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Preparation and modeling of energy-saving building materials by using industrial solid waste

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ABSTRACT

A new kind of foamed cement (FC) made of Portland cement (PC), fly ash (FA), steel slag (SS), and foam agent has been developed with the purpose of preparing energy-saving building materials. The effect of SS and FA on the properties such as bulk density and compressive strength of base mix was systematically investigated. The results indicated that the base mix with 50% PC, 30% FA and 20% SS showed the optimum properties. By proper control in dosage of foam agent, a series of FC with a range of bulk densities (350–1340 kg/m^3) were obtained for the further experimental measurement. The corresponding thermal conductivity (k_e) of the samples was measured by a guarded hot plate apparatus. In addition, k_e was also predicted by a modified model. Comparison with the previous model, the modified model had better accuracy and shorter calculated time. Finally the predictions were compared with the experimental data and other existing analytical models. The results indicated that the predicted results agree well with the measured values.

1. Introduction

Nowadays, the world is facing a grim situation of energy conservation and emission reduction. The building sector is known to contribute largely in total energy consumption and CO_2 emissions [1–5]. It was estimated that about 38% of the total energy are consumed by buildings including space heating, ventilation and air conditioning [6]. The building thermal insulation contributes in reducing the required air-conditioning system power and the energy cost of buildings as well. The excellent insulation in buildings such as foam cement (FC) also reduce unwanted heat loss or gain and decreases the energy demands of heating and cooling systems, resulting in lower energy bills and protecting the environment by cutting CO_2 emissions [7].

As a traditional material for manufacture FC, cement has been produced from the existing natural resources and will have intrinsic distinctiveness for damaging the environment due to its continuous exploitation. Nevertheless, during the cement processing, air pollution compounds, such as CO_2, SO_2, NOx and suspended particulate matter, are invariably emitted to the atmosphere [8]. This will lead to major contamination of air, water, soil and finally influences human health and their living conditions. In view of the importance of saving of energy and conservation of resources, it is essential to find a functional substitute of cement in manufacture of FC.

Fly ash (FA) is an industrial waste with a pozzolanic nature. The total amount of FA produced worldwide is enormous, which has been estimated to exceed 750 million tons per annum, but only less than 50% of world FA production is utilized [9]. For example, FA has been used to make fly ash Portland cement in many countries [10–13]. Steel slag (SS) is also a kind of industrial waste generated from the steel-refining process in a conversion furnace. It was reported that the production of steel slag is over 70 million tons in recent years with the slag generation rate of about 0.08–0.15 ton per ton steel [14]. From the theoretical point of view, SS can be used to substitute partially as clinker for producing composite Portland cement [15–17]. In this paper, these two solid wastes both of FA and SS were used as the cement replacement to manufacture FC.

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Table 1
Chemical composition of three main raw materials (wt%).

Compound m/m%	SiO_2	Al_2O_3	Na_2O	K_2O	CaO	Fe_2O_3	MgO	TiO_2	S	MnO	SO_3	LOI
Portland cement	25.94	10.46	1.16	–	42.20	1.71	8.42	–	1.18	–	–	6.32
Fly ash	42.85	39.78	0.13	0.48	4.60	2.18	0.62	1.35	–	0.01	3.12	4.43
Steel slag	26.12	13.08	0.35	0.70	35.14	0.94	8.27	13.73	0.73	0.49	–	0

This paper reports the findings of a laboratory-based study that examined the optimum proportion of raw materials that were applied to develop FC due to their effect on bulk density and compressive strength. FC exhibits good thermal insulation properties that are suitable for the insulating construction industry. In this paper, FC with a large range of densities (350–1340 kg/m^3) was fabricated by the pre-forming method for the thermal test.

In addition, to facilitate the design and development of FC, the prediction of its thermal properties is essential. A modified random simulation method was introduced to predict the effective thermal conductivity (k_e) of FC. The improvement will be discussed from several aspects: the relative deviation, the accuracy and the calculated time, respectively. Finally the predictions were compared with the experimental data and other existing analytical models. It shows that the present model can accurately predict k_e by using a reasonable computational cost.

2. Experiment process

2.1. Materials

Materials used in this experiment consisted of Portland cement (PC), FA, SS, foam agent and potable water. All solid materials were ground by ball mill for 5 h to reduce its size smaller than 74 μm. The properties of PC, FA, and SS used in this study are presented in Table 1. The stacking density and the true density of PC are 1250 kg/m^3 and 1800 kg/m^3, respectively. PC mainly consists of 42.20% calcium oxide and 25.94% silicon dioxide and other minor components are alumina, ferric oxide, sulphur, sodium oxide and so on. FA is an industrial waste with a pozzolanic nature, which is from Shanxi province in China. SS is also a kind of industrial waste resulting from the steel-refining process in Chongqing province in China. The general mineral compositions are composed of C3S, C2S, CMS, C3MS2, RO phase, free lime and others [18]. The foaming agent consists of hydrolyzed proteins and is manufactured in China. And the foaming agent was diluted with water in a ratio of 1:30 (by mass), and then aerated to a density of about 70 kg/m^3.

2.2. Methods

For the test of determining the base mixes, 11 groups of samples were produced by using the pre-formed foam procedure with no aggregate. As the cement replacement, FA and SS have been used in the range of 0–50% to study their effect on the properties such as bulk density and compressive strength of base mix, as shown in Table 2.

In the production process of the base mix, using FA in mortar or concrete will reduce water demand of the mixtures [19]. Therefore, to avoid effects due to water to binder ratio on compressive strength, all mixtures in this investigation were controlled the ratio of water to binder (PC, FA and SS) at constant of 0.3 instead of using constant flow. PC, FA and SS were firstly dry-mixed for 3 min in a vertical mixer. The total quantity of water was then added and mixed with the dry materials for 5 min until a homogeneous mortar without lumps. Then all mixtures were poured into plastic moulds and kept for 24 h. After demolding, the samples were kept in a room at the temperature of 50 °C and the humidity of 90% up to the day of testing.

For the synthesis of FC, the base mix sample with the replacement of 30% FA and 20% SS was used for further experimental measurement. It was mixed with different foaming agent contents to make FC with different bulk densities. For the synthesis of FC, the water requirement for a mix depends upon the composition and the use of admixtures and is governed by the consistency and stability of the mix. At lower water content, the mix is too stiff causing bubbles to break while a high water content make the mix too thin to hold the bubbles leading to separation of bubbles from the mix and thus segregation [20,21]. In this part, the water/binder ratio by weight was 0.4 and kept the same in all groups. The same as earlier, PC, FA and SS were firstly dry-mixed for 3 min in a vertical mixer. The total quantity of water was then added and mixed with the dry materials for 5 min until a homogeneous mortar without lumps. The pre-formed foam was then produced by the foam generator and the approximate quantity was added to the base mix, immediately after preparation. The pre-formed foam was combined with the mixture for at least 5 min, until all foam was uniformly distributed and incorporated in the base mix. Then the mixture was also poured into plastic moulds and kept for 24 h. After demolding, the samples were kept in a fog room at the temperature of 20 °C and the humidity of 90% up to the day of testing.

For the compressive strength test, six 10 cm cubes were prepared (Fig. 1 (a)). The mean compressive strength was the average of three cubes (with the relative error limited to less than 10%). Cubes were crushed after the cure of 7 days. The thermal conductivities were measured in a vapor-tight envelope by a guarded hot plate apparatus (GHP) at the mean temperature of about 25 °C. The measurement uncertainty and repeatability of GHP were controlled within ±3% and ±1%, respectively. For this test, two slabs

Table 2
Configuration and characteristics of foam cement.

Base mix number	PC (wt%)	FA (wt%)	SS (wt%)	The bulk density (kg/m^3)	The compressive strength (MPa)
1	100	0	0	1800	52.7
2	70	30	0	1620	37.4
3	70	20	10	1630	44.4
4	70	15	15	1680	45.9
5	70	10	20	1730	46.2
6	70	0	30	1740	42.9
7	50	50	0	1460	23.9
8	50	30	20	1550	33.6
9	50	25	25	1580	32.3
10	50	20	30	1590	34.2
11	50	0	50	1700	27.4