



Temperature dependence of autogenous shrinkage of silica fume cement pastes with a very low water–binder ratio



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ABSTRACT

Ultra-high-strength concrete with a large unit cement content undergoes considerable temperature increase inside members due to hydration heat, leading to a higher risk of internal cracking. Hence, the temperature dependence of autogenous shrinkage of cement pastes made with silica fume premixed cement with a water–binder ratio of 0.15 was studied extensively. Development of autogenous shrinkage showed different behaviors before and after the inflection point, and dependence on the temperature after mixing and subsequent temperature histories. The difference in autogenous shrinkage behavior poses problems for winter construction because autogenous shrinkage may increase with decrease in temperature after mixing before the inflection point and with increase in temperature inside concrete members with large cross sections.

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1. Introduction

High-strength concrete has become widely used because its dense material structure enables high-rise concrete structures, smaller cross sections for load bearing members and highly durable structures. Design strengths as high as 200 MPa have been adopted in recent years and it is expected to be more widely applied in the future.

However, high-strength concrete exhibits considerable autogenous shrinkage and brittle fracture. Hence, its properties have been studied mainly in terms of these drawbacks. Control of cracking in high-strength concrete due to autogenous shrinkage is even more important than in the normal concrete because excellent durability is expected owing to its dense material structure. Thus, a large number of studies have been devoted to the autogenous shrinkage of high-strength concrete with low water–cement ratios and its control [1–7].

In general, ultra-high-strength concrete can be obtained with a very low water-to-binder ratio, fine particle additives (normally silica fume, which occupies spaces between portland cement particles), and super plasticizer for dispersion of particles. Due to this low water-to-binder ratio, cement hydration is regulated by the water content, which plays an important role by providing space for precipitation, and hydration rate is gradually decreased due to shortage of water, resulting in self-desiccation in cement paste matrix and shrinkage. When silica fume is added, the pozzolanic reaction is increased. This reaction may cause significant self-desiccation and autogenous shrinkage [8]. There are two mechanisms of argumentation of autogenous shrinkage due to

pozzolanic reaction. One is that the pozzolanic reaction itself consumes much water and accelerates self-desiccation [8,9]. The other is that the pozzolanic reaction consumes portlandite. It was confirmed that space occupied by portlandite becomes empty after the pozzolanic reaction [10] and this decreases the retaining material with regard to C–S–H shrinkage in the cement paste matrix [11].

In addition, there are many kinds of drying or autogenous shrinkage mechanisms, such as change in surface tension, capillary pressure in pore solution, and disjoining pressure between surfaces of cement hydrates [12–17]. The possibility of continuous creep strain produced by the bearing force in response to the capillary force in pore solution on autogenous shrinkage was another topic to be discussed when the theoretical calculation results were compared with experimental data [11].

Very early shrinkage behavior is another issue to be considered. It was reported that large and rapid autogenous shrinkage with almost no relative humidity change is observed within 1-day at room temperature [11]. There is no reasonable explanation of this phenomenon. Even in this period, Young's modulus is normally high enough [18], therefore this phenomenon cannot be attributed to chemical shrinkage.

Ultra-high-strength concrete, because of its larger unit cement content, considerable temperature increase inside of the members was observed due to hydration heat even for members with small cross sections. This has led to a requirement that any crack control strategy and cracking risk assessment for structural members in practice should consider the time-dependent variation of thermal expansion coefficient and autogenous shrinkage taking account of actual temperature variations. In addition to the temperature effect on shrinkage strain through water behavior in the cement paste matrix, elevated temperature may also affect the pozzolanic reaction of silica fume.

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Recently, one of the authors has reported that 1) a temperature increase of more than 45 °C in a column 900 × 900 mm in section due to heat of hydration was confirmed with low heat portland cement partially replaced by silica fume, 2) autogenous shrinkage of concrete is greatly affected by temperature in the fresh state and temperature history due to hydration, and 3) shrinkage and resultant cracking in a column placed in winter were larger than those observed in a concrete member placed in summer [19]. It is therefore important to understand shrinkage behavior under different temperature conditions of low heat portland cement partially replaced by silica fume with a very low water–cement ratio.

2. Experiments

In the present paper, effects of temperature histories due to the temperature after mixing and subsequent hydration heat on the thermal expansion coefficient and autogenous shrinkage were investigated using the same cement as in paper [19]. The same apparatus capable of simultaneously determining thermal expansion coefficient and total strain as reported in the previous study [21] was used.

The following two experiments were conducted.

First, the temperature dependence of autogenous shrinkage of cement pastes was studied during temperature histories that can be actually observed in ultra-high-strength concrete members. The temperature varied for 10 °C, 20 °C and 30 °C to model the temperatures after mixing in winter, intermediate season and summer, and for 0 °C, 25 °C and 45 °C to model the subsequent temperature increase due to hydration heat at each part of a structural member. These experiments are summarized in Table 1.

Next, as a supplementary experiment, cases with temperature after mixing of more than 20 °C were conducted. Within these experiments, autogenous strain and chemical shrinkage were measured. This is summarized in Table 2.

2.1. Temperature dependence of autogenous shrinkage of cement pastes subjected to temperature history

In this experiment, the autogenous shrinkage of cement pastes subjected to temperature histories imitating actual construction conditions was studied.

2.1.1. Materials

The cement used in this experiment was a low-heat portland cement premixed with 10% of silica fume (density of 3.08 g/cm³), and Blaine surface area of 5600 cm²/g (denoted as B). The base low-heat cement comprises C₃S of 29.1%, C₂S of 50.1%, C₃A of 4.3% and C₄AF of 9.6% as estimated by the Bogue equation, and Blaine surface area of 3600 cm²/g and density of 3.22 g/cm³. The silica fume comprises 95% silica and with a specific surface area of 17.1 m²/g and a density of 2.24 g/cm³. Chemical admixtures were a superplasticizer of

Table 1

Summary of temperature conditions of experiments in Series 1. The measured items were total strain, thermal expansion coefficient, Young's modulus and equilibrium relative humidity. Autogenous shrinkage was calculated from the data of total strain, thermal strain and temperature history.

Temperature of fresh concrete	Temperature difference in the history	Maximum temperature in the history	Notation
10 °C	+0 °C	10 °C	P-10-10
	+25 °C	35 °C	P-10-35
	+45 °C	55 °C	P-10-55
20 °C	+0 °C	20 °C	P-20-20
	+25 °C	45 °C	P-20-45
	+45 °C	65 °C	P-20-65
30 °C	+0 °C	30 °C	P-30-30
	+25 °C	55 °C	P-30-55
	+45 °C	75 °C	P-30-75

Table 2

Summary of temperature conditions of experiments in Series 2. The measured items were autogenous strain and chemical shrinkage.

Temperature of fresh concrete	Temperature before 7 day	Temperature after 7 days	Notation
20 °C	20 °C	20 °C	P-c20-20
30 °C	30 °C	20 °C	P-c30-20
40 °C	40 °C	20 °C	P-c40-20
50 °C	50 °C	20 °C	P-c50-20
60 °C	60 °C	20 °C	P-c60-20

polycarboxylic ether denoted as SP and an anti-foaming agent denoted as D.

The water–binder ratio of the cement paste was 0.15 and the SP was dosed at 1% of the cement mass. Dosages of both SP and A were not corrected with solid content and were included in the unit water content. Mixing was performed with an Omni mixer for 3 min after introducing water and for another 4 min after scraping the adhered paste from the inside of the mixer.

2.1.2. Temperature history

Imitating the concrete placement in various seasons, temperatures after mixing were targeted to be 10 °C, 20 °C and 30 °C. The difference between the targeted and actual temperatures was a maximum of 9 °C while the difference was mitigated with the subsequent temperature control and all the mixes attained their targeted temperatures within 40 min after the water was added.

In addition to each temperature after mixing, temperature histories with a maximum temperature of +25 °C and +45 °C, imitating the temperature increase due to hydration heat liberation, were imposed. The applied temperature increase was based on the measured actual temperature histories at the edge and center of the full-scale columns [20].

Commencement of the temperature increase was assumed to be at the age of 12 h for all the experiments. Simple comparison of the temperature dependence though the actual hydration heat liberation may depend on the unit cement content, the temperature after mixing and the dosage of superplasticizer. The temperature increased at a constant rate, reached a maximum at the age of 32 h and then decreased to reach the same temperature as that after mixing. The measured temperature histories of specimens are described later (Fig. 5).

In this paper, each temperature history is reflected in its specimen name. For instance, a cement paste specimen with a temperature after mixing of 20 °C and a temperature increase of +45 °C should be denoted as P-20-65. During the temperature history, specimens were subjected to thermal pulses to measure the coefficient of thermal expansion.

2.1.3. Thermal expansion coefficient and autogenous shrinkage strain

Details of the length change measuring apparatus and the method of determining thermal expansion coefficient and autogenous shrinkage have been reported in a previous paper [21]. A schematic of the measurement system is shown in Fig. 1.

The thermal expansion coefficient was determined by applying thermal pulses during the temperature history. A thermal pulse comprises four incremental changes in temperature, a 5-degree ascent and descent followed by a 5-degree descent and ascent, applied at a specified material age as shown in Fig. 2. The least-square fit of the temperature changes and associated thermal strains gave the thermal expansion coefficient at the age and the mean temperature. The ascent and descent temperature rate was 0.2 °C/min.

An example of thermal strain measurement of specimen P-20-65 during a thermal pulse is shown in Fig. 2, where the effect of autogenous shrinkage is considerable at the age of 10 h (upper) and comparatively small at the age of 131 h (lower).

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