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Effects of shrinkage reducing admixture and wollastonite microfiber on early-age behavior of ultra-high performance concrete

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ABSTRACT

In this study, the effect of incorporating shrinkage reducing admixtures (SRA) and/or wollastonite microfibers on the early-age shrinkage behavior and cracking potential of ultra-high performance concrete (UHPC) was explored. Wollastonite microfibers were added at rates of 0%, 4% and 12% as partial volume replacement for cement, while SRA was added at 1% and 2% by cement weight. Results show that the reinforcing effect induced by wollastonite microfibers mitigated the reduction in compressive strength induced by SRA. Addition of wollastonite microfibers to SRA mixtures did not impart a significant change in the measured free shrinkage strain, while it enhanced the cracking resistance compared to that of mixtures incorporating SRA alone. Moreover, adding wollastonite microfibers reduced the leaching of SRA from concrete under submerged conditions, thus leading to higher efficiency of SRA in reducing shrinkage. Partially replacing cement with natural wollastonite microfibers also leads to a reduction in the cement factor, which represents economic and environmental benefits.

1. Introduction

Ultra-high performance concrete (UHPC) represents a leap development in concrete technology. Its very high strength and enhanced durability motivate its use in an increasing number of applications. UHPC can be achieved through enhancing homogeneity (for instance by eliminating coarse aggregates) [1], producing stronger and higher packing density microstructure through using very low water-to-cement ratio (w/c) [2], and incorporating high content of effective pozzolans. However, a very low w/c combined with a high cementitious content leads to significant shrinkage that may induce early-age cracking in the presence of restraint. Such shrinkage cracks can facilitate the penetration of aggressive substances to concrete, leading to a reduction in its performance, serviceability, and durability [3]. Shrinkage can generally be divided into two main types: drying shrinkage and autogenous shrinkage. Drying shrinkage is the reduction in the concrete volume due to moisture loss. It is mainly affected by the total moisture loss, rate of evaporation and bleeding. Contrary to conventional drying, autogenous shrinkage is driven by the internal drying (without mass loss) of capillary pores as a result of water consumption by the hydration reactions of cement [4]. Furthermore, the high cementitious materials content of UHPC increases its carbon-footprint and environmental impact due to a high energy consumption and CO_2 emissions associated with cement production.

Several methods have been proposed to minimize the cracking potential of concrete including using coarser cement particles, expansive additives, shrinkage reducing admixtures and/or improving curing conditions [5–8]. These approaches primarily focus on reducing shrinkage in concrete, thereby reducing the level of residual stress that develops [9]. Among these, the most commonly used technique is the addition of shrinkage-reducing admixtures (SRAs). SRAs directly influence shrinkage by decreasing the surface tension of the pore solution, leading to lower capillary stresses and consequently a reduced shrinkage [8]. On the other hand, microfibers (e.g. steel, carbon, etc.) were reported to act as a local restraint for shrinkage [10]. Microfibers generally bridge micro-cracks, leading to a reduction in crack widths and delaying occurrence of cracking [11].

While these methods reduce shrinkage and the propensity for cracking, they do not generally reduce the environmental footprint of UHPC. Indeed, at very low w/c, the content of un-hydrated cement acting as filler in UHPC can exceed 42% [12]. Hence, partially replacing cement with a less costly material that can also improve the shrinkage behavior and reduce the environmental impact would be desirable. A potential material is wollastonite microfibers, which is widely used in other industrial applications (e.g. ceramics, plastics, paint, etc. [13]).

Wollastonite is a naturally occurring acicular, inert, white mineral (calcium meta silicate [β-CaO–SiO_2]), which is less costly than

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steel or carbon microfibers [14]. Previous studies have shown the potential for using natural wollastonite microfibers as a reinforcing material in cementitious materials [14–16]. Addition of wollastonite microfibers to cement-silica fume matrices showed significant improvement in pre-peak and post-peak load, flexural toughness and ductility [15]. Moreover, wollastonite microfibers imbedded in cementitious materials achieved high stability without any surface or bulk deterioration with time [17].

The aim of this research is to develop a strategy for producing UHPC with lower cracking propensity to traditional UHPC, while having a more positive environmental foot-print, through combining the benefits of SRA and wollastonite microfibers.

2. Research significance

With the increasing use of UHPC in the construction, strengthening and rehabilitation of different infrastructure, controlling the early-age shrinkage cracking of UHPC is essential to ensuring an enhanced long-term performance and longer service life. Reducing the early-age shrinkage and improving the resistance to microcracking of UHPC should lead to a wider implementation of the material. In this study, using wollastonite microfibers as a relatively low-cost crack reinforcement method was proposed for UHPC. The reduction in shrinkage strain and cracking potential due to the addition of wollastonite microfibers, used separately or combined with SRA, can enhance the sustainability and durability of UHPC. From an environmental point of view, achieving comparable performance with lower cement content when using natural wollastonite as partial replacement for cement should lead to a reduction in the cement factor of UHPC and consequently lower CO_2 emissions from cement production.

3. Experimental program

In this study, monitoring of the strength development (compressive strength, heat of hydration, and degree of hydration) and characterization of the shrinkage behavior have been investigated on UHPC mixtures incorporating different dosages of SRA and/or wollastonite microfibers. All tests were conducted on UHPC specimens without heat curing in order to understand real effects that govern UHPC shrinkage in structural elements cast in situ.

3.1. Materials and mixture proportions

Ordinary Portland cement containing 61% C_3S, 11% C_2S, 9% C_3A, 7% C_4AF and 0.82% equivalent alkalis was used. Silica fume with a specific surface of 18.2 m^2/g was added as a dry powder. Its chemical composition includes 93.10% SiO_2, 1.00% Fe_2O_3, 0.13% Al_2O_3, 0.71% MgO, and 0.43% SO_3. According to the suggestions in [18] to produce UHPC, a coarse aggregate was not used. Quartz sand having a particle size in the range of 0.1–0.8 mm was used as aggregate. A polycarboxylate-based high-range water-reducing admixture (HRWRA) was added at a rate of 3% by mass of cement. A commercially available SRA mainly composed of poly-oxyalkylene alkyl ether was used in this study. SRA dosages of 1% and 2% by mass of cement were added as partial replacement for mixing water. Commercially available natural wollastonite microfibers (length 152 μm and diameter 8 μm) were added at two contents (4% and 12%) as partial substitution for cement by volume. Water from the HRWRA and SRA was included in the specified w/c. The selected composition of the control mixture (which is a well-known class of UHPC without aggregate [19,20]) and the characteristics of the tested mixtures are shown in Tables 1 and 2, respectively.

Table 1
Composition of control mixture.

Material	(mass/cement mass)
Cement	1.00
Silica fume	0.30
Quartz sand (0.1–0.5 mm)	0.43
Quartz sand (0.3–0.8 mm)	1.53
Water	0.25
HRWRA	0.03

Table 2
Tested mixtures.

Mixture	SRA (%)[a]	Wollastonite microfiber (%)[b]
C	–	–
R1	1	–
R2	2	–
W4	–	4
W12	–	12
R1W4	1	4
R1W12	1	12
R2W4	2	4
R2W12	2	12

[a] Added as % by mass of cement.
[b] Added as % by volume of cement.

It should be mentioned that the workability of UHPC mixtures incorporating wollastonite microfibers was lower than that of the control mixture. The higher the wollastonite microfibers content, the lower was the workability achieved. This can be attributed to the increased interlocking of microfibers because of their needle-like shape [21]. However, this reduction in workability can be overcome through applying vibration during placing or using higher dosage of HRWRA [21,22].

3.2. Tests and specimens preparation

Compressive strength testing was conducted on 50 mm [2 in.] UHPC cubes at the ages of (6, 8, 10, 12 and 24 h) and 3, 5, 7 and 28 days. During the first 24 h, cubes in their molds were stored in double-sealed plastic bags until testing at 20 ± 1 °C [68°°F] inside a walk-in environmental chamber. Specimens were moved to the environmental chamber immediately after casting. Specimens for testing at ages >24 h, were demolded at 24 h and kept in a calcium hydroxide solution at 20 ± 1 °C [68°°F] until the testing age.

Semi-adiabatic calorimetry studies were conducted on UHPC specimens during the course of 2 days of hydration using a custom-built experimental setup. The UHPC was prepared and cast into a prismatic mold of 60 × 100 × 250 mm [2.5 × 4 × 10 in.] in size. The mold was immediately placed in a micro-porous insulation box. Three Type-T thermocouples were inserted into the center of the concrete volume along its length. The UHPC specimen temperature and room temperature were monitored. Replicate specimens indicated a standard deviation of 1.8 °C [35 °F] for the maximum specimen temperature.

Thermo-gravimetric (TGA) combined with derivative thermo-gravimetric (DTG) analysis was used to determine the evolution of the chemically bound water (BW) content during hydration. Since only one binder composition was used, a linear correlation between the amount of BW and the degree of hydration was assumed, in agreement with previous studies [23–25]. At the specific testing age, hydration was stopped using the freeze drying tech-