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Characterizations of autogenous and drying shrinkage of ultra-high performance concrete (UHPC): An experimental study

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ABSTRACT

Due to the high content of binder and low water to cement ratio, ultra-high performance concrete (UHPC), exhibits higher levels of autogenous shrinkage compared to ordinary concrete. This shrinkage has been shown to lead to a reduction in strength over time as a result of the formation of thermal and shrinkage cracks. Aiming to mitigate the negative impacts associated with shrinkage, the efficacy of three different techniques to reduce the impact of shrinkage are investigated, namely: reducing the binder content; incorporating high levels of shrinkage reducing admixture; and using crushed ice to partially replace mixing water. The effects of these techniques are experimentally investigated and the underlying mechanisms of the actions are characterized. It is found that autogenous shrinkage predominates the overall shrinkage of UHPC and that the three techniques can effectively reduce shrinkage without significantly compromising its mechanical strength. The results also suggest, that from the perspective of reducing shrinkage: the optimal binder-to-sand ratio is in the range of 1–1.1; the optimal dosage rate of shrinkage reducing admixture is 1%; and replacing of mixing water by crushed ice up to 50% by weight has also induced a significant reduction in shrinkage.

1. Introduction

Ultra-high performance concrete (UHPC) is characterized by very high compressive strength and superior durability [1–5]. These characteristics are typically achieved using mix designs with high quantities of binder (cement and silica fume) and low water to cement ratios (in the order of 0.2 or less). As a result, partially hydrated binder is often present within the mortar resulting in an increase in autogenous shrinkage [6,7] up to an order of magnitude greater than that of conventional concrete [8–13]. Hence total shrinkage strains in UHPC (including both the autogenous- and drying-shrinkage) are expected to be higher than conventional concrete. This is significant as high early age shrinkage strains may result in early age cracking [4,9,14–16]; and if containing fibers, a reduction in strength over time due to the restraint provided by fibers [9,11,17,18].

The importance of quantifying shrinkage strains has led to a number of recent studies aimed at understanding the underlying mechanisms governing autogenous shrinkage of UHPC and its impact on performance. For example, experimental programs conducted by Yoo et al. [15,19,20] and Şahmaran et al. [16,21,22] systematically examined the effects of mixing proportion, curing condition, geometry and specimen restraint on autogenous shrinkage of UHPC specimens. Research has also identified several means for reducing both the magnitude of shrinkage strains, as well as the time over which they develop. For example, Rößler et al. [23] have shown that by curing at a temperature of 20 °C, a reduction of 85% in autogenous shrinkage strains is possible compared to those obtained under at 90 °C heat curing. Alternatively [24,25] have shown that it is possible to reduce drying shrinkage via the inclusion of moisture retaining superabsorbent polymers into the mix. These release water over time, replacing that lost due to hydration and drying, resulting in a reduction of shrinkage strains of up to 75%. The effects of shrinkage reducing admixtures on the autogenous shrinkage of UHPC have been investigated by Refs. [11,26,27].

In this paper a standard UHPC mix which has been widely investigated at both the material [14,28,29] and member levels [1,30,31] is taken as a baseline, and simple means for improving its dimensional stability is investigated. Approaches considered in this study include:

- The use of iced water in the mix design to lower concrete temperature and hence reduce the potential for autogenous shrinkage and temperature induced deformations [32].
- Varying mix design proportions to identify the beneficial restraining influence of (fine) aggregate, and the presence of unhydrated binders that may act as a filler providing additional dimensional stability.
- Varying mix design proportions to identify the reduction in

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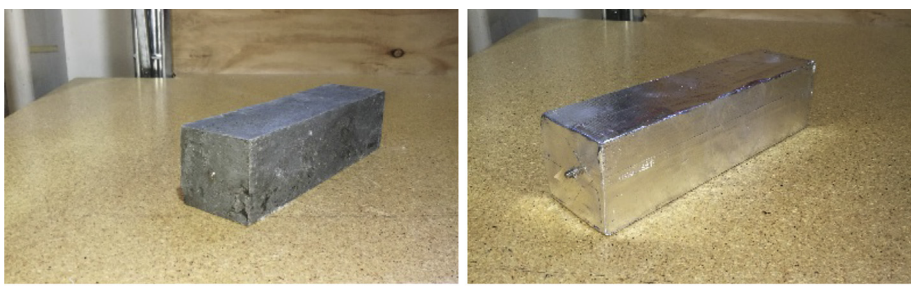
Table 1
Mix proportion of the UHPCs.

Mix	Cement (wr)	Silica fume (wr)	Sand (wr)	water (wr)	Crushed ice (wr)	SRA[1] (wr)	SP[2] (wr)	*w/b*	*b/s*	Paste weight fraction	Mixing water weight fraction
U-0.8	0.632	0.168	1.000	0.104			0.024	0.152	0.800	0.480	0.063
U-0.9	0.711	0.189	1.000	0.117			0.027	0.152	0.900	0.509	0.067
U-1.0/SRA-0/Ice-0	0.790	0.210	1.000	0.130			0.030	0.152	1.000	0.535	0.070
U-1.1	0.869	0.231	1.000	0.143			0.033	0.152	1.100	0.559	0.073
U-1.266	1.000	0.266	1.000	0.165			0.038	0.152	1.266	0.593	0.078
SRA-1	0.790	0.210	1.000	0.129		0.008	0.030	0.152	1.000	0.535	0.070
SRA-2	0.790	0.210	1.000	0.127		0.016	0.030	0.152	1.000	0.535	0.070
SRA-3	0.790	0.210	1.000	0.126		0.024	0.030	0.152	1.000	0.535	0.070
Ice-25/75	0.790	0.210	1.000	0.098	0.033		0.030	0.152	1.000	0.535	0.070
Ice-50/50	0.790	0.210	1.000	0.065	0.065		0.030	0.152	1.000	0.535	0.070

[1]. Containing 20% water.
[2]. Containing 70% water.



(a) (b)

Fig. 1. Shrinkage test specimens: a) sealed prism for autogenous shrinkage measurement; b) unsealed prism for free total shrinkage measurements.

Table 2
Influence of binder-to-sand ratio on rheological properties of fresh UHPCs.

Specimen	*b/s* ratio	Slump (mm)	Flow table (mm)	J-ring (mm)
U-0.8	0.8	165	375	412
U-0.9	0.9	240	440	451
U-1.0	1	235	425	443
U-1.1	1.1	250	430	455
U-1.266	1.266	250	470	506

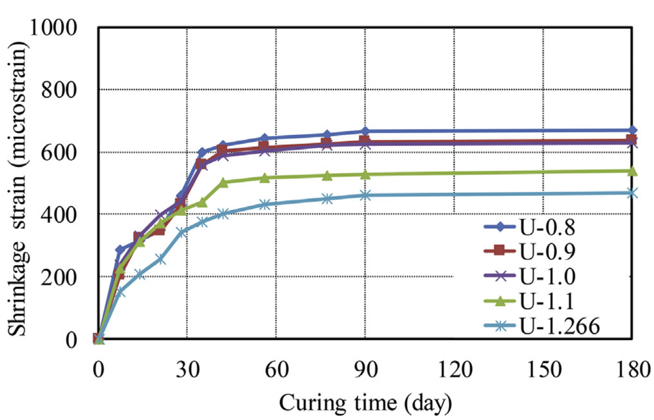


Fig. 2. Effect of binder-to-sand ratio on autogenous shrinkage.

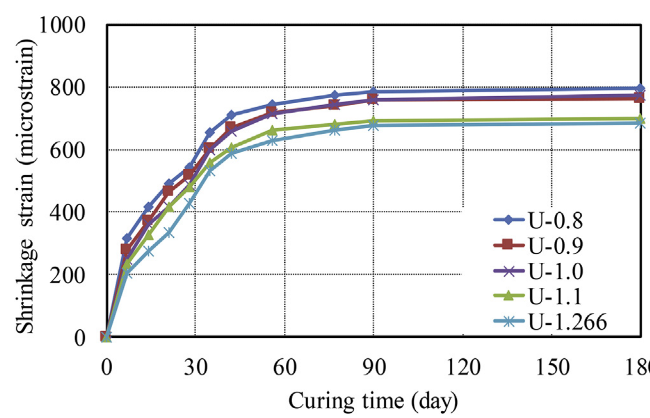


Fig. 3. Effect of binder-to-sand ratio on free total shrinkage.

autogenous shrinkage due to a reduction in cementitious binder content.

- The use of high dosages of conventional shrinkage reducing admixtures to physically reduce shrinkage by reducing the surface tension in the concrete pore water.

For each approach investigated a range of material and characterization tests are conducted to determine the relative effectiveness of each approach, as well as the underlying mechanism of action. It is envisaged that this work will assist in allowing concrete technologists to decide on the most appropriate means for achieving the desired reduction in shrinkage.

In the remainder of the paper the characteristics and constituents of the UHPC materials investigated are first described. This is followed by a description of the experimental method and tests conducted; finally, the change in autogenous and drying shrinkage achieved by each approach is presented as well as a discussion of the mechanism of action.

2. Experimental program

2.1. Ingredients used for UHPC mix

Two types of cementitious binder were used, namely sulphate resisting cement and silica fume. The sulphate resisting cement, which