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Autogenous shrinkage of high performance concrete containing mineral admixtures under different curing temperatures

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HIGHLIGHTS

- We provided a database of autogenous shrinkage of HPC under different temperatures.
- We updated the measurement method of autogenous shrinkage.
- FA and BS will decrease and increase autogenous shrinkage respectively.
- Both the rate and the magnitude of autogenous shrinkage vary with temperature.
- We proposed an equation of estimating autogenous shrinkage at different temperatures.

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ABSTRACT

The present study investigated experimentally autogenous shrinkage behaviors of high performance concrete (HPC) containing fly ash (FA) and blast-furnace slag (BS) exposed to different isothermal temperatures. The deformation of concrete specimen after initial setting was determined using a modified method which is based on non-contact measurement technique. The results indicated that the method can precisely monitor non-load induced deformations of HPC mixtures. The inclusions of BS and FA resulted in significant increase and decrease of autogenous shrinkage of HPC, respectively. While both the rate and the magnitude of autogenous shrinkage for almost all mixtures were increased with rise of curing temperature, extents of the influence were varied with water–binder ratio, composition of cementitious materials and age. It is noted that although the equivalent age equation was widely applied to evaluate temperature dependence of mechanical properties of cement-based materials, its applicability on autogenous shrinkage of HPC was questionable. In addition, on a trial and error basis, a modified autogenous shrinkage equation was performed in terms of numerical fitting of the measured data.

1. Introduction

In recent years, as a typical structural material, high performance concrete (HPC) is widely used in civil engineering because of its excellent performance, namely high workability, high strength, high durability and long-term performance [1–3]. For the purpose of improving performance of concrete, lower and lower w/b are executed [2,3], and a series of mineral and chemical admixtures (such as fly ash (FA), ground granulated blast furnace slag (BS) and superplasticizer) are introduced [1–3]. Accordingly, many aspects of micro-structures of HPC are distinguished from normal concrete, which further results in differences of macro-properties [1,2]. As a predominant aspect, considerable early-age volume changes of HPC usually compromise its “high performance”. Due to various types of internally and/or externally restraints in concrete structures, these volume changes cannot release freely, and tensile stress often arises. As tensile stress increases and exceeds tensile strength of HPC at a specific age, early-age cracking happens. Once cracking, the strength, long-term performance and global stability of HPC structures will be deteriorated seriously. In general, early-age volume changes of HPC are mainly composed of autogenous shrinkage, thermal deformation and drying shrinkage [1], which induced by self-desiccation of capillary porosity, by temperature and moisture gradients between concrete and exterior surroundings, respectively [1–3].

It is observed that compared to thermal deformation and drying shrinkage, autogenous shrinkage accounts for the foremost

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significance in volume change components of HPC at early ages [3,4]. Researchers have issued a great quantity of scientific literature and technical reports on terminology, experimental methods, mechanism, and prediction models on autogenous shrinkage and induced restrained stress [1,3–6] in last two decades. As a typical aging material, concrete is subjected to vital temperature variations induced by heat release (temperature rise) associated with hydration of cementitious materials, by subsequent cooling (temperature drop) due to heat transfer [3,6,7], and by changes in ambient temperature when concreting is performed under relatively hot and cold climatic conditions. Autogenous shrinkage mainly results from self-desiccation in porosity, which is intensively related to cement hydration. Whereas the rate and degree of hydration closely depend on the exposed temperature history of concrete, it can be inferred that a link is existed between the exposed temperature history and autogenous shrinkage.

However, limited research work on this topic is available, and most of the work focuses on cement pastes. The influences of curing temperature on autogenous shrinkage have been investigated firstly by Tazawa and Miyazawa in Japan [8], who confirmed temperature effects of autogenous shrinkage can be estimated by an equivalent age equation. Jensen and Hansen demonstrated that the traditional maturity concept generally is not applicable to autogenous deformation and autogenous RH change of hardening cement paste [10]. Weiss, Lura and Sant examined the influences of curing temperature on autogenous deformation in cement paste containing shrinkage reducing admixtures [9,27]. Based on experimental investigation, Chu et al. [7] concluded that high curing temperature at early ages results in lower autogenous shrinkage at later ages when compared to the cases subjected to relatively low curing temperature at early ages. They suggested that the equivalent age function [10,11] is not applicable to evaluate temperature dependence of autogenous shrinkage at early ages [9]. From the point of view of development rate, Maruyama and Teramoto [12] divided autogenous shrinkage of ultra high strength concrete into two stages, i.e., the earlier age followed by the later age stage. Lower temperature increased autogenous shrinkage at earlier-age stage; higher temperature produced larger autogenous shrinkage at later-age stage. Therefore, in these literatures, no consensus is reached on autogenous shrinkage behavior exposed to different temperature conditions. Meanwhile, little work is focused on effects of FA and BS that is commonly used as supplementary cementing materials [24,28–31] on autogenous shrinkage.

In order to explore the influence of temperature on autogenous shrinkage of HPC in depth, an experimental investigation is performed on a series of typical HPC containing FA and BS exposed to 3 different isothermal temperatures. For the sake of monitoring volume change strain of HPC exactly, especially at early ages, a testing method based on a non-contact measurement technique is used. Also, a modification based on Tazawa and Miyazawa's model of autogenous shrinkage [8] is performed.

2. Experimental program

2.1. Experimental parameters

As tabulated in Table 1, experimental parameters mainly including w/b, composition of cementitous material and curing temperature. Corresponding levels of each parameter are set based on characteristic of HPC mixtures and typical exposure conditions, respectively. Also, substitution ratios of FA and BS are in the range of typical applications.

Table 1
Testing parameters and their levels.

Testing parameters	Corresponding levels
Water binder ratio (w/b)	0.20; 0.30; 0.40
Composition of cementitious materials (by mass)	OP[a]: 100%OP, no inclusions of FA and BS FA[b]: 65%OP + 35%FA BS[c]: 50%OP + 50%BS
Curing temperature (°C)	10; 20; 30
Age of strength test (*d*)	1; 3; 7; 14; 28

[a] OP stands for ordinary Portland cement.
[b] FA stands for fly ash.
[c] BS stands for blast furnace slag.

2.2. Materials and mixture proportions

2.2.1. Materials

Ordinary Portland cement (OP) in accordance with China National Standard GB 175-2009, fly ash (FA) and ground granulated blast furnace slag (BS) are used as cementitious materials (binders). Their oxide compositions based on X-ray fluorescence analysis and potential mineral compounds of cement are tabulated in Table 2. Crushed stone with a maximum nominal size of 20 mm, and river sand are used as coarse and fine aggregates, respectively. Also, a liquid polycarboxylate-based superplasticizer (SP) is used to adjust workability of different w/b HPC mixtures to the same level.

2.2.2. Concrete mixture proportions

As shown in Table 3, the mixtures without mineral admixture are viewed as control mixtures. As far as the mixtures with the same w/b, total mass contents of binders are constant, i.e., FA and BS replace cement by equivalent mass, respectively. For the purpose of gaining similar slump, slump flow and air content, the dosages of superplasticizer are properly adjusted. One more thing, in order to keep the same level of restraint effects of aggregate to volume change, the same amount of fine and coarse aggregate are adopted in all mixtures excluding "VF-30".

2.3. Autogenous shrinkage

2.3.1. Testing methods

Measurements of autogenous shrinkage have been carried out in two fundamentally different ways: measurement of volumetric strain and of linear strain (one-dimensional strain). Compared to measuring volumetric strain, linear strain provides more explicit engineering definition, and its measurement is much easier to handle and control. One major disadvantage of the previous linear method [3,13–15] is the tremendous obstacle of starting the measurements immediately after casting, because measurement apparatus (e.g., linear variable differential transducer) is difficult to install when concrete is at a plastic state before setting.

Recently, early-age linear strain of concrete is generally measured with non-contact sensors [13–15,27], such as laser-based sensor and capacitive sensors. In this work, they are replaced by an eddy-current displacement sensor (ECDS) which operate with electromagnetic induction effect. The details of the testing apparatus using the ECDS are shown in Fig. 1. There has certain advantages of ECDS used over laser-based sensors, such as the requirements on testing environment of the former are lower than those of the latter, which cannot be applied in dirty and dusty surrounding, and the prices of the ECDS are generally superior to the laser-based ones [15]. To improve the reusing rate of the ECDS, up to the age of 3 days, electric

Table 2
Oxide and potential mineral compositions (by mass) and physical properties of cementitious materials.

Items	Unit	OP	FA	BS
CaO	%	62.64	3.60	31.33
SiO_2	%	22.24	59.31	33.05
Al_2O_3	%	5.34	22.10	15.47
Fe_2O_3	%	3.20	8.26	0.27
MgO	%	0.63	1.82	16.11
Na_2O	%	0.29	0.33	0.72
SO_3	%	2.64	0.28	0.37
LOI[a]	%	1.67	–	–
Potential mineral compounds				
C_3S	%	45.5	–	–
C_2S	%	29.5	–	–
C_3A	%	8.7	–	–
C_4AF	%	9.7	–	–
Specific gravity	g/cm^3	3.12	2.25	2.90
Fineness[b]	m^2/kg	376	343	436

[a] LOI stands for loss on ignition of cement.
[b] Test by the Blaine air permeability method.