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Effects of bentonite slurry on air-void structure and properties of foamed concrete

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HIGHLIGHTS

- Bentonite slurry was used to prepare foamed concrete.
- The fluidity can be improved with bentonite slurry more than 20%.
- Changes of air-void structure and matrix microstructure are observed.
- Thermal conductivity was decreased by addition of bentonite slurry.

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ABSTRACT

The increase of nano-scaled pores may further improve the thermal insulation properties of foamed concrete. However, air voids in foamed concrete prepared by pre-fabricated foams through surfactant or hydrolyzed protein solutions are commonly above micron level. It becomes a key issue to decrease the air-void sizes and increase the nano-scaled pores in foamed concrete by the modification of pore-forming methods. In this study, gel-like bentonite slurry with solid content of 9.1% was used to replace some of cement and pre-fabricated foams to prepare foamed concrete with dry bulk density of 300 and 600 kg/m^3, respectively. Apparent viscosity of the fresh pastes decreased with the increase of bentonite slurry, and the fluidity firstly decreased and then increased. Compressive strength decreased with the increase of bentonite slurry, specially the as-prepared foamed concrete with dry bulk density of 300 kg/m^3. Much better thermal insulation properties of the foamed concrete with bentonite slurry could be obtained. Thermal conductivity of the foamed concrete with 50% of bentonite slurry decreased by 29.8% and 15.3% for dry bulk density of 300 kg/m^3 and 600 kg/m^3, respectively. It is found that the increased pores with nano-scaled sizes in foamed concrete with bentonite slurry could be responsible for the lower thermal conductivity.

1. Introduction

More interests have been focused on the thermal insulation materials used in modern civil buildings because of the increased requirement of energy saving and efficiency energy utilization. As one of the most low-cost, fire-proofing and simple thermal insulation materials, foamed concrete was proposed to be applied as self-insulation masonry, cast-in-place wall, insulation board and subgrade filler, etc [1–3]. However, relatively high thermal conductivity of foamed concrete compared with other thermal insulation materials like aerogel or polymer limits its application in civil buildings [4]. It is still a great challenge to further reduce the thermal conductivity of foamed concrete at a given density level.

It is found that the thermal conductivity of foamed concrete would be influenced by shape, size, size distribution and volume of pores [5–8]. At present, increasing the porosity (pore volumes) of foamed concrete through mix design [9], admixtures or high stability foaming agents [10–13] is considered to be the most efficient way to reduce the thermal conductivity [14]. However, it seems that the thermal conductivity reduction is not obvious but the mechanical properties of foamed concrete decreases sharply with the increase of pore volumes. In fact, pore size is one of the most important parameters for the thermal insulation improvement of porous materials in addition to the pore volume [15–17]. Nano-scaled pores could lead to the lower thermal conductivity in porous materials. A particular example as aerogel, which contains

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nanopores (below 100 nm), has a thermal conductivity lower than sealed air (0.026 $W \cdot m^{-1} \cdot K^{-1}$) [18,19]. It can be interpreted as the elimination of thermal convection caused by vibration and collision of the gas molecules. The molecular motion will be prevented by pores with sizes less than the mean free path of gas in the air [18]. Moreover, smaller pores in porous materials at same porosity possesses many more reflecting and refracting surfaces of heat, which will effectively block the radiative transfer. It can be speculated that the decreased pore size and increased nano-scaled pores could further improve the thermal insulation of foamed concrete. It is known that air voids in foamed concrete prepared by pre-fabricated foams through surfactant or hydrolyzed protein solutions are commonly above micron level. Smaller pores, such as capillary pores (<20 μm) and gel pores (<10 nm) are produced by the cementitious matrix during hydration and hardening [20–23], which related to the water to cement ratio. Therefore, it is hard to decreased pore size and increased nano-scaled pores through pre-fabricated foams and cementitious matrix in foamed concrete with fixed density level and water to cement ratio. As a natural clay mineral mainly consisted of layer structure montmorillonite, bentonite has better water retention and expansibility. Small amount of sheet-like bentonite particles can be arranged to form a closed-cell honeycomb with nano-scaled pores dominated by edge-to-face and face-to-face contacts after saturating with water [24–27]. That is, bentonite slurry has the potential to be used as the nano-scaled pores forming agent in foamed concrete. Moreover, as a typical non-newtonian pseudoplastic and water-swelling fluid, bentonite slurry has positive impacts on fluidity and anti-segregability of foamed concrete [28,29].

In order to further improve the thermal insulation properties by the decrease of pore size and the increase of nano-scaled pores, bentonite slurry was introduced to replace some of cement and pre-fabricated foams to prepare foamed concrete. The effects of bentonite slurry on rheological behavior, fluidity, hardened properties, air-void structure and matrix microstructure were investigated.

2. Materials and methods

2.1. Materials

Ordinary Portland cement (P.O 42.5R, conforming to Chinese standard: GB 175-2007 [30]) obtained from the Lafarge Shuangma Cement Plant (Jiangyou, Sichuan Province, China) was used as the binding material. Lithium bentonite, obtained from the Shengshi Montmorillonite Technology Co., Ltd. (Weifang, Shangdong Province, China), was used due to its satisfactory water retention. Compositions and physical properties of cement and bentonite are summarized in Tables 1 and 2. The SEM micrograph and the particle-size distribution are shown in Figs. 1 and 2. Naphthalene formaldehyde superplasticizer (FDN, Sichuan SikaKeshuai Construction Material Co., Ltd., Shandong Province, China) was used to improve the workability of foamed concrete. The prefabricated foams (30 kg/m^3) were prepared by mixing the foaming agent (FP-180, Ketai Building Materials Co., Ltd., Linyi, China), water and compressed air in predetermined proportions (10 g water to 1 g foaming agent) in a foam generator. Bentonite slurry (BS) has a mass ratio of water to bentonite of 10, which was originally based on the same fluidity with cement paste. An electric mixer was used to made bentonite disperse homogeneously, and then BS was aged about 24 h to form water-rich gel. The specific gravity and solid content of BS are 1040 kg/m^3 and 9.1% respectively.

2.2. Mix design

Twenty-four different mixes were prepared as follows: conventional mixes FC and modified mixes FCB via decreasing different volume fraction (10%, 20%, 30%, 40% and 50%) of prefabricated foams and adding the corresponding volume of BS with two water/binder (w/b) ratios at two dry density levels, 0.6 and 300 kg/m^3 (6FC3, 6FC3B1, 6FC3B2, 6FC3B3, 6FC3B4 and 6FC3B5), 0.4 and 300 kg/m^3 (4FC3, 4FC3B1, 4FC3B2, 4FC3B3, 4FC3B4 and 4FC3B5), 0.6 and 600 kg/m^3 (6FC6, 6FC6B1, 6FC6B2, 6FC6B3, 6FC6B4 and 6FC6B5), 0.4 and 600 kg/m^3 (4FC6, 4FC6B1, 4FC6B2, 4FC6B3, 4FC6B4 and 4FC6B5), see Table 3. Moreover, prefabricated foams and BS ratios of different mixes are shown in Fig. 3. The detailed design of mix proportions is described below [31].

Assuming a given target dry density (D, kg/m^3), cement content (M_c, kg/m^3), bentonite content (M_b, kg/m^3), water/binder ratio (w/b), the total mix water (M_w, kg/m^3), foams content (M_f, kg/m^3), substituted fraction of BS for foams (x, volume %), and BS content (M_{bs}, kg/m^3), were calculated from Eqs. (1)–(5) as follows:

$$\text{Target dry density, } D = (M_c + M_b) \times 1.2 \tag{1}$$

$$\text{The total mix water, } M_w = (M_c + M_b) \times (w/b) \tag{2}$$

$$\text{Foam content, } M_f = (1 - (M_c + M_b)/3050 - M_w/1000) \times (1 - x) \times 1.25 \tag{3}$$

$$\text{BS content, } M_{bs} = ((1 - (M_c + M_b)/3050 - M_w/1000) \times 1040 \times x)/30 \tag{4}$$

$$\text{Cement content, } M_c = D/1.2 - M_{bs}/11 \tag{5}$$

Where 1.2 is the mass coefficient about a ratio of nonevaporating content to dry raw material content after curing 28 days, 1.25 is the breakage constant of foams, 11 is the mass ratio of BS to bentonite, and 3050, 1000 and 1040 are the densities (kg/m^3) of cement, water and BS respectively.

2.3. Preparation

The mixes were all prepared as the following sequence at 20 ± 1 °C in the laboratory. According to the mix proportions in Table 3, component materials were precisely weighed. All water, which contained dissolved FDN, was added into a vertical mixer, and then pouring Portland cement into the mixer to prepare the homogeneous cement slurry. BS was added into the cement slurry to prepare the bentonite-cement slurries, and then prefabricated foams were added to prepare the foamed concrete. The resulting mixes were placed in 70.7 × 70.7 × 70.7 mm^3 and 300 × 300 × 30 mm^3 molds. After leveling the surface, all mixes were covered with cling film to prevent evaporation and cured in ≥90% relative humidity (RH) chamber at 20 ± 2 °C for 24 h. Then the mixes were demoulded and stored in ≥90% RH chamber at 20 ± 2 °C until provisions of age.

Table 1
Chemical composition of bentonite and cement.

Oxide constituents (%)	CaO	SiO_2	Al_2O_3	SO_3	Fe_2O_3	MgO	K_2O	TiO_2	P_2O_5	Na_2O
Bentonite	1.88	76.17	14.38	0.91	3.17	1.11	0.54	0.60	0.04	1.06
Cement	63.00	20.95	5.39	4.52	3.21	1.34	0.77	0.39	0.19	0.07