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Effects of autoclave curing and fly ash on mechanical properties of ultra-high performance concrete

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HIGHLIGHTS

- The higher fly ash added UHPC needs the higher autoclave curing pressure.
- Fly ash eliminates the detrimental effect of autoclaving on fracture toughness of UHPC.
- Fly ash improves mechanical properties and microstructure of autoclave curing UHPC.

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ABSTRACT

This study investigated compressive strength, flexural strength and fracture toughness of ultra-high performance concretes (UHPC) containing silica fume and different dosage of fly ash (0%, 10%, 20% and 30%) after exposure to different autoclave curing conditions with pressure of 0.5 MPa, 1.0 MPa and 1.5 MPa and duration time of 6 h, 8 h, 10 h and 12 h. The microstructure of UHPC samples were also measured by using MIP, XRD and SEM. The results show that the mechanical strength of UHPC specimen presents an increasing at first stage and a decreasing or stable trend later with the higher pressure or the prolonged duration time of autoclaving. The increasing autoclave pressure is needed for UHPC containing more fly ash to obtain the best strength. Incorporation of steel fibers could improve flexural strength while has little impact on compressive strength and the reinforcement effect of steel fibers gets more significant as the increasing autoclave pressure and duration. Autoclave curing degrades the fraction toughness for pure cement UHPC and the incorporation of FA can counteract or even eliminate this detrimental effect. The incorporation of fly ash and the increasing autoclave duration reduce the porosity of UHPC samples. The autoclave curing leads to the formation of xonotlite ($Ca_6[Si_6O_{17}](OH)_2$) and decreases the content of portlandite in UHPC samples.

1. Introduction

Compared with ordinary cement concrete, ultra-high performance concrete (UHPC) is normally characterized by incorporation of micro-cementitious materials such as silica fume to improve particle compactness and pozzolanic reaction, combined with the use of superplasticizer to reduce the water-to-cementitious materials ratio [1]. Since the first application of UHPC in real structure—the Sherbrooke Bridge, UHPC has been increasingly used in construction engineerings due to its characters of high strength, high durability and outstanding volume stability [2,3]. When exposed to room temperature, most of cement grains in UHPC mixtures remain unhydrated after 28 days due to the high cement content and low water-cement ratio [4]. The low water content prevents silica fume grains from dissolving and depresses the pozzolanic reaction of mineral admixtures [5]. Thermal curing has an obvious improvement on mechanical and durability properties of UHPC by contrast, mainly for the development of a denser microstructure with the formation of calcium silicate hydrate (C-S-H). As the temperature rises, the pozzolanic materials take part in hydration reaction increasingly. It was reported that the thermal treatment at early ages could make an obvious effect on compressive strength of UHPC while no significant influence on ordinary concrete [6]. In related studies [4,7,8], water curing, steam curing and autoclave curing were applied and the UHPC specimens with different compressive strength were achieved. It was believed that autoclave curing is the best type of curing for UHPC because it increases the mechanical strength by 20–30% [9].

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Table 1
Chemical composition of cementitious materials (%).

Materials	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Loss on ignition
Cement	21.40	5.45	3.50	64.48	1.46	2.51
SF	94.50	0.50	0.45	0.60	0.70	0.80
FA	49.22	27.80	1.29	3.14	0.86	0.30

Table 2
Physical and mechanical performances of quartz sand.

Quartz sand	Particle size (μm)	Apparent density (g/cm^3)	Packing density (g/cm^3)
Coarse	360 ~ 600	2.65	1.405
Fine	180 ~ 360	2.65	1.329

Mineral admixtures are very essential for preparing high performance and ultra-high performance concretes, which could fill the voids among the larger cement particles, enhance the rheological properties, reduce cracking related with hydration heat release or early age shrinkage [10–12], and contribute to the denser microstructure due to secondary hydration effects. Silica fume (SF) plays a significant role in UHPC, considering its influence on improving both rheological and mechanical properties [13]. As well, silica fume works as a nucleation center for the formation of C-S-H phase [14]. Due to the high particle fineness and pozzolanic reactivity, most researchers prepared UHPC by incorporating SF. An [15] reported that the addition of SF could improve the initial hydration degree in a low water-binder ratio system. Chan [16] reported that incorporation of silica fume in UHPC matrix enhanced the bond characteristics between steel fibers and matrix. In autoclave curing condition, if silica fume is absent, rapid generation of hydration products would result in formation of porous structure and low compressive strength [17]. FA is a kind of byproduct of electricity production plant. It could be used in UHPC as a binary system combined with SF. Otherwise, FA demands less water contrast with other pozzolanic materials such as granulated blast furnace slag (GGBFS) and limestone powder [18]. Yazici [19,20] found that the combination of GGBFS and FA can enhance flexural strength of UHPC after exposure to different curing conditions. Çağlar Yalçınkaya [21] found that FA replacement in UHPC may trigger the formation of elephant skin under dry condition which could reduce water escape and limit RH sensitivity of UHPC.

So far, several investigations have been carried out to study the influence of curing condition and incorporation of pozzolanic admixtures, including silica fume, GGBFS and rice husk ash, on strength development of UHPC [22–26]. It is not clear the influence of different autoclave curing conditions on mechanical property and microstructure for UHPC containing silica fume and different dosage of fly ash. Hence, the influences of autoclave pressure, curing duration and FA addition on the mechanical properties (flexural strength, compressive strength and fracture toughness) of UHPC containing constant dosage of silica fume were investigated. The influence of steel fibers was also considered. On the other hand, typical samples were selected for microstructure measurement by using MIP, XRD and SEM methods.

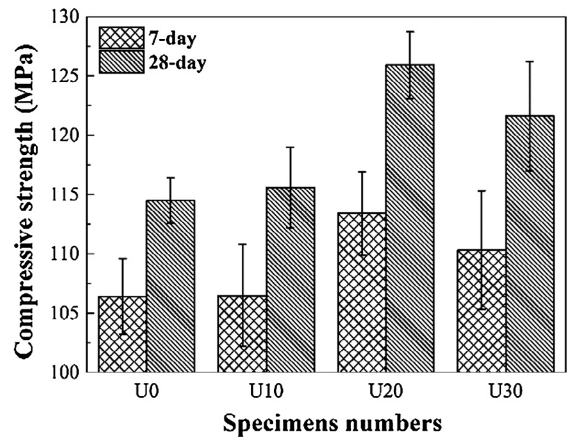

Fig. 1. Compressive strength of UHPC after standard curing.

2. Experimental

2.1. Raw materials and mixing proportion

Cementitious materials used in this study were as follow: Ordinary Portland cement with strength grade of 42.5 complying with the Chinese Standard GB175-2007, silica fume (SF) with specific surface area of 1.5×10^5 cm^2/g and SiO_2 content of more than 96% according to the Chinese Standard GB/T 21236-2007, class Ⅰ fly ash (FA) complying with the Chinese Standard GB/T1596-2005. The chemical compositions of these cementitious materials are given in Table 1.

Aggregates included the standard sand according to Chinese Standard GB/T17671-1999 and two types of quartz sands (shown in Table 2) produced by Harbin Jinghua Water treatment Materials Company. For preparing UHPC mixtures, each of them was accounted for 1/3.

A polycarboxylate-based superplasticizer (SP) from Harbin Qiangshi Company was used, with a solid content of about 40%. Organic silicon defoamer was produced by Harbin Wancheng Company. Brass-coated steel fiber had a length of 13 mm, diameter of 0.22 mm and aspect ratio of 59.1.

The mixing proportion of every mixture is presented in Table 3. The total content of cementitious materials was kept at 1170 kg/m^3 and fly ash was added by 10%, 20% and 30% of cementitious materials mass. Steel fiber was added by 1.5% of mixture volume.

Table 3
Mixing proportions of UHPC mixtures.

Material	U0	U10	U20	U30	f-U0	f-U10	f-U20	f-U30
Cement (kg/m^3)	1040	936	832	728	1040	936	832	728
SF (kg/m^3)	130	130	130	130	130	130	130	130
FA (kg/m^3)	0	104	208	312	0	104	208	312
Coarse quartz sand (kg/m^3)	380	380	380	380	380	380	380	380
Fine quartz sand (kg/m^3)	380	380	380	380	380	380	380	380
Standard sand (kg/m^3)	380	380	380	380	380	380	380	380
Steel fiber (vol.%)	–	–	–	–	1.5	1.5	1.5	1.5
Water (kg/m^3)	235	235	235	235	235	235	235	235
Defoamer (L/m^3)	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33
SP (L/m^3)	27.5	27.5	27.5	27.5	27.5	27.5	27.5	27.5