurement

The length, height and width of 10 × 10 × 10 cm^3 specimens (cut from the 36 × 36 × 46 cm^3 specimens) were measured, and then the volume of specimens was calculated. Meanwhile, the weight of the specimens was tested, thus apparent density (ρ_A) can be obtained by Eq. (1):

$$\rho_A = \frac{m}{v} \quad (1)$$

where, m is the weight of the specimen, and v is the volume of the specimen.

The average apparent density of six specimens with the same mix proportion was chosen as the apparent density of the foam concrete.

2.3.2. Compressive and tensile strengths measurement

10 × 10 × 360 cm^3 specimens and 10 × 10 × 10 cm^3 specimens were cut from the 36 × 36 × 46 cm^3 specimens for compressive and tensile strengths measurement, respectively. The load-bearing surface areas of each specimen were measured carefully to calculate the strength of foam concretes. Since the strengths of the foam concretes prepared in the present study lay in the range of 0.1–1.0 MPa, the loading

Table 2
Fundamental properties of the Portland cement used in the experiment.

Material	Blaine specific surface area/($m^2\ kg^{-1}$)	Water requirement for normal consistency	Setting time/min		Compressive strength/MPa		Flexural strength/MPa	
			Initial	Final	3 days	28 days	3 days	28 days
Portland cement	367	0.255	139	235	34.4	56.2	7.2	9.9