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Drying shrinkage prediction of paste containing meta-kaolin and ultrafine fly ash for developing ultra-high performance concrete

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ABSTRACT

The drying shrinkage development of the paste fraction of ultra-high performance concrete containing binary and ternary blends of meta-kaolin, fly ash and cement were investigated and predicted. The test results showed that, compared with the use of pure cement, the binary use of silica fume and cement or the binary use of fly ash and cement resulted in an increase in the drying shrinkage of paste, and the binary use of meta-kaolin and cement resulted in a decrease in the drying shrinkage of paste. The ternary use of meta-kaolin, fly ash and cement could produce paste with lower drying shrinkage than the binary use of silica fume and cement at the same supplementary cementitious materials content. Modified Gardner model and modified Bazant–Baweja B3 model were developed to predict the drying shrinkage development of the paste fraction of ultra-high performance concrete.

1. Introduction

Ultra-high performance concrete (UHPC) is a new type of concrete. It typically refers to concrete having compressive strength higher than 150 MPa at the age of 28 days [1–4]. UHPC is produced with very low w/cm (<0.2), high cementitious materials content, and high HRWRA content. This may result in high autogenous shrinkage of UHPC which is caused by the self-desiccation at the early age of cement hydration [5–7], and high drying shrinkage of UHPC which is caused by the loss of water from the hardened concrete in a long term [5,7]. A study on autogenous shrinkage of UHPC (by ASTM C1698) showed that the autogenous shrinkage of UHPC did not further increase at 36 h after the final setting, and the maximum autogenous shrinkage value was 440 micro strains [8,9]. Moreover, the drying shrinkage of the same UHPC (by ASTM C596) did not further increase after period of exposure of 117 days, and the maximum drying shrinkage value was 630 micro strains [8,10].

From the perspective of structural application, cracks may occur in restrained structural members due to excessive shrinking of UHPC. The tendency of crack depends on the relation between the development of stress induced by shrinkage and the development of tensile strength of concrete materials. Although no threshold drying shrinkage strain at which shrinkage cracks occurs in UHPC has been reported in the available literature, it is desirable to reduce the drying shrinkage of UHPC from the consideration of the long term durability of structural members. Many previous studies focused on the use of aggregate and reinforcing fibers to reduce the drying shrinkage of concrete, due to the fact that the increase in the aggregate content or fiber content reduced the volume of paste in concrete and restrained the shrinking of paste [5–8,11–14]. Limitations of this approach was recognized, including reduced workability of fresh concrete [15–17]. Thus, it is of interest to reduce the drying shrinkage of the paste itself in order to reduce the drying shrinkage of concrete.

Silica fume (SFU) was the most widely used supplementary cementitious materials (SCM) in UHPC formulation to achieve superior mechanical properties [1–4,18–20]. Noticing that the use of SFU increased the drying shrinkage of concrete [4,8,21–24], it had great significance to investigate the drying shrinkage behavior of UHPC containing other types of SCM. Meta-kaolin (MK) was found to reduce the drying shrinkage of concrete [21,22,25,26]. Studies on the relation between drying shrinkage and water loss of concrete revealed that the reduced drying shrinkage could be attributed to the reduced rate of water loss from hardened paste in presence of MK [27,28]. However, the use of MK reduced the workability of fresh concrete. A combined used of fly ash (FA) and MK would be a potential approach of producing low drying shrinkage paste with good workability.

The present study focused on the free drying shrinkage behavior of paste fraction of UHPC containing binary and ternary blends of MK, FA and cement. The free drying shrinkage behavior of paste containing binary blend of SFU and cement was also investigated for comparison. Free drying shrinkage was measured following the

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Table 1
Physical and chemical properties of materials.

	Cement	SFU	FA	MK
SiO_2 (%)	20.5	95.5	54.1	50.4
Fe_2O_3 (%)	3.5	0.3	8.01	0.45
Al_2O_3 (%)	4.9	0.7	27.8	42.6
CaO (%)	64.1	0.4	1.34	0.02
MgO (%)	1.3	0.5	0.90	0.16
Na_2O_{eq} (%)	0.47	1.4	2.13	0.22
SO_3 (%)	3.6	–	0.16	0.00
LOI (%)	1.34	2.0	2.39	1.63
Specific gravity	3.15	2.20	2.49	2.20

test procedures described in ASTM C596 [10]. In this test, the first measurement was at 3 days after mixing fresh mixture. Considering that the autogenous shrinkage of UHPC did not further increase within 36 h after the final setting of fresh mixture [8], the drying shrinkage value measured by ASTM C596 was not affected by autogenous shrinkage of paste. Predictions of the free drying shrinkage development of paste containing binary and ternary blends of MK, FA and cement were developed as well.

2. Experimental program

2.1. Materials

A Type III portland cement meeting ASTM C150 specification was used for the experimental study [29]. The Blaine's surface area of the cement was 540 m^2/kg. Three types of SCM were used for study, which were class F ultrafine FA with an average particle size of 3 μm, high reactive MK with an average particle size of 1.4 μm, and a low carbon content SFU with an average particle size of 0.15 μm. The chemical compositions and physical properties of the portland cement and the SCMs are given in Table 1.

A powder form of polycarboxylate ether-based high-range water-reducing admixture named Melflux® 4930F was used to improve the workability of paste.

2.2. Mixture proportions

In total, 18 paste mixtures were prepared to study the drying shrinkage behavior of pastes containing binary and ternary blends of MK, FA and cement, in comparison with paste using binary blend of SFU and cement at the same supplementary cementitious materials content. The supplementary cementitious materials content was expressed as the mass ratio of supplementary cementitious materials to portland cement (SCM/c). The investigated levels of SCM/c included 0, 0.05, 0.1, 0.2, 0.3 and 0.4. For the entire investigation, the w/cm by mass was fixed at 0.2, and the HRWRA dosage was fixed at 1% by mass of the total cementitious materials. The relative mixture proportions of the 18 paste mixtures are shown in Table 2.

As Table 2 shows, the first paste C was the control which only contained Type III portland cement as cementitious material.

The next three pastes S1, S2, and S3 contained binary blend of SFU and cement, and the corresponding levels of SCM/c were 0.1, 0.2 and 0.3, respectively. The following three pastes M1, M2 and M3 contained binary blend of MK and cement, and the corresponding levels of SCM/c were 0.05, 0.1 and 0.2, respectively. Similarly, the following three pastes F1, F2 and F3 contained binary blend of FA and cement, and the corresponding levels of SCM/c were 0.1, 0.2 and 0.3, respectively. The effect of different types of SCM and their content on the properties of paste was determined by comparing these nine mixtures.

The last eight pastes MF1, MF2, MF3, MF4, MF5, MF6, MF7 and MF8 were prepared by using ternary blend of MK, FA and cement at different proportions. The levels of SCM/c investigated included 0.1, 0.2, 0.3 and 0.4.

The quantities of materials used for 1 m^3 of paste are presented in Table 3.

2.3. Specimens preparation

Fresh pastes were prepared by a UNIVEX M20 planetary mixer. The mixing procedure was divided into three stages, as some of the mixtures took much longer time to reach fluid state than others, in particular when MK content was high. First, the cementitious materials and the HRWRA were dry mixed for about 4 min at low speed (100 RPM). Then the mixing water was added to the dry mixture. The mixing continued at low speed until the dry mixture started to behave as fluid. As soon as the paste reached fluid state, the mixing speed was increased to medium speed (300 RPM), and the fluid mixture was mixed for another 3 min. The workability of paste was measured immediately after mixing process was finished.

The fresh pastes were cast into molds without external vibration. Then, the specimens were kept in the moist room maintained at 100% relative humidity and 23 °C in accordance with ASTM C511.

Table 2
Relative proportions of materials in paste (by mass).

Paste ID	c[a]/c[a]	SFU/c[a]	MK/c[a]	FA/c[a]	SCM[b]/c[a]	Water/cm[c]	HRWRA/cm[c] (%)
C	1.00	0	0	0	0.00	0.20	1.0
S1		0.10	0	0	0.10		
S2		0.20	0	0	0.20		
S3		0.30	0	0	0.30		
M1		0	0.05	0	0.05		
M2		0	0.10	0	0.10		
M3		0	0.20		0.20		
F1		0	0	0.10	0.10		
F2		0	0	0.20	0.20		
F3		0	0	0.30	0.30		
MF1		0	0.05	0.05	0.10		
MF2		0	0.05	0.15	0.20		
MF3		0	0.10	0.10	0.20		
MF4		0	0.05	0.25	0.30		
MF5		0	0.10	0.20	0.30		
MF6		0	0.20	0.10	0.30		
MF7		0	0.10	0.30	0.40		
MF8		0	0.20	0.20	0.40		

[a] Cement.
[b] Supplementary cementing materials: silica fume alone or meta-kaolin + fly ash.
[c] Cementitious materials: cement + SCM.