



Investigation of the properties of high-porosity cement foams based on ternary Portland cement–metakaolin–silica fume blends



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HIGHLIGHTS

- The pre-foaming method was successfully used to prepare high-porosity cement foams.
- The addition of metakaolin and silica fume hinders the collapse of fresh high-porosity cement foam.
- The air-void structure of high-porosity cement foam can be stabilized by the addition of metakaolin and silica fume.
- Cement foam with a compressive strength of 0.74 MPa and thermal conductivity of 0.054 W/m K at 91.6% was achieved.

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ABSTRACT

High-porosity cement foams based on ternary blends of Portland cement, metakaolin and silica fume were prepared by the pre-foaming method. The effects of ternary blends on the early-age properties, air-void structure and hardened state properties of cement foams were investigated. The effect of metakaolin and silica fume on stabilizing air-voids was observed, and the collapse of cement foams during the hardening process was avoided by addition of metakaolin. Moreover, the compressive strength of the prepared 91% high-porosity cement foams was enhanced by addition of metakaolin and silica fume. The compressive strength and thermal conductivity reached 0.74 MPa and 0.054 W/m K, respectively. However, metakaolin and silica fume had a negative impact on the workability of the cement foam.

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1. Introduction

Cement and concrete foams with a density of 300–1800 kg/m³ have been studied extensively and are used in energy savings of urban buildings to replace organic insulation materials because of their fire resistance and safety [1]. However, the relatively high density of cement foams compared with other porous organic materials has limited their thermal insulation properties, which are dependent mainly on porosity and air-void structures of porous materials. Higher porosity with a pore size lower than 4 mm and

closed cells should decrease convective heat transfer [2–3]. High ratios of strength to thermal conductivity should also be considered. Therefore, higher porosity and strength, and suitable pore structures are necessary for thermal insulation materials in urban buildings.

Much effort has been expended to prepare high-porosity (>90%) cement foams (HPCF) by adding porosifier, aluminum powder, hydrogen peroxide, foam agent or preformed foam into cement slurry [2–8]. Akthar and Evans [2] prepared cement foams with a porosity of about 90% by stirring and drying modified cement slurries. Hydrogen peroxide addition into cement slurry is also used extensively to produce HPCF in China [9]. Preformed foam can achieve well-controlled workability, density and cell structure, which is more suitable for making low-density cement foams on construction sites [10–11]. Using this method, Tonyan and Gibson [5] prepared cement foams with a density of 160 kg/m³.

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However, the thermodynamically unstable nature of fresh cement foams is a critical issue, no matter which preparation method is chosen. Foam instability arises from the high energy associated with gas-liquid interfaces, and constitutes a driving force for decreasing the total interfacial area of the foam through coalescence and disproportionation of the bubbles [12]. Cells in HPCF merge easily and are usually large [13], this affects thermal insulation negatively. The air-void structure of HPCF may also collapse, the design density and properties will not be achieved. The low strength of HPCF is also a critical issue, for example, 160 kg/m³ at 0.04 MPa and 224 kg/m³ at 0.12 MPa [2].

To prevent coarsening and collapse, set-accelerator (SA) and foam stabilizer are usually added into cement foams. SA is used mainly to accelerate cement hydration and hardening to stabilize air bubbles, foam stabilizer can be used to improve the resistance of foam to changes. Metakaolin (MK) and silica fume (SF) are very fine. More than 95% of the SF particles are less than 1 μm and its surface area is about 13,000–30,000 m²/kg. MK has almost the same surface area (10,000–25,000 m²/kg) and about 20–80% of the MK grains are smaller than 2 μm [14]. SF and MK could increase the viscosity of cement paste, may be used to hinder the bleeding and growing of bubbles, which stabilize foams for the production of cement foams with smaller bubbles, but little information is available currently in this regard. In addition, many attempts have been made to improve strength, such as by introducing polyurethane fibers, polyvinyl alcohol fibers, glass microballoons and styrene-butadiene rubber [2,15–19]. MK and SF, which contain large amounts of amorphous silica or alumina, show high pozzolanic activity. In the presence of water, they can react with portlandite to form gels (C–A–H, C–A–S–H or C–S–H), which can improve the mechanical properties [14,20–25]. The filler effect of grains can promote a decrease in porosity and enhance mechanical properties. MK and SF may enhance HPCF strength and the replacement of cement by MK may contribute to reducing CO₂ emissions because less cement is produced and used.

In this paper, an attempt to enhance HPCF properties by MK and SF addition was made. HPCF was prepared based on ordinary Portland cement, MK and SF, and the effect of MK and SF on air-void structure, early-age and hardened HPCF properties was investigated. Rheology and mechanical tests were used to evaluate workability and mechanical properties. Optical microscopy, X-ray diffractometry, thermogravimetric analysis and scanning electron microscopy were used to investigate the air-void structure and microstructure.

2. Material and methods

2.1. Materials and preparation

HPCF slurries were prepared using ordinary Portland cement, supplementary cementing materials (SCMs), accelerating agent, superplasticizer (SP), foam agent and water. In this study, cement (P.O 42.5R according to the Chinese standard) produced at Lafarge Shuangma cement plant, Jiangyou, Sichuan Province, China was used to stabilize the foam structure, with an initial and final setting time of 206 min and 318 min, respectively. MK and SF were treated as SCMs for introduction into cement slurries. The raw material chemical compositions, mineral phases and particle size distributions are shown in Table 1, Figs. 1 and 2. SA, which consisted mainly of aluminum sulfate, was used to accelerate hardening and its dosage was 4 wt% of the cement. A polycarboxylic-type superplasticizer (KS-JS50Z) from Sichuan SikaKeshuai Construction Material Co., Ltd, Sichuan Province, China was

Table 1
Chemical composition of raw materials.

Compositions (%)	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SO ₃	Loss
Cement	21.06	6.10	3.08	57.98	2.74	2.40	4.07
Metakaolin	51.79	42.92	0.58	0.27	0.17	0.17	2.13
Silica fume	91.97	0.26	0.29	0.69	0.20	1.16	3.40

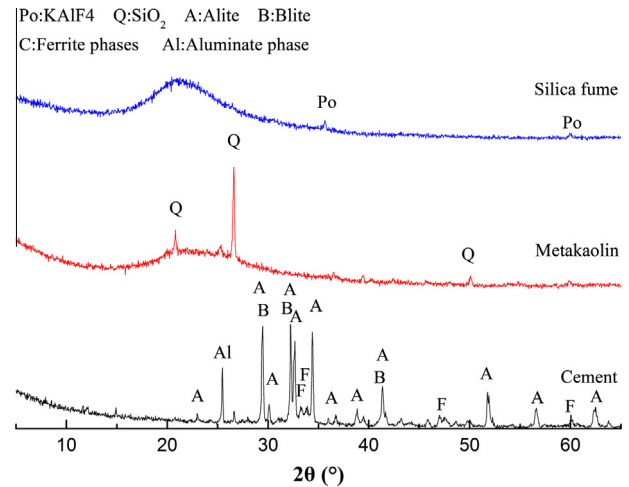


Fig. 1. XRD patterns of raw materials.

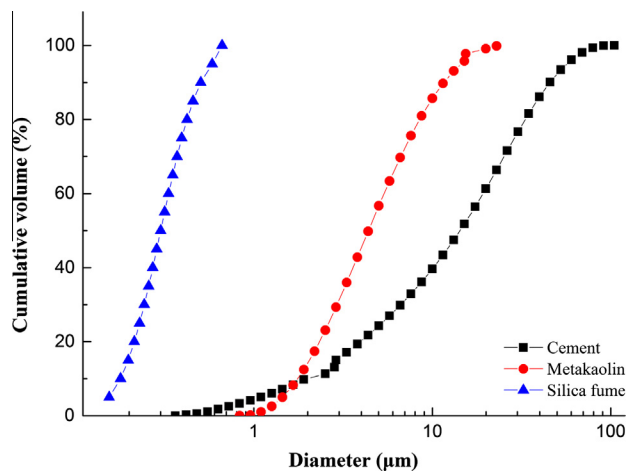


Fig. 2. Particle size distributions of raw materials.

used to modify the rheological behavior of the cement pastes. Foam was produced by aerating a commercial animal protein-based foaming agent solution (dilution ratio 1:15 by weight) using a foam generator to a density of 35 kg/m³.

The porosity, pore size and pore distribution are influenced significantly by mixing procedures, so establishing specimen preparation characteristics is important. In this study, HPCF specimens were prepared in the laboratory at 20 ± 2 °C and proportions are shown in Table 2. Eighty percent of water was added to a vertical mixer (along with superplasticizer). Portland cement was then poured into the mixer and mixed with water for 90 s until a homogeneous cement paste without lumps, was obtained. The remaining water, which contained dissolved accelerator, was then added to the cement pastes and mixed with paste for 60 s until a well-blended paste formed. Preformed foam was added immediately to the cement paste and mixed for 60 s until uniformly distributed to prepare HPCF slurries. The resulting HPCF was molded in 70.7 × 70.7 × 70.7 mm³ and 300 × 300 × 30 mm³ molds, covered with clinging film and cured in a 90% RH (relative humidity) chamber at 20 ± 2 °C for 72 h. After 72 h, specimens were removed from the mold and cured in the >90% RH chamber at 20 ± 2 °C for 7, 28 and 56 days.

2.2. Test methods

The rheological properties of cement paste and fresh HPCF slurry were characterized by rheometer (Fig. 3, Viskomat NT, Schleibinger, Germany) immediately after preparation. Fresh cement-based material is accepted as a visco-plastic material, and is a rigid body at low stresses but can flow as a viscous fluid at high stresses. This behavior follows Bingham's model:

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

where τ_0 is yield stress, η is plastic viscosity and $\dot{\gamma}$ is shear rate. Together with the rheometer tests, the workability of fresh HPCF slurry was also assessed by a mini-slump flow test, with dimensions given in Fig. 3.

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