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# Investigation of the properties of high-porosity cement foams containing epoxy resin

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## HIGHLIGHTS

- Epoxy resin can enhance the compressive strength of high-porosity cement foam.
- The workability was improved by the addition of epoxy resin.
- Epoxy resin increased the air-void size and changed thermal conductivity slightly.
- The water absorption of cement foam decreased with the introduction of epoxy resin.

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## ABSTRACT

Different dosages of waterborne epoxy resin were added to cement slurries, which were used to prepare high-porosity cement foam via the pre-foaming method. The effect of resin on the properties of high-porosity cement foam was investigated. The results revealed that the resin resulted in improved workability and reduced yield stress and plastic viscosity of the cement foam slurries. Although the resin yielded increased air-void sizes, the mechanical properties of the cement foam improved. A compressive strength and thermal conductivity of 0.77 MPa and 0.069 W/m·K, respectively, at a porosity of 89.4%, were obtained for the resin-modified cement foam. Moreover, resin addition also resulted in a decrease in the water absorption and a slight increase in the thermal conductivity of the cement foam.



## 1. Introduction

To reduce the energy consumption of buildings, high-porosity cement foams (HPCF) with attributes such as low density, simple preparation process, excellent fire-resistance, and low cost [1–5], have been extensively studied and used to replace porous organic materials. The pre-foaming method, which allows better control of the workability, density, and pore structure of HPCFs, can be used at construction sites and is more convenient than other preparation methods [4–6]. However, owing to the higher porosity of pre-foamed cement foam, compared with that of conventional cement foam, a larger amount of pre-foam must be added to a smaller amount of cement paste or mortar, leading to: a poor paste or mortar between the air bubbles, reduced self-weight, and greater cohesion resulting from higher air content [5,7,8]. These factors lead to the poor workability of HPCFs. In addition, the high porosity and interconnected air voids resulting from the low fraction of cement paste (which is used in the preparation of pre-foamed HPCF) promote the transport of moisture in the HPCF. This results in high levels of water absorption, and may negatively affect the thermal insulation performance, durability, and mechanical properties of the HPCFs [9–13].

The workability is usually improved by using water reducers and increasing the amount of mixing water [5]. However, these methods may be detrimental to the mechanical properties or stability of the foam. Several studies considering the sorptivity and hygroscopicity of cement foam have indicated that the susceptibility of the foam to water absorption is influenced by the types of foam agents, density, water-proofing agents, and mineral supplementary materials of the foam [6,14–17]. However, a few studies have shown that the properties of the cement foam can be improved, and the corresponding water sorptivity can be lowered.

Epoxy resins, especially water-soluble epoxy resins, exhibit excellent mechanical properties, are alkali-, acid-, and water-

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resistant, and are one of the principal resins used in the production of polymer modified cement-based materials. These resins can form a continuous polymer-network, thereby optimizing the porosity, and leading to improved waterproof capacity and properties (especially the impermeability, workability, mechanical properties, ductility, and durability) of cementitious materials [18–24]. However, resin-modified HPCF have only been considered in a few studies.

Therefore, in this study, an attempt was made to lower the water sorptivity and enhance the properties of HPCF produced via the pre-foaming method. The effects of water-soluble epoxy resin on the workability, air-void structure, hardened properties, and water absorption were investigated. The workability and mechanical properties of HPCF were evaluated via rheology and mechanical testing. Moreover, optical microscopy, X-ray diffraction, Fourier transform infrared spectroscopy analysis, and scanning electron microscopy were used to investigate the air-void structure and microstructure.

## 2. Materials and methods

### 2.1. Materials and preparation

HPCFs were prepared from ordinary Portland cement, epoxy resin (ER), epoxy hardener, set-accelerator (SA), superplasticizer (SP), foaming agent, and water. Ordinary Portland cement (P.O 42.5R in accordance with Chinese standard: GB175-2007) produced at the Lafarge Shuangma Cement Plant (Jiangyou, Sichuan Province, China) was used to stabilize the foam structure and produce strength, using initial and final setting times of 206 and 318 min, respectively, (in accordance with Chinese standard GB/T 1346–2011). The chemical composition of the cement and the corresponding particle-size distribution (as determined by a Masterizer 2000, Malvern, UK) are shown in Table 1 and Fig. 1. The ER is a commercial product widely used as floor material in China. This resin is water soluble and consists of two components, A (ER) and B (hardener, solid content 50.0%). The mixture ratio (by weight) of these two components is A:B = 1:1; the properties of the resin are shown in Table 2. A SA, composed predominantly of aluminum sulfate, and a polycarboxylic type of superplasticizer (KS-JS50Z; Sichuan SikaKeshuai Construction Material Co. Ltd., Sichuan Province, China) were used to accelerate the hardening reaction and improve the workability, respectively, of HPCF. The preformed foam (density: 35 kg/m$^3$) was prepared using a foam generator. During this process, compressed air and a commercial animal-protein-based foaming agent solution (Ketai Building Materials Co. Ltd., Linyi, China; dilution ratio 1:10 by weight) were forced into the mixing chamber of the generator. The foam was then generated by subjecting the air and solution to a series of high-density restrictions.

In this study, the HPCFs were all prepared (see Table 3 for mixing proportions) at a temperature of 20 ± 2 °C in the laboratory. Approximately 80% of water and dispersed polymer (ER and hardener) were added to a vertical mixer (along with SP). Portland cement was then poured into the mixer and mixed with the water for 90 s until a homogeneous lump-free cement slurry was obtained. The remaining water, which contained dissolved SA, was then added to the slurry and mixed for 60 s until well-blended pastes were formed. Preformed foam, in the amounts listed in Table 3, was immediately added to the cement slurry and mixed for 60 s until uniformly distributed therein. The resulting HPCF was molded in 70.7 × 70.7 × 70.7 mm$^3$, 300 × 300 × 30 mm$^3$, and 400 × 300 × 30 mm$^3$ molds, covered with cling film, and cured at 20 ± 2 °C for 72 h in a 90% relative humidity (RH) chamber. The specimens were then removed from the mold and cured in the >90% RH chamber at 20 ± 2 °C.

### 2.2. Test methods

Immediately after preparation, the rheological properties of the HPCF slurry were characterized by using a rheometer (Viskomat NT, Schlebinger, Germany). Fresh cement-based material is considered a visco-plastic material, and is a rigid body at low stresses, but can flow as a viscous fluid at high stresses. This behavior is described by Bingham's model, which is governed by:

$$\tau = \tau_0 + \eta \cdot \dot{\gamma}$$

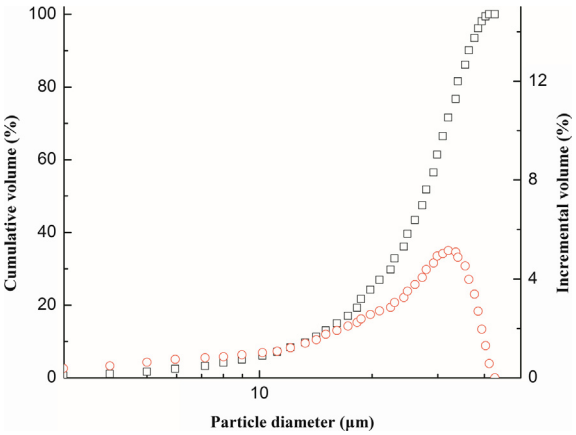


**Fig. 1.** Particle-size distribution of the cement.

where $\tau_0$ is the yield stress, $\eta$ is the plastic viscosity, and $\dot{\gamma}$ is the shear rate; the test is described and the parameters obtained are provided in [25]. The workability of the fresh slurry was also assessed via a mini-slump flow test, performed on a cone of dimensions shown in Fig. 2 [7].

Artificial air voids in the cement foam were typically larger than 50 μm [26]. To determine the pore-size distribution, images of each sample were captured using an industrial digital microscope. Six representative images of each composition were obtained from the center of each sample. The image processing step consisted of five operations namely, dilation, erosion, opening, closing, and hole-filling. Using this set of operations, each image was digitized and then converted to binary form, with air voids and the surrounding matrix denoted as white and black, respectively. A typical image and its binary form are shown in Fig. 3. After image processing, the air-voids were identified using computer software. The mean diameter of each defined region in the image was stored in an Excel spreadsheet, and the pore size distribution was plotted [5,26]. Furthermore, the porosity of HPCF was calculated from $\rho = (1 - \rho_{apparent}/\rho_{th}) \times 100\%$, the apparent density was determined by weighing a known volume of dry cement foam, and the theoretical density was calculated as follows:

$$\rho_{\mathrm{th}} = \sum_{i=1}^{n} v_i \rho_i$$

where $v_i$ is the volume fraction of component $i$ and $\rho_i$ is the density of component $i$.

After curing for 7, 28, and 56 days, three samples (70.7 × 70.7 × 70.7 mm$^3$) of each composition were kept at 20 °C and 60% RH for 24 h, and then subjected to mechanical testing (SANS CMT5105, Shenzheng, China) at a loading rate of 500 N/s. The dry density and water absorption measurements of 28-day-cured HPCF were performed in accordance with Chinese standard JC/T 2200–2013 [27]. Moreover, the thermal conductivity of this sample was measured, in accordance with Chinese standard GB/T10294-2008, using a heat-flow conductometer (JW-III, Beijing, China). Sample hydration was stopped through immersion in anhydrous alcohol and vacuum drying at 45 °C until the mass remained constant. The microstructure and mineral phases were evaluated using a scanning electron microscope (SEM; MAIA3LMU; Tescan, Czech Republic) and via X-ray diffraction (XRD; PANalytical X'Pert Pro, copper target, step size: 0.03°). The chemical reactions occurring in the resin-modified cement foam were determined via Fourier transform infrared spectroscopy (FTIR; SPECTRUM ONE AUTOIMA; PerkinElmer; USA), where spectra were recorded over wavenumbers ranging from 500 to 4000 cm$^{-1}$.

## 3. Results and discussion

### 3.1. Workability

The workability of HPCF was influenced by the cement pastes and air bubbles in the cement foam. The rheological properties of resin-modified HPCF (see Fig. 4a and b) reveal that the addition of resin led to a decrease in the plastic viscosity and yield stress

**Table 1**
Chemical composition of the cement.

| Composition (%) | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | CaO | MgO | $SO_3$ | Loss |
|---|---|---|---|---|---|---|---|
| Cement | 21.06 | 6.10 | 3.08 | 57.98 | 2.74 | 2.40 | 4.07 |