Effects of steel slag and silica fume additions on compressive strength and thermal properties of lime-fly ash pastes

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HIGHLIGHTS

- BOFS and SF had influence on formation of hibschite, α-C_2SH and tobermorite.
- Pore structure was coarsened at high lime content or by BOFS, but refined by SF.
- Compressive strength and thermal properties wereclosely related to pore structure.
- A random model was developed to simulate pore structure and thermal conductivity.
- Temperature profile and heat flow based on the simulation model were discussed.

ARTICLE INFO

ABSTRACT

Lime-pozzolana pastes with high volumes of fly ash (FA) are widely used as masonry cement and autoclaved building materials. In this work, four sets of pastes with varying lime content from 12% to 25% were prepared and autoclaved at 180 °C for 8 h, and basic oxygen furnace steel slag (BOFS) and silica fume (SF) were added as replacements of FA in each set. The properties assessed were compressive strength, thermal properties by transient plane source method, porosity and pore size distribution by mercury intrusion porosimetry (MIP). The microstructure was investigated by means of XRD and SEM-EDS. Results show that both pore structure and microstructure of the pastes were significantly altered by variations in compositions. High lime content resulted in an increase of porosity and more capillary pores were formed, replacement of FA with BOFS coarsened the pore structure but the opposite was observed for SF. The compressive strength was closely related to pore structure and microstructure as expected. The thermal conductivity and thermal diffusivity decreased with increasing lime content and were further decreased by incorporating BOFS and SF. Only SF could effectively increase the specific heat due to the interfaces between SF particles and matrix as a thermal barrier. A random model was developed to simulate pore structure and thermal conductivity of the pastes based on the assumption of two phases (gas and solid). These achievements contribute to better understanding of the lime-pozzolana pastes and are desirable for their proper modeling and design.

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1. Introduction

Fly ash is a by-product of thermal power plants and contains partially active silica and alumina [1–3]. Due to the pozzolanic nature, it is usually utilized in the cementitious system. Production of light weight building blocks from lime-fly ash pastes is one of the utilization ways of FA as a construction material. Especially, pastes with high volumes (up to 60–80%) of FA have been widely used as masonry cement and for production of aerated concrete [1]. In such situations, developments of mechanical and other properties of these materials are due to the lime-pozzolana reactions, which take place slowly under ambient temperature [4]. Autoclaving is an effective method to enhance the pozzolanic reactions and produce more calcium silicate hydrates (C-S-H) by increasing the dissolution rate of FA [5–9]. The advantages of autoclaving include producing high strength within few hours, reducing drying shrinkage, and improving resistance to chemical attacks [10]. Thus autoclaving is a proven and versatile method for utilizing industrial by-products such as fly ash and slag on a large scale for manufacture of building materials such as dense concrete, autoclaved aerated concretes, thermal insulation boards, and fiber-reinforced cement products [10–14].

The hydration products of the lime-fly ash pastes have been thoroughly studied. Generally, tobermorite, poorly crystallized

C-S-H, α-C₂SH, and katoite are formed under the hydrothermal conditions depending on types of FA as well as lime to FA ratio [5,6,10,15]. However, the information of pore structure, which has an essential role on the properties, is scarce. Other mineral additives, such as silica fume, are also usually used in the lime-pozzolana pastes. In particular, SF is useful for strength development [14]. The high specific surface area and pozzolanic activity of SF contribute to a denser microstructure thus resulting in an increase of compressive strength [16–19].

It should be noted that FA and SF have become gradually scarce resources in many countries nowadays. It will make sense to develop more kinds of mineral admixtures for the lime-pozzolana pastes. Steel slag is a by-product from steel production. The amount is very large, however, its utilization rate is very low. The cementitious activity of steel slag is much lower than that of FA and SF, and the enhancement effect under autoclaving conditions is rarely reported. Mostafa [20] partially replaced lime and sand with air-cooled slag (AS) and found that the optimum strength was obtained by 50% AS substitution for low-lime mixes (10% CaO) and 30% AS substitution for high-lime mixes (25% CaO). The compact and uniform microstructure filled with tobermorite was responsible for the strength enhancement. Accidentally, Xi et al. [21] confirmed that the replacement of cement with slag and SF markedly increased the compressive strength of the autoclaved pastes because the harmful α-C₂SH phase disappeared and the pore structure was refined.

Although much work has been done on the mechanical properties of the autoclaved lime-pozzolana pastes, thermal properties have received little attention. Taken the urgent requirements of reducing energy consumption whilst maintaining or improving comfort conditions in buildings into account, it is valuable to design building materials with desired thermal properties [22,23]. In particular, higher specific heat is required to damp the exterior temperature fluctuations. Moreover, lower thermal conductivity is desired for the purpose of thermal insulation.

The objective of this work is to investigate the effects of steel slag and silica fume additions on the compressive strength and thermal properties of the autoclaved lime-pozzolana pastes. Four sets of pastes with varying lime content from 12% to 25% were prepared at 180 °C for 8 h. Then FA was replaced with BOFS and SF in each set. The hydration products were evaluated by XRD, and the morphology of hydration products was observed by SEM. The porosity and pore size distribution of the pastes were measured by the *MIP* method. The variations in compressive strength were interpreted by changes in the pore structure and hydration products. The thermal properties assessed in this work included thermal conductivity, thermal diffusivity, and specific heat measured by the transient plane source method. Taken the dominant contribution of pore structure to the thermal conductivity into consideration, a random model was developed to simulate the pore structure and thermal conductivity of the pastes based on the assumption of two phases (gas and solid). The proposed model was validated by comparisons with experimental results and other existing models, and the deviations between the predicted and experimental results were also discussed. The knowledge of thermal conductivity and other thermal properties of construction materials involved in the process of heat transfer is essential in predicting the temperature profile and heat flow through the material.

2. Experimental

2.1. Starting materials

The lime-pozzolana pastes were prepared using pure calcium hydroxide (Fuchen Co., Ltd, Tianjin, China), Portland cement (PⅡ 42.5, Zhujiang Co., Ltd, Guangzhou, China), low calcium FA (Class F fly ash according to ASTM C 618), BOFS (obtained from Shaoguan Iron and Steel Group Co., Ltd., China), and SF (Elkem, China). The chemical compositions of the starting materials used are given in Table 1, and the mineral phases and particle size distributions are shown in Figs. 1 and 2.

2.2. Preparation and test methods

The mix proportions of lime, cement, FA, BOFS and SF are given in Table 2. The mix proportions are prepared in terms of dry weights of the ingredients. Four main groups (P1 – P4 series) with different lime to FA ratios were prepared. The bulk CaO to SiO₂ molar ratio (CaO/SiO₂) of the mixtures was directly proportional to the lime content and was inversely proportional to the FA content. BOFS and SF were used as replacements for FA in each series and also changed the CaO/SiO₂ ratio. Water was added to the mixture of dry materials and the water to solid ratio was adjusted to obtain pastes of a similar consistency. Slump was kept constant at 175 ± 10 mm. For each paste, average 12 samples of 40 × 40 × 40 mm³ cubes were cast into steel mould. After 24 h, the specimens were remolded from the moulds and transferred to the autoclave. The autoclave was maintained at 180 °C for 8 h and then allowed to cool gradually. Finally, all specimens were dried in an oven as long as constant weight was obtained.

Physical and mechanical tests for each specimen were carried out on 6 samples and the average value of the results was used.

Table 1
Chemical compositions (wt%) of cement, FA, BOFS and SF.

Composition	Cement	FA	BOFS	SF
CaO	63.51	7.23	45.16	0.88
SiO₂	21.86	49.20	13.46	91.14
Al₂O₃	4.45	24.82	3.56	1.66
Fe₂O₃	2.35	9.70	21.78	3.80
MgO	1.67	3.50	9.60	–
SO₃	2.91	1.03	–	0.08
Na₂O	0.26	1.00	0.08	–
K₂O	0.51	1.20	0.01	0.76
TiO₂	0.11	–	–	0.15
LOI*	1.89	1.92	1.61	1.38
Others	0.48	0.40	4.74	0.15

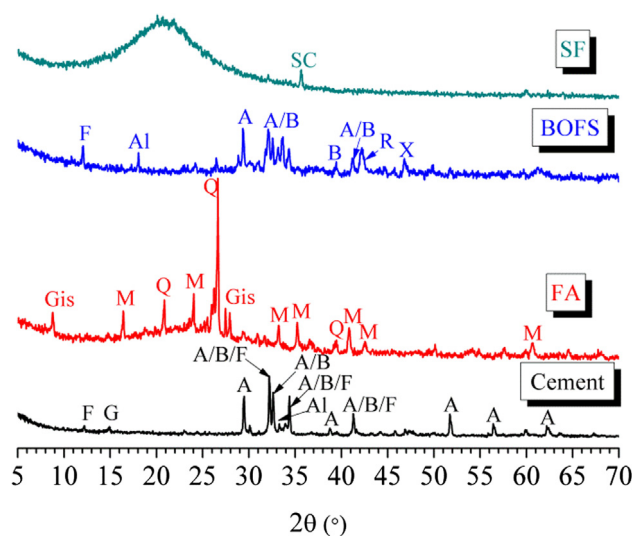* LOI: Loss on ignition.

Fig. 1. XRD patterns of cement, FA, BOFS and SF. (A: Alite; B: Blite; Al: Aluminum phase; F: Ferrite phase; G: Gypsum; Q: Quartz; M: Mullite; Gis: Gismondine; R: RO phase; X: Ca₂Al₂Si₃O₁₂; SC: Silicon carbide).