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Effects of mineral admixtures on the thermal expansion properties of hardened cement paste

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ABSTRACT

Concrete is a heterogeneous composite material with multiple components that have different thermal expansion properties. Internal stresses are generated if the concrete is rapidly heated or cooled, causing cracking in the micro- or macro-scale. If the coefficient of thermal expansion (CTE) of hardened cement pastes (HCP) is adapted, the thermal stress caused by the mismatch of thermal expansion properties of the components can be mitigated. The effects of the commonly used mineral admixtures (fly ash, ground granulated blast furnace slag and silica fume) on the thermal expansion properties of HCP are investigated. The thermal dilation rates (TDR) of HCP in which Portland cement is partially replaced with mineral admixtures are tested with a dilatometer and the CTE are derived. Replacing Portland cement with mineral admixtures is found to lower the CTE of HCP, which is beneficial for mitigating the thermal mismatch between the HCP and the aggregates. The extent of this lowering effect increases with the increasing replacement proportions of mineral admixtures in the pastes. Through quantitative determination of the porosity and the amount of portlandite in the paste and microscopic observations, it is revealed that the effects of the mineral admixtures are mainly due to the change of the porosity and the amounts of hydration products in the pastes.

1. Introduction

Thermally induced cracks are among the main forms of deterioration of concrete if the structures are exposed to large temperature variations in a short period, for example, during the construction of massive concrete structures. Concrete is a heterogeneous composite material with multiple phases such as the cement paste, aggregates and the interfacial transition zone. The hardened cement paste and the aggregates have different thermal expansion properties, which leads to different volumetric changes if the concrete is rapidly heated or cooled. Internal stress is thus generated, causing cracking of concrete in the micro- or macro-scale [1–3].

The internal stress of concrete caused by temperature variations could be reduced by choosing proper aggregate whose coefficients of thermal expansion (CTE) matches with that of hardened cement paste (HCP). However, selection of proper aggregates could not mitigate the difference of CTE between HCP and the aggregates radically. Furthermore, considerations on the availability and cost of aggregates impede the choice of alternative aggregates frequently in practice. Therefore, it would be more feasible to change the mix of the cement paste or to choose appropriate supplementary materials as binders to adapt the CTE of HCP, so that the thermal stress caused by the different CTE of HCP and aggregates could be minimized [4].

Typical values of the CTE of hardened cement pastes are about $15–20 \times 10^{-6}/°C$ [5], which are approximately two times of that of the normal coarse aggregates [6]. The solid composition, the amount of water and the pore structure are the main factors acting on the CTE of HCP [7]. The linear and volumetric CTE of free water (not chemically bonded in the hydration products) is $69 \times 10^{-6}/°C$ and 207×10^{-6}, which are much higher than that of the HCP. Hence, the presence of large amount of free water is the main reason for the high CTE of cement paste at very early hydration ages [8]. The CTE of hardened cement paste is also a function of its internal relative humidity [9]. The CTE of a compacted material is greater than that of a porous material [10]. It has been reported that the structural physical properties of hydration products such as density play an important role in the thermal dilation of cement pastes [11].

Mineral admixtures such as fly ash, ground granulated blast furnace slag (GGBS) and silica fume (SF) are widely used in concrete to improve the workability and strength or to reduce the costs. They may also contribute to reduce the heat release of cement hydration at early ages, which is very important for controlling the temperature rise of mass concrete and hence reducing the risks of thermal cracking [8,12,13].

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Table 1
Chemical compositions and physical properties of materials.

Materials	Chemical composition (wt.%)									Physical properties	
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	L.O.I.	Blaine ($m^2\ kg^{-1}$)	Density ($kg\ m^{-3}$)
PC	21.02	5.70	3.85	60.10	3.45	2.35	0.40	0.56	2.57	314	3090
GGBS	33.97	11.23	0.35	42.5	7.11	2.69	0.28	0.36	0.86	386	2860
FA	47.86	32.5	4.52	4.09	1.05	–	0.55	1.62	5.71	450	2320
SF	90.12	1.22	0.67	1.14	1.45	–	0.46	0.31	0.47	16800	2250

Notes: "–", not tested.

Although there are some researches about the thermal behavior of HCP and factors affecting its CTE [14], effects of the commonly used mineral admixtures on the thermal expansion properties of HCP are not sufficiently clarified. Replacing Portland cement with these admixtures is known to reduce the total amount of portlandite ($Ca(OH)_2$, abbreviated as CH) and change the porosity of the paste at early ages. Furthermore, the porosity and mean pore diameter of the cement paste were increased with the addition of fly ash and GGBS, which is decisive factor of the strength of concrete [15]. Therefore, it is expected that incorporating these admixtures in the pastes changes the CTE of HCP as well.

In this paper, the thermal expansion properties of HCP with mineral admixtures are investigated. The thermal dilation of HCP in which Portland cement is partially replaced with different types of mineral admixtures is tested and the CTE are analyzed. It is found that partially replacing Portland cement with mineral admixtures lowers the CTE of HCP, which is beneficial for mitigating the thermal mismatch between the HCP and the aggregates. The extent of this lowering effect is closely related to the type and level of mineral admixtures in the pastes. For revealing the mechanism of this lowering effect, the amount of CH and porosity of the HCP is quantitatively measured, and the microstructure of the HPC was observed with the scanning electron microscope technique.

2. Experiments

2.1. Materials

A type of ordinary Portland cement (P.O. 42.5) supplied by the Huaxin Cement Co. Ltd. was used. The fly ash (FA) was supplied by the Yangluo Power Plant. The GGBS was supplied by the Anshan Iron and Steel Group Co. Ltd. Chemical compositions and physical properties of the Portland cement (PC), FA, GGBS and silica fume (SF) are listed in Table 1.

2.2. Sample preparation

Both the Portland cement and mineral admixtures are taken as binders and all cement pastes were mixed with a water to binder (w/b) ratio of 0.35. Mix proportions of the cement pastes are listed in Table 2. For measuring the thermal dilation of the HCP, the freshly mixed cement pastes were casted into plastic cylinder moulds with 8 mm diameter and 50 mm length, and then were sealed immediately. Cube specimens were also made for other tests. All the specimens were cured in a moisture room (RH > 95%) at 20 °C for 28 days and were then taken out for tests.

Table 2
Mix proportions of binder in cement pastes (wt.%)[a].

Specimen notation	PC	FA	GGBS	SF
PC	100	0	0	0
FA15	85	15	0	0
FA30	70	30	0	0
BS15	85	0	15	0
BS30	70	0	30	0
SF10	90	0	0	10
SF15	85	0	0	15

[a] All cement pastes were prepared with w/b = 0.35.

2.3. Tests

2.3.1. Thermal dilation measurement

The thermal dilation rate (TDR) of the specimens was tested with a horizontal dilatometer (model: WorkHorse-1, manufacture: the Anter Corporation). The tests were performed in air with controlled relative humidity RH > 85%. The specimens were heated from 20 °C to 85 °C at a heating rate of 0.5 °C per minute. For every temperature increment of 5 °C, the temperature of the furnace was kept constant for 2 min to allow sufficient temperature equilibrium of the specimen. The length of the specimen at the end of each equilibrium period was then recorded.

The strain and CTE of each specimen was calculated as:

$$\varepsilon = \frac{\Delta L}{L_0} \tag{1}$$

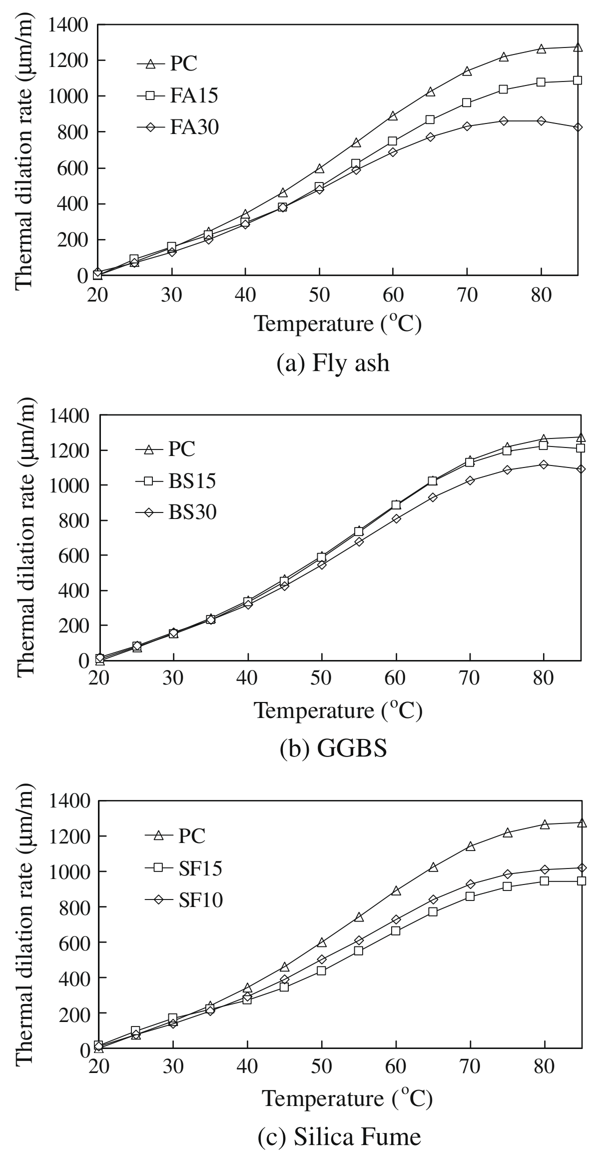

Fig. 1. Thermal dilation rate of cement pastes with mineral admixtures.