Comparative study on flexural properties of ultra-high performance concrete with supplementary cementitious materials under different curing regimes

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Abstract: This study investigated the effects of curing regimes (standard, hot water, and steam curing) on mechanical properties of ultra-high performance concrete (UHPC) with different supplementary cementitious materials (SCMs). The flowability, compressive strength, flexural load-deflection relationship, ultimate flexural strength, and toughness of UHPC mixtures with 0, 20%, 40%, and 60% of either ground granulated blast-furnace slag (GGBS) or fly ash, by the mass of cement, were evaluated. Test results indicated that the GGBS or fly ash content had limited or negative influence on the compressive strength of UHPC in terms of curing regime. For the flexural strength, there existed an optimal content of GGBS or fly ash, which were 40% and 20%, respectively. Exceeded this dosage could result in a drop in flexural strength and toughness. The hot water and steam curing significantly improved the flexural properties. However, prolonging the standard curing over 28 d led to comparable flexural properties as those under hot water and steam curing showed. The production of UHPC with appropriate GGBS or fly ash content with adequate standard curing, therefore, offers an effective way to obtain satisfactory flexural properties.

Keywords: Ultra-high performance concrete; Supplementary cementitious materials; Curing regime; Flexural properties; GGBS; Fly ash

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1. Introduction

Ultra-high performance concrete (UHPC) is a new generation concrete developed based on four main theoretical principles, including the reduction in porosity, improvement in microstructure, enhancement in homogeneity, and increase in toughness [1, 2]. It is well known that UHPC has a very high compressive strength typically over 150 MPa, good tensile ductility and toughness, and superior durability [3-5]. Therefore, it has potential applications in bridge and industrial products as pre-cast structure members to ensure light-weighted, flexible, durable, and aesthetic structures [6,7].

To make UHPC more durable and sustainable, a high amount of supplementary cementitious materials (SCMs) and a small dosage of nanoparticles are often used to replace part of cement and/or silica fume [8,9]. High temperature curing is also adopted to accelerate the hydration of cement and enhance the secondary hydration between SCMs and $\text{Ca}(\text{OH})_2$ [7]. The high temperature and/or pressure curing can significantly increase the overall properties of UHPC. Massidda et al. [10] studied the effects of autoclave curing at 180°C on the physical properties of reactive powder concrete (RPC). The results indicated that specimens cured at 180°C for 3 h after 3 d of pre-curing at ambient temperature reached the flexural and compressive strengths of 30 and 200 MPa, respectively. Zhang et al. [11] reported that 24 h of steam curing increased the compressive strength of RPC specimens by about 15 to 30 MPa compared to that after 28 d of room temperature curing. After 8 h of autoclave curing, RPC with 3% or 4% fiber reinforcements could achieve a compressive strength over 200 MPa. Yazici et al. [12] studied the mechanical properties of reactive powder concrete containing SCMs under room temperature, autoclave, and steam curing. They found that the compressive strength increased considerably after steam and autoclave curing, while the flexural strength and toughness decreased compared to those after room temperature curing. It was suggested that the pozzolanic activity of silica fume, crushed quartz, and the chain length of C-S-H were increased after high temperature curing [13]. Unfavorable crystalline product α -calcium silicate hydrate (α -

C₂SH) can be converted to tobermorite in the presence of silica under high temperature curing. This can eventually result in decrease in porosity, improvement in strength as well as bond between matrix and aggregate/fiber [14,15]. However, high energy consumption and low production efficiency associated with high temperature curing restrict its applications. So far, extensive research on UHPC incorporated with SCMs has been conducted, but very limited information has been published about the effects of type and content of SCMs on the mechanical properties under different curing regimes [16]. If satisfied mechanical properties can be obtained with the use of high amount of SCMs under room temperature curing, this would not only facilitate the applications of UHPC but also reduce cost as well as energy consumption.

Two types of SCMs with four different contents were used in this study. The replacements of cement with ground granulated blast-furnace slag (GGBS) or fly ash were 0, 20%, 40%, and 60%, respectively. Three curing regimes, including standard, hot water, and steam curing, were adopted. The flowability and compressive strength were evaluated. Flexural load-deflection relationship, ultimate flexural strength, and toughness were used characterized the flexural properties. The study seeks to enhance the sustainability of UHPC without sacrifice of mechanical properties.

2. Materials and experimental program

2.1. Materials

Portland cement (P.I. 42.5) complying with the Chinese Standard GB175-2007 was used [17]. Table 1 summarizes the chemical composition and density of the cement, silica fume, fly ash, and GGBS. Silica fume has an average particle size of 0.1 to 0.2 μm and specific surface area of 18,500 m^2/kg . The Blaine specific surface area for the fly ash and the GGBS were 427 and 410 m^2/kg , respectively. Straight smooth steel fibers with a diameter of 0.2 mm and a length of 13 mm were used. Their tensile strength is 2,800 MPa. River sand with a maximum particle size of 2.36 mm were used. Apolycarboxylate-based superplasticizer

(SP) with a solid content of 20% was used.

Table 1 Chemical composition and density of cementitious materials

Chemical composition	CaO (%)	SiO ₂ (%)	Al ₂ O ₃ (%)	Fe ₂ O ₃ (%)	SO ₃ (%)	MgO (%)	Na ₂ O _{eq} (%)	K ₂ O (%)	C (%)	Density (kg/m ³)
Cement	62.49	21.18	4.73	3.41	2.83	2.53	0.56	-	-	3,110
Silica fume	1.85	93.90	-	0.59	-	0.27	0.17	0.86	1.06	2,150
GGBS	39.11	33.0	13.91	0.82	-	10.04	-	-	-	2,900
Fly ash	4.63	42.52	32.62	9.35	1.21	0.73	-	-	-	2,600

2.2. Mixture proportion

Based on the previous study [9,18], UHPC with water-to-cementitious materials ratio (W/CM) of 0.18, silica fume content of 20% to 25%, straight steel fiber content of 2%, by volume of concrete, can obtain good flowability, fiber-matrix bonding, and mechanical properties. Therefore, S0 or F0 incorporated with 25% silica fume and with the remaining binder as cement was selected as a reference mixture. The superplasticizer dosage was fixed at 2% by the mass of the cementitious materials. Replacements of cement with 20%, 40%, and 60% of either GGBS or fly ash, by the mass of cement in the reference mixture, were used. The UHPC mixtures incorporated with different GGBS contents were designated as S20, S40, and S60, while those with fly ash were designated as F20, F40, and F60, as summarized in Table 2.

Table 2 Mixture proportions of UHPC

No.	Cement (kg/m ³)	GGBS (kg/m ³)	Fly ash (kg/m ³)	Silica fume (kg/m ³)	Sand (kg/m ³)	Water (kg/m ³)	SP (kg/m ³)	Steel fiber (kg/m ³)
S0	792	0	0	264	1,056	173	21.1	156
S20	634	159	0	264	1,056	173	21.1	156
S40	475	317	0	264	1,056	173	21.1	156
S60	317	475	0	264	1,056	173	21.1	156
F0	792	0	0	264	1,056	173	21.1	156
F20	634	0	159	264	1,056	173	21.1	156
F40	475	0	317	264	1,056	173	21.1	156
F60	317	0	475	264	1,056	173	21.1	156

2.3. Mixing procedure and sample preparation

During mixing, dry powders, including cement, silica fume, GGBS or fly ash, and river sand, were mixed first at a high speed for 3 min. Water and superplasticizer were then added and mixed for approximately 6 min at a low speed. Steel fibers were added slowly by passing a sieve with size of 5 mm and mixed for another 6 min until uniformly distributed.

After the flowability testing, the mixtures were cast into 40×40×160 mm molds for three-point flexural properties testing. Specimens with molds were then kept in a room at 20°C and RH > 95% for approximately 24 h. They were then demolded and cured in the following procedures:

(1) Standard curing: cured in saturated limestone water at 20°C for 3, 7, 28, and 90 d.

(2) Hot water curing: cured in hot water at 90°C for 3 d.

(3) Steam curing: cured in steam at 90°C for 3 d.

2.4. Experimental methods

2.4.1. Flowability

The flowability of all mixtures was measured in accordance with the Chinese Standard GB/T 2419-2005 [19]. The mixtures were cast into a mini cone mold and jolted for 25 times. Two diameters perpendicular to each other were then determined and mean values were reported.

2.4.2. Flexural behavior

Three-point flexural testing through displacement control was conducted. The span was 100 mm. The deflection at the center of the specimens was measured using a LVDT installed at the center of the specimens. An MTS[®] testing machine with 20,000 KN load cell was used. Its loading rate was set at 0.2 mm/min. Averages of three samples for each batch were reported.

2.4.3. Compressive strength

The six broken specimens after three-point flexural testing with a size of approximately 40×40×80 mm were tested for compressive strength. The loading rate was set at 2.4 KN/s. The mean values were reported.

3. Results and discussion

3.1. Effect of SCM content on flowability of UHPC

Figure 1 shows the effects of different types and contents of SCMs on flowability of UHPC. It can be seen that the flowability increased with the increase of SCM content. The reference batch without any SCM had a flowability of 160 mm. With replacements of 20%, 40%, and 60% cement with GGBS, the flowability increased by 3, 10, and 20 mm, respectively, compared to the reference mixture. The flowability of UHPC mixture with the same fly ash content was slightly higher than that with GGBS, which increased by 5, 13, and 23 mm, respectively. The improvement in flowability associated with fly ash was due to the following aspects [20]: (1) spherical shape and glassy surface - providing lubricating effect to reduce the degree of water absorption and internal friction force among the angular particles; (2) high superplasticizer absorption - increasing electrostatic repulsion and steric hindrances [21]. However, the lower flowability associated with GGBS at the same dosage might be attributed to: (1) lower SP absorption when compared to fly ash [21]; (2) more irregular and larger particles with less smoothed surface, which increases the internal friction among particles. The lower SP absorption of slag was proven by Sun et al. [21]. They investigated the superplasticizer dosage required in mortars with different fly ash or slag contents. It was found that the mortar with the same content of slag required more SP dosage to obtain the same fluidity.

Fig. 1 Effects of GGBS and fly ash replacements on flowability of UHPC

3.2. Effects of curing regimes on compressive strength of UHPC with different SCMs

The effects of curing regimes on compressive strengths of UHPC with either slag or fly ash is illustrated in Fig. 2. The increase in slag content had little effect on compressive strength of UHPC under standard curing. For the reference specimen without any slag at 28 d of standard curing, the compressive strength was 149.8 MPa. It changed to 142.3, 144.0, and 138.2 MPa, respectively, when 20%, 40%, and 60% slag was incorporated. The 3 d of hot water and steam curing significantly increased the compressive strength of the samples without slag to 200.7 and 191.0 MPa. However, the compressive strength decreased with the increase of slag content.

As illustrated in Fig. 2(b), under standard curing, the incorporation of fly ash decreased the compressive strength, especially in the early ages up to 7 d. It is reported that fly ash has negative effect on the compressive strength of concrete at early ages [22]. At later ages of 28 and 90 d, the compressive strength was slightly improved. The hot water and steam curing improved the compressive strength. However, the compressive strength decreased with the increase of fly ash content. With incorporation of 60% fly ash, the compressive strengths of UHPC under hot water and steam curing were comparable to that under 90 d of standard curing.

(a) GGBS

(b) Fly ash

Fig. 2 Effects of curing regimes on compressive strength of UHPC with different GGBS and fly ash contents

3.3. Effects of curing regimes on flexural properties of UHPC with different SCMs

3.3.1. Effects of curing regimes on flexural properties of UHPC with GGBS

The effects of curing regimes on flexural properties of UHPC with different GGBS contents are illustrated in Fig. 3. The flexural deflection-load curves exhibited a linear ascending part followed by a nonlinear ascending part to the peak load, and then a gradually descending part with saw teeth. These saw teeth indicated improved strengthening effect associated with steel fiber and GGBS.

From Fig. 3(a), after 28 d of standard room temperature curing, the peak load of UHPC specimens increased first and then decreased with the increase of GGBS content. UHPC with 40% GGBS obtained the highest peak load, which increased by 50% compared to the reference mixture. However, with further increase of GGBS content to 60%, the peak load decreased to a certain value that was even slightly lower than that of the reference mixture. Its toughness, area under load-deflection curve to a deflection of 6 mm, was 47% greater than that of the reference specimen, as summarized in Table 3.

For UHPC after hot water curing, the peak loads were comparable to each other regardless of GGBS content, as shown in Fig. 3(b). Under steam curing, UHPC with 40% GGBS demonstrated the highest peak

load and toughness, as standard curing showed.

(a) After 28 d of standard curing

(b) After 3 d of hot water curing

(c) After 3 d of steam curing

Fig. 3 Effects of curing regime on flexural load-deflection curves of UHPC with different GGBS contents

Figure 4 and Table 3 illustrate the effects of GGBS content on ultimate flexural strength and toughness of UHPC under different curing regimes. The flexural strength and toughness increased first with the increase of GGBS content, then decreased when surpassed 40%. This agrees well with the results in literature [15,23]. There existed an optimal GGBS content, excessed which the strength remained unchanged or decreased. This might be due to the presence of unreacted GGBS as a filler in the paste.

Three days of hot water and steam curing significantly improved the flexural strength up to 30 MPa. This was because high temperature curing can increase the rate of reaction of binder [24]. Moreover, the high temperature can lead to increase in C-S-H chain length so as to secure denser and higher strength hydration products [13]. The flexural strengths of UHPC after 3 d of hot water or steam curing were higher

185 than that after 28 d of standard curing. However, at 90 d of standard curing, the flexural strengths and
186 toughness were comparable to those after 3 d of steam curing. Therefore, prolongation of standard curing up
187 to 28 d can obtain satisfactory flexural behavior.

188
189 Fig. 4 Effects of curing regimes on flexural strength of UHPC with different GGBS contents

190
191 Table 3 Effects of curing regimes on flexural behavior of UHPC with different GGBS contents

No.	Curing regime	Ultimate flexural strength (MPa)	Toughness (N-mm)
S0	28 d of standard curing	27.8	25,322
S20		27.6	37,761
S40		39.4	42,846
S60		25.7	37,208
S0	3 d of hot water curing	35.0	31,507
S20		30.5	28,056
S40		33.6	36,399
S60		30.8	33,216
S0	3 d of steam curing	31.6	26,875
S20		36.6	36,623
S40		40.6	42,768
S60		32.2	30,113

192
193 3.3.2. Effects of curing regimes on flexural properties of UHPC with fly ash

194 Figure 5 illustrates the effects of different curing regimes on flexural load-deflection curves of
195 UHPC with different fly ash contents. It can be observed that the peak load increased first then decreased
196 with the increase in fly ash content. The UHPC mixture with 20% fly ash reached the highest peak load and

197 toughness. When hot water curing was applied, there was no much difference among the UHPC mixtures
 198 with and without fly ash, as shown in Fig. 5(b). This might be due to similar activation energy associated
 199 with temperature for the hydration of cementitious materials. However, when steam curing was applied,
 200 obvious changes in load with fly ash content could be observed as standard curing indicated. Besides, UHPC
 201 with 60% fly ash decreased the peak load even lower than that of reference batch.

205 Fig. 5 Effects of curing regimes on flexural load-deflection curves of UHPC with different fly ash contents

206 The effects of curing regimes on ultimate flexural strength and toughness of UHPC with different fly
 207 ash contents are depicted in Fig. 6 and summarized in Table 4. The flexural strength increased gradually
 208 with the prolongation of standard curing time. After 28 d of standard curing, there was little change in
 209 flexural strength. In addition, like UHPC with GGBS, the flexural strength increased with the increase of fly
 210 ash content up to 20% and then decreased. The UHPC mixture without any fly ash had a flexural strength of
 211
 212

213 27.8 MPa at 28 d, it increased to 36.9, 33.4, and 31.4 MPa, respectively, when 20%, 40%, and 60% fly ash
 214 was incorporated.

215 Hot water and steam curing increased the flexural strength a lot. Hot water curing decreased the
 216 compressive strength by 4% to 8% with the increase of fly ash content. Moreover, the flexural strength and
 217 toughness of UHPC mixtures after hot water curing were lower than those after standard curing, except the
 218 control batch. The temperature and duration of hot water curing can affect the mechanical properties due to
 219 the differences in the thermal expansion coefficient of the concrete ingredients, which could lead to micro-
 220 cracking and increased porosity [25]. For steam curing, the flexural strengths of UHPC with 0, 20%, 40%,
 221 and 40% fly ash were increased by 13.7%, 7.0%, 9.6%, and 0%, respectively, compared to those after 28 d
 222 of standard curing. The flexural strength under steam curing was almost comparable to that after 90 d of
 223 standard curing. Payá et al. [26] investigated the compressive and flexural strengths of mortar replaced with
 224 fly ash (15%, 30%, 45%, and 50%) under different temperatures (20°C, 40°C, 60°C, and 80°C). It was
 225 found that the specimens with 15% to 30% fly ash under curing temperature of 60 to 80°C obtained the
 226 highest strength.

227
 228 Fig. 6 Effects of curing regimes on flexural strength of UHPC with different GGBS contents
 229

230 Based on the previous results and discussion, appropriate replacement level of GGBS or FA generally

positively affected the flexural strength of UHPC in all curing regimes. The improvement in flexural behavior can be attributed to the enhancement in bond strength between the fibers and the matrix. However, when excessive GGBS or fly ash content was used, the flexural strength decreased. This might be due to the change of Ca/Si ratio and eventually the reactivity of the binder system.

Table 4 Effects of curing regimes on flexural behavior of UHPC with different fly ash contents

No.	Curing regime	Ultimate flexural strength (MPa)	Toughness (N-mm)
F0	28 d of standard curing	27.8	25,322
F20		36.9	35,758
F40		33.4	42,734
F60		31.4	31,632
F0	3 d of hot water curing	35.0	31,507
F20		33.9	30,966
F40		31.9	30,050
F60		29.2	30,161
F0	3 d of steam curing	31.6	26,875
F20		39.5	45,338
F40		36.6	37,894
F60		31.3	21,283

3.3.3. Effects of curing regimes on flexural properties of UHPC with the optimal GGBS or fly ash content

Figure 7 shows the effects of curing regimes on flexural load-deflection curves of UHPC with the optimal GGBS or fly ash content. As discussed in the previous section, the 3 d of hot water and steam curing significantly improved the compressive and flexural strengths in comparison with those under 3 d of standard curing. However, after 28 d of standard curing, satisfactory flexural behavior was obtained. The toughness of specimens under 28 d standard curing was almost comparable to that under steam curing. The UHPC specimens under 90 d standard curing achieved the highest toughness, when 40% GGBS was incorporated, followed by those under steam and hot water curing, as observed in Fig. 7(a). This suggests good energy reservation.

From Fig. 7(b), UHPC specimens with 20% fly ash under 90 d of standard curing reached the best toughness. Its peak load was 38.5 MPa, which was comparable to that of the specimens under steam curing.

Therefore, the appropriate use of SCMs and prolongation of standard curing time up to 28 d offers an effective way to enhance the sustainability of UHPC without sacrifice of the mechanical properties.

(a) UHPC with 40% GGBS

(b) UHPC with 20% fly ash

Fig. 7 Effects of curing regimes on flexural load-deflection curves of UHPC with the optimal GGBS or fly ash content

Table 5 Effects of curing regimes on flexural behavior of UHPC with the optimal GGBS or fly ash content

No.	Curing regime	Ultimate flexural strength (MPa)	Toughness (N-mm)
S40	28 d of standard curing	39.4	42,847
S40	90 d standard curing	41.5	51,880
S40	3 d of hot water curing	33.6	36,399
S40	3 d of steam curing	40.6	42,769
F20	28 d of standard curing	36.9	35,758
F20	90 d standard curing	38.5	44,195
F20	3 d of hot water curing	33.9	30,967
F20	3 d of steam curing	39.5	45,338

4. Conclusions

This study investigated the flowability, compressive strength, flexural behavior, including load-deflection relationship, ultimate flexural strength, and toughness, of UHPC mixtures with 0, 20%, 40%, and 60% of either GGBS or fly ash, by the mass of cement. Based on the results presented in this research, the following conclusions can be drawn:

The flowability of UHPC increased gradually with the increase of both GGBS and fly ash content. At the same content, UHPC mixture with fly ash showed greater flowability than that with GGBS. The

incorporation of GGBS or fly ash had limited influence on the compressive strength of UHPC under standard curing. Under hot water and steam curing, the compressive strength decreased with the increase of GGBS or fly ash content.

There existed an optimal GGBS and fly ash content for the flexural properties of UHPC. The optimum GGBS content was 40%, while 20% for fly ash. When exceeded these values, a drop in flexural strength and toughness were observed.

Hot water curing and steam curing significantly increased the flexural properties compared to standard curing with the same curing duration. However, prolongation of standard curing time up to 28 d resulted in comparable ultimate flexural strength and toughness. Therefore, UHPCs with 40% GGBS or 20% fly ash with adequate standard curing could lead to low cost and energy conservation without sacrifice of flexural properties.

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