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Effect of microwave curing on the hydration properties of cement-based material containing glass powder

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HIGHLIGHTS

- Microwave curing accelerates the cement hydration by Na dissolved from glass powder.
- Microwave curing increases the porosity slightly at early age by the increase of pores smaller than 50 nm.
- Microwave curing increases the compactness of interfacial transition zone.
- Microwave curing increases the adsorption of Na by alkali-silica reaction gel.

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ABSTRACT

The effects of microwave curing on the hydration of cement-based materials containing coarse glass powder were studied by performing compressive strength, XRD, TG-DSC, SEM-EDS and MIP analysis. The results showed that microwave curing could effectively improve the early-age compressive strength of mortar prepared with composite binder containing coarse glass powder. Microwave curing accelerated the hydration of cement particles by dissolution of Na^+ from glass powder and thermal effect. Although microwave curing increased the porosity slightly at the early age, the porosity of pores larger than 50 nm did not increase, which has little effect on the decrease of compressive strength. Additionally, microwave curing increased the connection of aggregate, CH, hydrated glass powder and cement particles by reticular C–S–H, leading to a denser microstructure of the interfacial transition zone of mortar. The adsorption of Na^+ by alkali-silica reaction gel under microwave curing reduced the adverse effect of Na^+ on the late hydration of cement and the compressive strength. But the total porosity of mortar under microwave curing was increased by the increase of pores in the range of 50–100 nm, which goes against the improvement of compressive strength.

1. Introduction

In China, municipal solid waste in the large and middle cities is about 168.161 million tons in 2014 [1]. According to the statistics by Wang et al. [2], the glass waste is about 4.2% of municipal solid waste generated in northeast China. Utilization of waste glass in concrete undoubtedly is a potential and incentive way to provide a sustainable solution for waste glass storage. In addition, addition of glass powder is beneficial to aesthetic function [3] and durability [4].

Waste glass consists of mainly amorphous SiO_2 (about 70%). In addition, a certain amount of CaO, Al_2O_3 and Na_2O exist [5,6]. Glass can be used in the concrete as fine aggregate. However, this is easy to come up alkali-silica reaction (ASR) by the delayed Na^+ dissolution [7], which leads to a remarkable strength regression and excessive expansion [4]. This has limited the use of waste glass as fine aggregate replacement. Waste glass can also be used as a kind of supplementary cementitious material [8,9]. The composite binder containing glass powder shows an enhancement in hydration at later ages. This is attributed to the hydration improvement due to a fine particle size and the pozzolanic reaction of glass powder [10]. Increasing the specific surface area [11] or curing temperature [12] can improve the activation of glass powder at early ages. Mirzahosseini et al. also found that glass composition was seen to have a large impact on reactivity. Green glass showed higher reac-

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tivity than clear glass [9]. Glass powders can be well encapsulated into dense and mature gel [13], increasing the long term compressive strength, flexural strength, resistance to ASR and sulphate attack [14,15]. Glass powder is also beneficial to reducing ASR expansions in a mortar prepared with glass waste aggregate [16–19]. Studies have found that the glass powder does not release lots of alkalis into the pore solution to trigger deleterious reaction [20,21], but the Na^+ dissolved from the glass powder is considered as an activator, which is conducive to the early-age hydration of cement [22,23], Na^+ has adverse effects to the later-age compressive strength [22,24].

Microwave curing is characterized by energy saving and rapid stripping for precast concrete [25,26] or concrete repair [27], which is effective in accelerating the hydration of cement [28–30] or improving the pozzolanic reaction of SCMs i.e. metakaolin [31], coal gangue [32], rice husk ash [33], lithium slag [34], fly ash [35] and silica fume [36]. Microwave also plays an important role in nucleation, crystallization and ion transfer during curing. According to the pieces of research conducted on alkali activated fly ash, microwave can increase the dissolution of the amorphous phase to form crystal phase and increase the degree of polymerization for N–A–S–H gel [37,38]. Stubby AFt and small sized CH is formed under microwave curing [30]. According to the research of glass fiber reinforced concrete by Pera et al., microwave curing impedes K^+ transfer to glass fiber when compared with normal curing [39]. This may be caused by the adsorption of K^+ by C–S–H [30]. Because K^+ has strong similarity with Na^+, therefore, microwave curing may also affect the transformation of Na^+ in the cement-glass powder-based material.

The utilization of glass powder under microwave curing has not yet been reported. In order to investigate the effects of glass powder on the hydration properties of cement-based materials under microwave curing, coarse waste glass powder with specific surface area of 230 m^2/kg was used. The cement-coarse glass powder-based material under microwave curing was compared against that cured using (a) normal curing at 20 ± 1 °C, >90% RH, (b) steam curing at 40 °C for 10 h and (c) steam curing at 80 °C for 4 h by performing compressive strength, X-ray diffraction (XRD), Thermogravimetry-differential scanning calorimetry (TG-DSC), Scanning electron microscope-Energy disperse spectroscopy (SEM-EDS) and Mercury intrusion porosimetry (MIP) analysis.

2. Experimental

2.1. Raw materials

The chemical composition of P.I 42.5 cement and the glass powder are listed in Table 1. The China ISO standard sand complied with GB/T 17671-2005 was used. The specimens with the diameter of 4 cm and the height of 8 cm were prepared by cylindrical molds processed by Nylon with wall thickness of 4 mm. The complex binder containing glass powder of 30 wt, % was used to prepare the mortars and pastes. Mortars with water to binder ratio of 0.45 and with the sand to binder ratio of 3.00 were prepared. The water to binder ratio of Pastes was 0.25.

In this study, the waste glass powder has a higher SiO_2, CaO and Na_2O, but much lower Al_2O_3 contents. According to ASTM C 618 and the chemical composition requirement, the glass powder can be classified as Class N natural pozzolan if Na_2O content is not a concern. The XRD and particle size distribution of waste glass powder are shown in Figs. 1 and 2. It can be seen from Fig. 1 that the glass powder mainly consists of amorphous phase. It has been shown that glass powder with particles smaller than 300 μm can effectively mitigate ASR and can even be used as ASR inhibitor in glass aggregate mortars [40]. In this study, the specific surface area of waste glass powder is 230 m^2/kg (the specific surface area of cement is 347 m^2/kg). The particle size of glass powder is smaller than 200 μm, which is better for mitigating the adverseness caused by ASR.

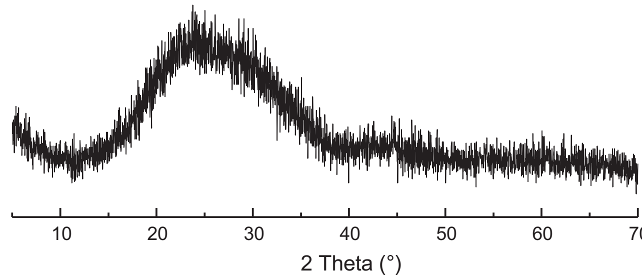

Fig. 1. X-ray diffraction pattern of glass powder.

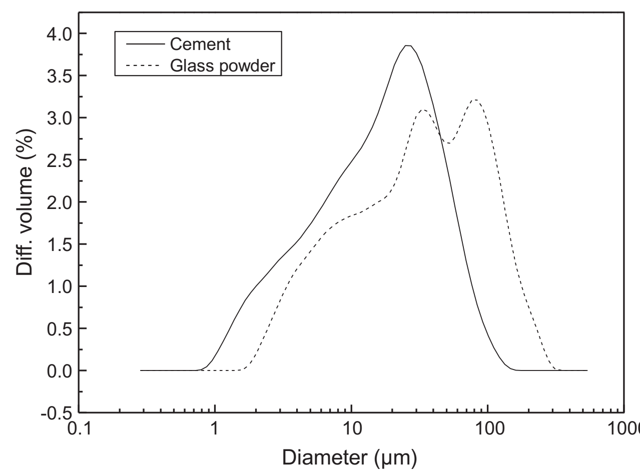

Fig. 2. Particle size distribution of cement and glass powder.

2.2. Curing regimes

Four curing regimes were used in this study: the normal curing with temperature of 20 ± 2 °C and relative humidity >95%; the steam curing at 40 °C for 10 h or 80 °C for 4 h with temperature increase and decrease rate of 15 °C/hour (2-h delay period prior to steam curing is needed); and microwave curing. Microwave oven with output power of 260 w and frequency of 2450 MHz is used for the microwave curing. Eight specimens with molds on a turntable at one-time were heated up. According to the authors' work [30], three microwave curing regimes were selected to optimize the curing regimes. The specific microwave curing regimes are listed in Table 2.

The continued microwave radiation increases the temperature of the samples quickly, leading to the vaporization of the free water, and forming the expanded destruction. In order to control the temperature of the sample before the specimens forming enough tensile strength, the microwave curing regimes as listed in Table 2 were used. The most important property for precast concrete is early-age compressive strength, therefore, in this study, the compressive strength of mortar at 6 h and 1 day was used to select an optimum microwave curing regimes. The results of the compressive strength are shown in Fig. 3. The lowest water to cement ratio and the highest temperature of the mortar after microwave curing are listed in Table 3.

It can be seen from the Fig. 3 and Table 3 that as has been demonstrated the microwave curing can reduce the water to cement ratio [30]. The compressive strength cannot increase adequately for shortening of the total microwave radiation time. However, increase of the microwave radiation time excessively reduce the water to binder ratio so much that there is not enough water for the cement hydra-

Table 1
Chemical composition of P.I 42.5 cement and glass powder (wt., %).

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	Cl	*f*-CaO	Loss on ignition
Cement	20.81	4.92	3.41	62.65	2.38	2.65	0.67	0.012	0.81	2.01
Glass powder	71.8	1.6	0.39	10.7	0.43	0.46	13.2	0.11	–	0.27