Construction and Building Materials 137 (2017) 160–168

Contents lists available at ScienceDirect

Construction and Building Materials

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

Experimental study on the preparation and properties of a novel foamed concrete based on magnesium phosphate cement

Cong Ma, Bing Chen *

Department of Civil Engineering, Shanghai Jiaotong University, Shanghai 200240, PR China

HIGHLIGHTS

- The properties of a novel foamed concrete from magnesium phosphate cement are studied.
- The relationships of the modulus of elasticity to compressive strength are analyzed.
- The effects of mineral admixtures on the properties of foamed concrete are investigated.

ARTICLE INFO

Article history:
Received 22 October 2016
Received in revised form 21 December 2016
Accepted 25 January 2017

Keywords:
Foamed concrete
Magnesium phosphate cement
High early-strength
Thermal conductivity

ABSTRACT

The long setting time of conventional OPC-based foamed concrete usually hinders the next step of constructions. Based on the unique advantages of magnesium phosphate cement (MPC), a novel foamed concrete with the characteristics of quick setting and high early-strength is prepared by using sodium bicarbonate (NAC) as a foaming agent in this study. In order to investigate the mechanical and physical properties systematically, the 3-h and 28-day compressive strength, splitting tensile strength, thermal conductivity and water resistance are measured during the experiments. The laboratory results indicate that the dry density, compressive strength, splitting tensile strength, thermal insulation and water resistance decrease as increasing the NAC content. It is notable that the 3-h compressive strength of MPC-based foamed concrete is about 70% of the 28-day compressive strength. The relationships of the modulus of elasticity and splitting tensile strength to compressive strength are analyzed by power functions. And a linear function is suitable to describe the reduction in strength retention coefficient with the increase of the water absorption. The compressive strength and water resistance of MPC-based foamed concrete with a target density of 550 kg/m^3 can be improved by adding the predetermined amount of fly ash. And the 28-day compressive strength and thermal conductivity of MPC-based foamed concrete with 10% fly ash are 2.4 MPa and 0.072 W/mK, which are superior to those of OPC-based foamed concrete with the same dry density.

1. Introduction

In China, the energy consumption of construction industry has roughly 35% of total energy consumption in society [1]. In the past several years, lightweight concrete, aerated concrete and foamed concrete with excellent thermal insulating properties have been used as exterior wall materials and studied by many researchers [2–7]. In addition, the foamed concrete with high fluidity and low cement and aggregate usage is also applied to sandwich structures, earth-remaining walls and running tracks or playgrounds [8,9]. The common used foamed concrete is defined as pre-foamed foam concrete by adding the projected amount of foam into cement slurry.

The conventional foamed concrete firstly reported in the twenty-twenties is prepared by ordinary Portland cement (OPC) [10]. During the past decades, the improvement in foaming technology and the introduction of high-efficiency superplasticizers, foam stabilizers and early strength agents have substantially improve the engineering properties of the foamed concrete [3,9]. Even so, the practical application of the OPC-based foamed concrete in many emergency constructions has been limited due to its slow hardening process. For example, the next step could be carried on until at least 28 days after the execution of the OPC-based foamed concrete with the density of from 300 kg/m^3 to 800 kg/m^3 [11]. In addition, the damaged structures prepared by foamed concrete require strengthening or rehabilitation and

* Corresponding author.
E-mail address: hntchen@sjtu.edu.cn (B. Chen).

http://dx.doi.org/10.1016/j.conbuildmat.2017.01.092
0950-0618/

the common repairing materials in China are mainly rapid-hardening cements [12–14].

Among the rapid-hardening cements, magnesium phosphate cement (MPC) has attracted more attention over the past decades [15–17]. MPC has unique advantages of quick setting, high early-strength and durability due to quick acid-base reaction between magnesia and phosphate. When MPC is used to repair the damaged structures, the repairing process lasts only about a quarter of an hour and the structures can return to service within only a few hours. In fact, the use of MPC for repairing the dilapidated foamed concrete may affect its thermal insulation and water permeability. As mentioned before, a foamed concrete with quick setting characteristic is more appropriate for cast-in-situ construction. However, preparation and properties of the foamed concrete based on MPC has not yet seen in any study.

The common used phosphate to prepare MPC is ammonium dihydrogen phosphate ($NH_4{\cdot}H_2PO_4$, ADP). ADP dissolves immediately after mixing with the water and its ionization reaction can be stated as the following equations [18,19].

$$NH_4 \cdot H_2PO_4 \rightarrow NH_4^+ + H_2PO_4^- \quad (1)$$

$$H_2PO_4^- \rightarrow H^+ + HPO_4^{2-} \quad (2)$$

$$HPO_4^{2-} \rightarrow H^+ + PO_4^{3-} \quad (3)$$

Meanwhile, the magnesia power dissolves in the water and the reaction process can be expressed as the follows.

$$MgO + H_2O \rightarrow MgOH^+ + OH^- \quad (4)$$

$$MgOH^+ + 2H_2O \rightarrow Mg(OH)_2 + H_3O^+ \quad (5)$$

$$Mg(OH)_2 \rightarrow Mg^{2+} + 2OH^- \quad (6)$$

The acid-base neutralization occurs between OH^- from the hydrolysis reaction of MgO and H^+ from ionization reaction of ADP, which can promote the generation of PO_4^{3-} and Mg^{2+}. In the presence of Mg^{2+}, NH_4^+, PO_4^{3-} and water, $MgNH_4PO_4{\cdot}6H_2O$ (MAP) is produced. Moreover, the hydration reaction could release large amount of heat and ammonia. Because the setting and hardening time of MPC is very short (about 10 min), the ammonia couldn't completely emit from hardened MPC [15,20]. Hence, MPC with a small quantity of pores can be regarded as a high-density foamed concrete. In order to obtain a MPC-based foamed concrete with low density, sodium bicarbonate ($NaHCO_3$) may be a suitable foam agent to generate more gas and the chemical reaction can be expressed as the following equation.

$$HCO_3^- + H^+ \rightarrow CO_2 + H_2O \quad (7)$$

In this study, $NaHCO_3$ is employed as a foam agent to prepare a MPC-based foamed concrete with low dry density of about 550 kg/m^3. The physical and mechanical properties of the foamed concrete are evaluated by testing dry density, compressive strength, thermal conductivity, splitting tensile strength and water absorption. The effects of different contents of $NaHCO_3$, fly ash and silica fume on the properties are investigated. In addition, the relationship of compressive strength to thermal conductivity, splitting tensile strength are analyzed by establishing some empirical models.

2. Experiment details

2.1. Materials

The based materials to prepare MPC-based foamed concrete include cementitious materials and admixtures. The cementitious materials consist of dead burnt magnesium (MgO), ammonium dihydrogen phosphate ($NH_4{\cdot}H_2PO_4$, ADP), fly ash (FA) and silica fume (SF). MgO powder with a specific surface of about 250 m^2/kg is obtained from Shenglu Chemical Materials Co., Ltd and its calcination temperature is about 1600 °C. The used ADP is industrial grade and its purity is 94.5%. Class F fly ash conforming to ASTM C618 is used and it is obtained from Suzhou Zhongliang Power Plant. Silica fume was obtained from Elken Materials Co., Ltd. Table 1 shows the oxide composition of MgO, FA and SF, respectively.

The admixtures include retarder, foam agent and foam stabilizer. The employed retarder (NAB) is industrial-grade sodium borate ($Na_2B_4O_7{\cdot}10H_2O$) and its purity is greater than 95%. The chemically pure sodium bicarbonate ($NaHCO_3$) is used as the foaming agent (NAC). The composite foam stabilizer (BES) developed in our laboratory consists of butyl ether and a type of nonionic surfactant at a given proportion.

2.2. Specimen preparation

To prepare MPC-based foamed concrete, the mass ratio of water to cementitious materials is fixed at 0.25, and that of MgO to ADP is always 1.5 in this study. The addition of NAC varies from 0 to 7% by weight of MgO. The MPC-based foamed concrete can be prepared by three steps. Firstly, cementitious materials, retarder and foam stabilizer are added into a paddle mixer and the dry mixing lasts about 1.5 min. And then, the predetermined amount of water is introduced into the mixture and sequentially mixed for about 1.5 min to obtain a homogeneous mixture. Finally, the projected amount of foam agent is added immediately into the fluid mixture and the mixture is continued to mix in high speed for about 0.5 min until the foam agent distributed uniform in the mixture.

Then, the fluid mixture is poured into the PVC cubic molds (100 mm × 100 mm × 100 mm) and the surface of each specimen is smoothed by hand only. Due to the rapid hardening of MPC mortar, the set MPC-based foamed concrete be demolded after only about 1 h of curing. Subsequently, the demolded specimens are transferred to curing room with a temperature of 22 ± 2 °C. At predetermined curing age, the specimens are taken out to measure the physical and mechanical properties.

3. Testing methods

3.1. Compressive strength and splitting tensile strength

After 3 h and 28 days of curing, the specimens are took out from the curing room for compressive strength measurements. Split-cube tests are conducted in accordance with ASTM C 496 standard at 28 days of curing. An MTS servo hydraulic testing machine with a capacity of 100 kN is employed to measure the compressive strength (f_c) and splitting tensile strength (f_t) of MPC-based foamed concrete. The loading rate is fixed at 0.5 mm/min and the strength is the mean value of four tests to confirm the reproducible of

Table 1
Chemical composition of cementitious materials (% by weight).

Oxide	MgO	FA	SF
SiO_2	4.91	54.90	92.40
Al_2O_3	2.35	25.80	0.80
Fe_2O_3	1.16	6.90	0.50
CaO	1.44	8.70	0.91
MgO	89.51	1.80	0.27
Na_2O	–	0.3	–
K_2O	–	0.3	–
SO_3	–	0.6	–
LOI (loss on ignition)	–	0.2	2.0