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Effect of water-retaining lightweight aggregate on the reduction of thermal expansion coefficient in mortar subject to temperature histories

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ABSTRACT

Cement paste containing blast furnace slag with a water to binder ratio of 0.40 showed considerable increase in thermal expansion coefficient due to self-desiccation. Hence the control of thermal expansion coefficient by internal curing with light weight aggregate was studied.

Three types of fine aggregate, hard sandstone, oven-dry light-weight aggregate (LWA) and water-saturated LWA, and three temperature histories were applied to the mortar specimens with a ground granulated blast furnace slag. Total strains and time-dependent thermal expansion coefficients of the mortar specimens were determined using a newly developed setup comprising a specimen temperature regulator and measuring devices for dimensional change of the specimen. As the experiments of total strain and time-dependent thermal expansion coefficient have shown, the water-saturated LWA was able to control the time-dependent thermal expansion coefficient during the temperature history and could be favorably applied to massive concrete undergoing considerable thermal strain. The effectiveness of water-saturated LWA was found to be valid not only for autogenous shrinkage but also for thermal strain produced by the change in thermal expansion coefficient during the temperature history. These strains have been separated from the total strain by the proposed method.

1. Introduction

The thermal expansion coefficient of cement paste is affected by the relative humidity within the cement paste and increases with a decrease in relative humidity at a relative humidity above 70% [1,2]. Bazant divided the thermal dilatation of cement paste into the thermal expansion of solid and deformation associated with water redistribution inside of the cement paste [3]. The effect of temperature on the relative humidity within cement paste was experimentally studied by Radjy et al. [4], and Grasley and Lange conducted experiments and analysis of the dependence of thermal expansion coefficient on relative humidity that acted as a driving force of shrinkage due to capillary tension [5]. The above studies have clarified to some extent the dependence of thermal expansion coefficient on relative humidity.

When water–binder ratio is relatively low, a decrease in relative humidity in concrete due to self-desiccation at early ages was observed associated with the development of hydration reactions. This also resulted in an increase in thermal expansion coefficient [6].

The time-dependent thermal expansion coefficient of OPC and BFS cement pastes with water–binder ratios of 0.4 and 0.55 were determined by the authors under constant temperature of 20 °C and elevated temperature histories [7]. It was shown that the thermal expansion coefficient of the OPC cement paste with a water cement ratio of 0.4 and BFS cement paste with a water–binder ratio of 0.40 and 0.55 increased with the development of hydration and the increase was accelerated when the elevated temperature was higher. This implied that the increase in thermal expansion coefficient due to self-desiccation, reported by Bjontegaard et al., might also be present at the region of relatively high water–binder ratios, and that, when subjected to elevated temperature histories, the increase in thermal expansion coefficient (which was larger at descent rather than at ascent) resulted in the presence of the residual shrinkage strain after the specimen temperature became constant.

The shrinkage strain originating from the time-dependent thermal expansion coefficient could be a cause of thermal cracking of massive concrete hence its preventive measures need to be developed. Internal curing is a measure to control the thermal expansion coefficient by which this study proposed a new method of maintaining a high relative humidity within the cement paste. Aggregate with high moisture content has often been used for controlling autogenous shrinkage strain [8]. Numerous test results of autogenous shrinkage strain under various constant temperatures have been reported, while little is known about the use of internal curing to control the autogenous shrinkage and the

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Table 1
Properties of Portland cement.

	Density (g/cm^3)	Blaine value (cm^2/g)	LOI (%)	Chemical composition (% mass)								
				SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	Cl^-
OPC	3.16	3110	0.64	21.8	4.49	2.90	63.9	1.84	2.26	0.20	0.38	0.007

Table 2
Properties of blast furnace slag.

	Density (g/cm^3)	Blaine value (cm^2/g)	LOI (%)	Chemical composition (% mass)										
				SiO_2	Al_2O_3	FeO	CaO	MgO	S	Na_2O	K_2O	TiO_2	MnO	Cl
GGBFS	2.90	4050	0.05	33.88	15.34	0.34	42.65	5.81	0.65	0.28	0.31	0.57	0.16	0.004

Table 3
Physical property of fine aggregate.

Materials	Type	Character
Fine aggregate: agg-N	Crushed sand	Surface dry density: 2.57 g/cm^3, water absorption: 2.62%
Fine aggregate: agg-LWA	Lightweight aggregate	Surface dry density: 1.86 g/cm^3, water absorption: 18.8%

increase in thermal expansion coefficient during temperature histories.

The target material in this study is blast furnace slag (BFS) cement mortar with a water–binder ratio of 0.4. Previous research has shown that the BFS cement is sensitive to the increase in thermal expansion coefficient due to self-desiccation [7] and the BFS cement mortar should undergo larger volume changes at early stages than those of ordinary mortar, with reference to past experiments showing larger autogenous shrinkage strain [9] and thermal expansion coefficient [10] of BFS concrete than those of ordinary concrete.

2. Experimental program

2.1. Materials

Binder types used in this experiments were ordinary Portland cement (OPC), ground granulated blast furnace slag (GGBFS) and anhydrite with a specific surface area of 4690 cm^2/g. Properties of the OPC and GGBFS are shown respectively in Tables 1 and 2. The binder compound used in this experiment was OPC substituted by 30% with a secondary binder compound comprising GGBFS substituted by 3.4% with anhydrite. The water to powder ratio was 0.40.

Mortar specimens were prepared with three types of fine aggregates: a crushed hard sandstone (agg-N), a shale-based LWA with a saturated surface-dry moisture condition (agg-LWA-S) and the shale-based LWA with oven-dry moisture condition (agg-LWA-D). The physical properties of aggregates are listed in Table 3. Three types of mortar with an aggregate content of 38% by volume were produced, where single use of agg-N (38%), agg-N (19%) plus agg-LWA-S (19%) and agg-N (19%) plus agg-LWA-D (19%) were applied. These mortar specimens are denoted as N, LWA-S, and LWA-D respectively.

Before mixing, materials were kept for 24 h in a thermostatic chamber at a temperature of 20 °C. Mixing of 20 l per batch was performed with the Omni mixer at room temperature of 23 °C. After introducing water and a mixing of 3 min, scraping was performed followed by a mixing of another 3 min. Then the fresh mortars were moved to the thermostatic chamber. The point of zero age for all data is the time when the powder materials are first mixed with water.

Fine aggregates were conditioned to have a saturated surface-dry moisture content. They were first vacuum-saturated and kept under water for a week. The day before the experiment, they were subjected to a blow drying associated with a repeated confirmation of the saturated surface-dry moisture content by the ASTM C127 cone method. The conditioned aggregates were sealed with a plastic bag and stored until weighing.

2.2. Temperature history

Three temperature histories were applied to the specimen, namely 20 °C–constant (denoted as −20), elevated up to 40 °C (denoted as −40) and elevated up to 60 °C (denoted as −60). The latter two were meant to simulate the hydration heat-induced temperature history in concrete such that, as shown in Fig. 1, keeping 20 °C for the first 10 h and increasing up to the maximum temperature from 10 to 22 h with a rate of temperature increase of 3.33 °C/h (in the case of max. 60 °C) and 1.67 °C/h (in the case of max. 40 °C). After reaching the maximum temperatures, they were kept for 10 h (from 22 to 32 h), after which temperatures were decreased to reach 20 °C at the age of 144 h. The rates of temperature decrease were 0.357 °C/h (in the case of max. 60 °C) and 0.179 °C/h (in the case of max. 40 °C).

Simultaneously with the above temperature histories, short thermal pulses were applied to the specimens to determine the thermal expansion coefficient at each material age. The thermal pulse was plus and minus 5 °C with a rate of 0.2 °C/min and applied every 340 min for the specimen kept under the constant temperature of 20 °C and, for the specimens subjected to a maximum temperature of 60 and 40 °C, at ages of 7, 13, 18, 23, 28, 33, 52, 77, 102, 127, 152, 159, 166 h. Typical temperature change profiles with thermal pulses are shown in Fig. 1. These temperature histories were determined based on the numerical results of a thick wall using FEM with an experimental adiabatic temperature rise data as an input [11,12], and on an experimental measurement.

2.3. Strain measurement [7]

The length-change measuring apparatus used in the experiments is shown in Fig. 2. Dimensions of the specimen for length-change measurement was 10 × 60 × 370 mm which was thin enough to ensure uniform temperature distribution within ±0.2 °C.