CHARACTERIZATION OF FLEXURAL PERFORMANCE OF ULTRA-HIGH PERFORMANCE CONCRETE WITHOUT THERMAL CURING

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ABSTRACT

An experimental study on the flexural performance of Ultra-high performance concrete (UHPC) without thermal curing was carried out via four-point bending tests. Based on the test results, discussions on how to effectively evaluate the flexural performance of UHPC were presented. The four-point bending test results indicated that UHPC possesses not only high flexural strength, but also high flexural toughness and ductility. ASTM C1609 and JSCE-SF4 were found to be suitable for the characterization of the flexural performances. However, they have certain limitations to evaluate the flexural toughness of UHPC at deformation larger than 1/150 of span， at which UHPC still has excellent loading capacity. It was found that the mid-span deflection extended from 1/150 to 1/75 of span can be more accurate to characterize the flexural performance of UHPC.

Keywords: Ultra-high performance concrete, steel fiber, four-point bending tests, flexural performance

1. INTRODUCTION

The ultra-high performance concrete (UHPC) is unlike traditional high strength concrete and fiber reinforced concrete and is not the traditional sense of "high performance concrete" either[1,2]. It belongs to a kind of new cement-based structural engineering material with excellent performances. Its greatest feature lies in the high bonding strength between steel fibers and the matrix, which on the one hand changes the brittleness of the UHPC, on the other hand can improve the strength and ductility and reduce shrinkage of concrete [3,4].

Flexural toughness is an important indicator to measure the toughening effect on fiber reinforced concrete after cracking, which is calculated based on the amount of absorbed energy in the bending process. Many countries have already launched their own standard to evaluate the toughness of the fiber reinforced concrete, such as the United States ASTM C1018 [5] and ASTM C1609 [6] standard, Japan JSCE SF4 [7] standard. Their toughness evaluation parameters include absolute energy absorption, dimensionless toughness indicator related with energy dissipation capacity, residual flexural strength at different deformations, equivalent bending strength, etc. These indicators have an accurate description on the toughness capacity of fiber reinforced concrete. As for UHPC, due to the "deflection hardening" behavior, it's bending deformation and energy dissipation capacity is much better than the ordinary fiber reinforced concrete.

In this paper, the flexural performances of UHPC without thermal curing were studied by four-point bending tests. A new method based on ASTM C1609 and JSCE SF4 was proposed to characterize the flexural toughness of UHPC at deformation larger than 1/150 of span.

2. EXPERIMENTAL DETAILS

2.1 Materials

The mix proportion of the UHPC matrix investigated in this study before adding fiber is listed in Table 1. The UHPC with 2% of steel fiber was designed to have a compressive strength of 130 MPa when it was cured in water at a temperature of 20 °C for 28 days. The water to binder ratio was held constant at 0.2 and P Ⅱ 52.5 Portland cement with the specific surface area of 350 m^2/kg and silica fume with the specific surface area of 20 000 m^2/kg were used as a binder. A filler of pure silica composed of over 99% SiO_2, with an average diameter of 2.2 μm, was adopted for increasing flowability and strength. Fine aggregate (an average particle size of 500 μm or less) with a density of 2.62 g/cm^3 was used to maintain adequate stiffness and volume stability. Optimized amounts of superplasticizer (SP) was used to achieve high flowability when different dosages of fiber were adopted. Properties of steel fibers (ST) coated with brass used in this study are given in Table 2.

Table 1 Mix proportions of UHPC matrix

Compound	Binder		w/b	Filler	Fine aggregate	SP
	Cement	Silica fume				
Proportion	1	0.25	0.2	0.3	1.1	0.019 - 0.022

Table 2 Properties of steel fiber

Fiber types	Tensile strength (MPa)	Elastic modulus (GPa)	Length (mm)	Diameter (μm)	Aspect ratio	Density (kg/m^3)
Steel (ST)*	2500	200	13	200	65	7.85

*Dramix® OL13/.16, straight with brass coating

2.2 Specimen size and test apparatus

For each mixtures, four 100100400mm prism specimens and three 100mm cubic specimens were cast for tests of flexural performance and compressive strength, respectively. After demold, these specimens were cured in water at a temperature of 20 °C for 28-day. According to ASTM C1609[6] and JSCE SF4[7], the flexural performance of 100100400mm prisms was determined by four-point bending tests (span length 300 mm) using an servo-controlled testing system, as shown in Fig.1. During the test, both applied load and mid-span deflection of the specimens were recorded. The deflections were measured by two linear variable displacement transducers (LVDTs) placed on both sides of the specimen. The output from this test was a load-deflection curve from which flexural performance parameters were derived using absolute values of load or strength at specific deflections. Four specimens were tested for each mixture, and the flexural load–deflection curves were averaged and concatenated by using Average Multiple Curves (AMC) function from Origin 9.0 software. The repeatability of the test results appears reasonable. An example of load-deflection curves from four test specimens of 3vol% fiber content UHPC is shown in Fig.2 (a) and their average and concatenated curves are shown in Fig.2 (b). The gray shaded area presents variability.

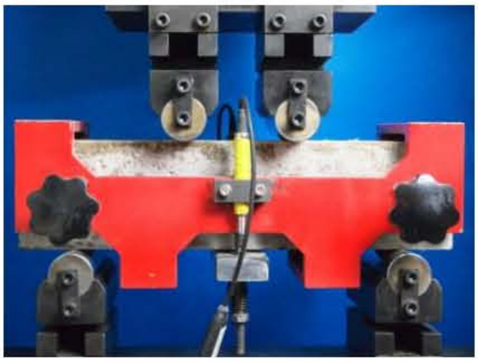
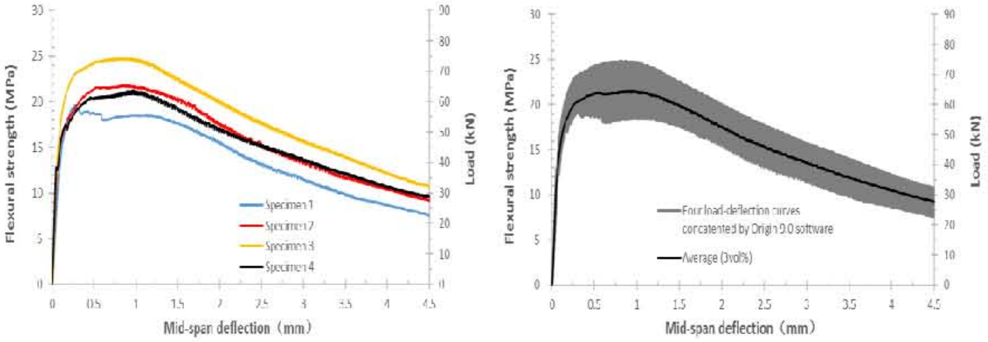


Fig. 1. ASTM C1609 test setup



(a) The curves for each mixture (b) The average and concatenated curves

Fig.2. Demonstration of four curves concatenated by software Origin 9.0

3. RESULTS AND DISCUSSION

3.1 Flexural performances of UHPC

Fig. 3 presents the load-deflection curves of UHPC of the four mixtures and each load-deflection curve is averaged from four specimens as previously mentioned. The test results exhibited deflection-hardening behavior. The load-deflection curves have the significant ascending segment from the first crack to the peak load, indicating that there is significant improvement of the toughness after the cracking of UHPC matrix. The curves follow small zigzag patterns due to the continuous pulling out of the fibers. In addition, all test specimens show the multiple-cracking behavior.

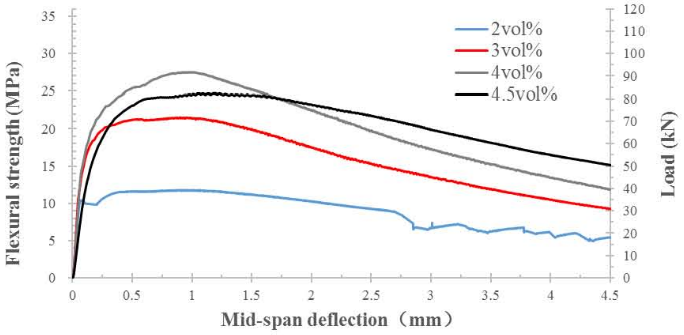


Fig. 3. Load-deflection curves of UHPC of the four mixtures

3.2 Flexural toughness of UHPC

In this study, ASTM C1609 and JSCE SF4 methods were chosen to evaluate the flexural toughness of UHPC. Table 3 shows the parameters calculated according to ASTM C1609 and JSCE SF4.

JSCE SF4 method defines $\bar{\sigma}$ as the flexural toughness factor. The equation is as follows [7]:

$$\bar{\sigma} = T_{150}^{100} \mathrm{L}/(\mathrm{bh}^2\delta_\mathrm{b}) \tag{1}$$

where b is the width of the specimen (mm); h is the height of the specimen (mm); and δ_b is the deflection of 1/150 of span (2 mm in this study).

The flexural toughness factor $\bar{\sigma}$ has the same unit with flexural strength. It can be used to calculate the equivalent bending capacity Mu of the UHPC structural members when deflection is within 1/150L. The equation is as follows [8]:

$$\mathrm{M_u} = \bar{\sigma}\,(\mathrm{bh}^2)/6 \tag{2}$$

As shown in Fig.3, the residual strengths of UHPC beyond 1/150 of span were still remarkable for the characterization of the flexural performance of UHPC, which is still able to maintain good structural integrity and load-holding capacity under large deformation conditions. For certain applications of UHPC, the flexural performance at large deformation (such as 1/75 of span) may be more important than the one at small deflection (such as 1/75 of span). For example, blast resisting structures which require higher energy absorption capacity at large deflections. Therefore，in this study, toughness factor $\bar{\sigma}_\mathrm{n}$ corresponding to the different deflections was proposed to characterize the equivalent flexural strength at different deflections. The equation is given as follows:

$$\bar{\sigma}_\mathrm{n} = T_{bn} l/(bh^2\delta_n) \tag{3}$$

where σ_n is the toughness factor corresponding to the deflection at *L/n* under the curve (MPa); T_{bn} is the area under the load-deflection curve up to a deflection at *L/n* (J); δ_n is the computing deflection (mm); in which *n* is selected as 150, 100 and 75 in this study. The calculated results according to equation (2) is shown in Table 4.

A comparison of the toughness factor $\bar{\sigma}_\mathrm{n}$ corresponding to the different deflections is shown in Table 3. The results showed that the toughness factors only have a small decline with the increase in the deflection. When deflection increased by two times from L/150 to L/75, the ratio between ^{75} and ^{150} of the four mixtures are within 84.7%-95.05%, which means that the difference of flexural performance of UHPC corresponding to L/150 to L/75 are marginal. UHPC maintains good flexural performance at large deflection.

Table 3 Flexural parameters (according to ASTM C1609 and JSCE SF4).

Mix ID	2vol%	3vol%	4vol%	4.5vol%
ASTM C1609 parameters				
P_P(kN)	39.34	71.81	91.76	82.43
$_P$(mm)	0.91	0.90	0.98	1.18
f_P(MPa)	11.80	21.54	27.53	24.73
(kN)	38.72	70.74	84.62	77.10
(MPa)	11.62	21.22	25.39	23.13
(kN)	34.37	58.50	75.17	77.57
(MPa)	10.31	17.55	22.55	23.27
(J)	73.37	130.80	161.50	148.57
JSCE SF4 parameters				
(J)	73.4	130.8	161.5	148.6
$_{150}$(MPa)	11.0	19.6	24.2	22.2
(J)	103.0	182.1	227.4	220.7
$_{100}$(MPa)	10.3	17.3	22.7	22.1
(J)	124.8	221.9	278.4	281.2
$_{75}$(MPa)	9.36	16.6	20.9	21.1
$_{75}/_{150}$*100(%)	85.10	84.70	86.36	95.05

Note: P_P - peak load; $_P$ - net deflection at peak load; f_P - peak flexural strength;, - residual loads at net deflections of *L/600* (0.5 mm in this study) or *L/150* (2 mm in this study), respectively; *L* – Span length (300 mm in this study); , - residual strength at net deflections of *L/150* or *L/600*, respectively; - flexural toughness (area under load–deflection curve up to a deflection at 2 mm).

4. CONCLUSION

(1) The four-point bending test results exhibited deflection-hardening behavior. The load-deflection curves had the significant ascending segment from the first crack to the peak load, indicating there is significant improvement of the toughness after the cracking of UHPC matrix.

(2) Toughness factor $\bar{\sigma}_{n}$ corresponding to the different deflections was proposed to characterize the equivalent flexural strength of UHPC at different deflections.

(3) The difference of flexural performance of UHPC corresponding to L/150 to L/75 were marginal. It means that UHPC maintains good flexural performance at large deflection.

(4) The modified JSCE-SF4 and ASTM C1609 method may provide overall evaluation of the flexural performance of UHPC.

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