Flow and Strength Characteristics of Ultra-high Performance Fiber Reinforced Concrete: Influence of Fiber Type and Volume-fraction

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Abstract: Ultra-High Performance Fiber Reinforced Concrete (UHPFRC) has emerged all of the concrete in the construction industry because of its high strength, durability, serviceability and excellent ductility recently. Due to its high production cost, UHPFRC restricts its large-scale structural application. The conventional UHPFRC preparation consists of expensive materials such as specially graded sands which require complex mixing and curing process. The aim of this paper is to determine flow and strength properties of UHPFRC with the variation of fiber type and fiber volume-fraction. The UHPFRC composition was selected with four different fiber volume fractions (V_f = 0%, 1%, 2%, and 3%) of three different steel fibers at varying curing ages of 7, 28, 56 and 90 days within an identical mortar matrix. The paper provides an overview on the workability properties of UHPFRC followed by the presentation of compressive strength test results with different fibers and its volume-fraction with varying curing ages. The higher fiber volume-fraction resulted in a lower flow, and consequently an improvement of compressive strength observed up to 3% volume-fraction of fibers at 56 days curing. Finally, test results are compared and discussed with regard to the main variables: fiber volume-fraction, types of fiber; and curing ages of the specimens.

Keywords: UHPFRC, Compressive strength, Flow, Curing, Fiber volume-fraction

1. Introduction

The use of Ultra-High Performance Fiber Reinforced Concrete (UHPFRC) has gained popularity in the construction industry in recent years. UHPFRC exhibits significantly higher workability, compressive strengths and serviceability behavior than the normal-strength concrete (NSC), which allows for extensions of a structural design by allowing structural members made from UHPFRC to carry higher loads and excellent ductility achieved at the softening region of concrete [1, 2]. Moreover, it is also familiarized as a super plasticized fiber reinforced concrete with an improved homogeneity with steel fibers because conventional coarse aggregates are totally replaced by an expensive fine aggregate such as silica sand. Due to high production cost, conventional UHPFRC large-scale structural application is very limited in the construction industry. A number of structural applications of UHPFRC in the bridge structures were conducted in the past decades in the worldwide [3-5]. The basic differences of conventional UHPFRC over NSC that it requires specially graded sands, special manufacturing technique, and different curing methods (standard or steam) [6, 7] for the development of rheological and hardened properties. Compressive strength of UHPFRC can achieve regularly 200MPa and it could increase up to 800MPa when use of relatively complex materials, mixing and curing techniques [7-9]. To apply the UHPFRC in the large-scale structural application, one of the promising solution is to reduce the cost of production which includes commonly available materials and methods of production be found in local [6, 10]. The UHPFRC mix was developed at the University of Adelaide, Australia using locally available conventional raw materials the details of which can be found in [11], which was reported in our previous research. In this investigation, UHPFRC with sufficient workability and with a target compressive strength of 150MPa is achieved from a series of experimental test results.

Following the existing research perspective and to achieve the goal of this research, the main objective of this experimental investigation is to determine the workability and strength of UHPFRC with variation of macro fiber and its volume-fraction with curing ages and correlate the flow and strength behavior of UHPFRC in order to achieve the suitable fiber matrix configuration for the real application in the construction industry.

2. Experimental test matrix

An experimental test matrix was developed to investigate the flow and strength characteristics of UHPFRC with influence of varying fiber type and fiber volume-fraction which ranged from 0 to 3%. The fibers investigated had a proprietary names of Dramix 3D, 4D and 5D and are available from Bekaert Ltd in South Australia. A total of 12 batches of concrete mixes were conducted to determine the flow and strength properties of UHPFRC. The compressive strength of all 100x200mm cylinders is given at days 7, 28, 56 and 90. The tests given are the mean of three identical specimens at each time step and the tests are divided according to the fiber type and quantity. In order to determine the flow properties, the different amounts of different fibers on the slump height, slump flow (flow ability) and j-ring flow (passing ability) were conducted. After that, compressive strength properties of UHPFRC with various curing ages were determined in the laboratory.

2.1. Material specifications

The mix compositions were adopted in this experimental section according to the basic mix design from our published work available in [11]. The mix compositions of the UHPFRC by weight are 1: 1: 0.266: 0.175 of sulphate resisting cement (Type SR), fine aggregate, silica fume and steel fibers. After fixing the cement, silica fume and fine aggregate ratio the water and superplasticizer content was proportionally optimized to get the suitable UHPFRC mix. Washed river sand with FM 2.34 was selected in all of the mixes instead of expensive silica sand to produce UHPFRC in this research. The basic composition of the ultra-high performance concrete is given in Table 1.

Table 1 Basic composition of UHPFRC mixture

	Material constituents					
	Cement	Sand	Silica fume	Steel fibers	Water	Superplasticizer
	Amount, kg/m^3					
Mix	920	920	245	161	163	41.4

The variation of steel fibers fraction and type is adopted in this experimental investigation. The different properties of steel fiber are described in Table 2. All of the steel fibers (Dramix-BG) were cold drawn, hooked end wire supplied by the Bekaert Ltd in South Australia. Table 2 shows the different steel fiber properties received from the manufacture data sheet.

Table 2 Types and properties of steel fibers

Properties	3D Fiber	4D Fiber	5D Fiber
Tensile Strength (MPa)	1345	1500	2300
Young Modulus (MPa)	210	210	210
Length of fiber (mm)	36	60	64
Diameter (mm)	0.55	0.9	0.9
Aspect ratio	65	66	70

2.2 Design of test specimen

This experimental test series has mainly been conducted to investigate the workability (e.g flow) and strength properties of UHPFRC with the varying amount of fiber and type. For this purpose, the scope of the experimental test series has two major influencing factors: steel fiber reinforcement amount and fiber type. Each series consisted of 0% fiber content (control) group as well as groups to investigate fiber content ranged from 1 to 3%. It is worth mentioning that the final results of each test series were taken to be the average of three specimens, and it was done to allow for variation between tests, which is particularly important in UHPFRC as variation in fiber volume and orientation in each sample tested can lead to increased scatter of results. Test series 1 was comprised of 144 cylinder specimens with dimension of 100x200mm with the three different types of fiber, volume-fraction and varying curing ages at 7, 28, 56 and 90 days. It is noticed from Table 3 that the specimen is designated using the following procedure: the first letter “S” refers to specimens; the second set of characters, for example “100x200” refers to the dimension of the specimen, third set of characters, for example “3D” indicates the fiber type and the last letter for example “0” refers to the fiber percentage. Each specimen dimension indicates height (H) and diameter (D). The post-peak softening branch of the stress-strain relationship of UHPFRC will be published in our next paper.

Table 3 Experimental design of test specimen

Specimen designation	Fiber (%)	Test series	Fiber type	Specimen dimension	
				H	D
S-100x200-3D-0	0	1	3D	200	100
S-100x200-3D-1	1	1	3D	200	100
S-100x200-3D-2	2	1	3D	200	100
S-100x200-3D-3	3	1	3D	200	100
S-100x200-4D-0	0	1	4D	200	100
S-100x200-4D-1	1	1	4D	200	100
S-100x200-4D-2	2	1	4D	200	100
S-100x200-4D-3	3	1	4D	200	100
S-100x200-5D-0	0	1	5D	200	100
S-100x200-5D-1	1	1	5D	200	100
S-100x200-5D-2	2	1	5D	200	100
S-100x200-5D-3	3	1	5D	200	100

2.3 Mixing procedure and sample preparation

A pan mixer of 80 liters capacity was used in the production of the UHPFRC. The mixer consisted of three concentric rotating steel paddles. It was monitored that the mixer could easily rotate the UHPFRC constituents with 1% and 2% volume-fraction of fiber of the mix; however the volume-fraction of 3% fiber mix could not be mixed satisfactorily. The fibers balled around the machine paddles stop rotating paddles. Balling of the fibers around the mixing paddles resulted in non-uniform distribution of the fibers with 3% fiber volume fraction and to compensate for this additional vibration of samples was required for these mixes when casting in cylinder moulds. Fresh properties were measured with varying fiber amounts and types as soon as mixing were completed and prior to casting in cylinder moulds. The preparation of concrete specimens and curing of concrete were following standard of ASTM-C31/C31M-12 [12].

After casting, all of the cylinders were then allowed to be cured at ambient temperature between 24 and 48 hours until the final setting was achieved. During this time, to prevent moisture loss, the specimens were covered with damp hessian and plastic. The moulds were kept at room temperature at around 20±5^{0}C in summer and 12±5^{0}C in winter. The specimens were then demoulded after 24 or 48 hours depending on that the specimen are surface drying condition and put on the table. Then, all the specimens stored in a fog room until the time of testing. Prior to testing, each specimens both compressive loading faces were ground carefully to obtain a smooth surface.

2.4 Test set-up and instrumentation

All test procedures to determine the fresh properties of the UHPFRC including slump cone measurement, slump flow and J-ring flow test procedures in the means of test set-up and instrumentation are considered according to the standard code of practice. Slump cone test is a measure of filling ability, or the ability of fresh concrete to flow. Slump test was done according to the ASTM-C143/C143M-12 [13] test method. Flow test aims to evaluate the workability (flowability) of fresh concrete. It measures two basic parameters: spread and spread time (T_{50}). The spread represents the free, unrestricted deformability and the time indicates the rate of deformation within a specified spread distance. For all of the mixes, slump spread ability of the concrete was tested by conducting a slump test according to ASTM-C1611/C1611M-09b [14]. J-ring spread and blocking step of the UHPFRC concrete was measured by J-ring test according to ASTM-C1621/C1621M-09a [15]. The purpose of the test is to measure the workability (passing ability) of fresh concrete by J-ring test. It measures three basic parameters J-ring spread, spread time T_{50} and blocking step.

All concrete specimen compression strength tests for all of the series were conducted according to the standard [16]. An Amsler Compression Testing Machine with the maximum capacity 5000kN was used to determine the compressive strength. The basic load configuration and test set-up were constant throughout the testing. The loads were applied on the top surface of 100mm diameter cylinders. The load application rate was maintained at 50kN/min throughout the testing. All of the other compression testing was undertaken at 7, 28, 56 and 90 days in order to quantify the compressive strength gain over time. UHPFRC specimen test set-up, instrumentation and tested specimen after failure are shown in Figs. 1 and 2.

Fig. 1 Test set-up and instrumentation

Fig. 2 Data recording system

3. Results and discussion

At first, the measured fresh properties of the UHPFRC with variation of fiber types and volume-fraction are described and compared amongst the fiber type in the results section. The fresh properties determined are the slump height, flow ability and passing ability of UHPFRC. After that, compressive strength properties of UHPFRC with various curing ages are discussed and compared with varying fiber types and volume-fraction.

3.1 Flow properties of UHPFRC

To obtain the fresh properties, the varying amounts of different fibers on the slump height, slump flow (flowability) and j-ring flow (passing ability) were conducted in the laboratory. Diameter of the flow had approximately measured in parallel and perpendicular position of ply wood board. It was observed from Figs. 3(a) to 3(d) that the fresh properties parameters including slump height, slump flow and J-ring flow decrease with increasing the fiber volume-fraction in the UHPFRC mixes. It is noticeable that flow was most significantly decreased for the 3D fibers and smallest reduced for 5D fibers.

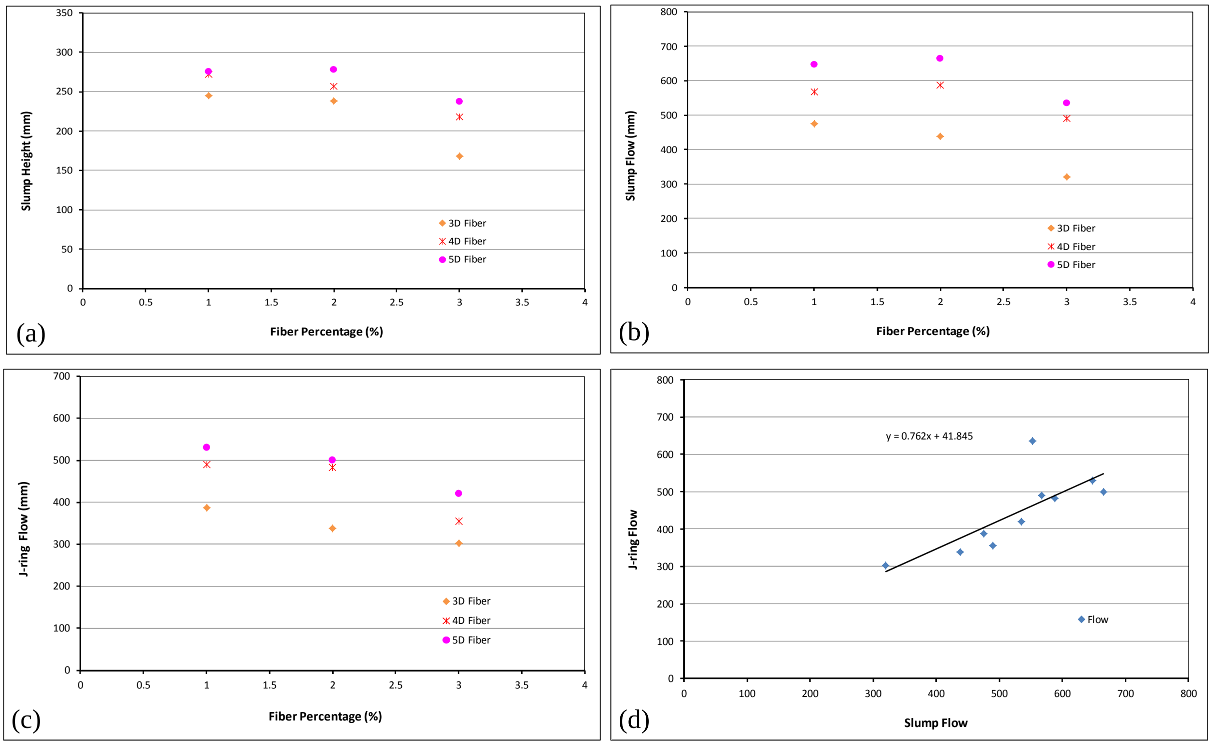

Fig.3 The fiber percentage versus (a) Slump height (b) Slump flow (c) J-ring flow and Fig.3 (d) J-ring flow vs. slump flow

From Fig. 3(a) and Fig. 3(b), it is clear that slump height and slump flow of 2% fiber volume-fraction show similar results to that of a fiber volume-fraction of 1% for all fiber type mixes, indicating that the influence of fiber addition in this range has negligible influence on the measurement of these fresh properties. However, 3% fiber volume fraction exhibits the lowest flow, especially the 3D fiber type which can be easily differentiated from other fiber flow. It may be caused due to the same mass of fiber in the mix resultant in higher amount of 3D fiber present in the same volume of concrete mix which can increase the cohesive forces between the fibers and the matrix that leads to reduction of the flow spread. Moreover, the stiff concrete matrix was formed and it changed the structure of the granular skeleton, and push apart particles that are relatively larger than those with fiber length that leads to reduction of flow for short fiber.

Flow time for slump and j-ring is illustrated in Fig. 4(a) and Fig. 4(b). It is observed that 5D fiber flow time is less than the 4D fiber types. There are no time values observed in Fig. 4(a) for 3D fiber and in Fig. 4(b) for 3D and 4D fibers. It demonstrates that the flow does not exceed the circle of 500mm on plywood and less than the longest fiber as well. It may be because in a certain mass of fibers which was added there are more fibers and due to the much number of fibers in a given volume they are interlocking, cohesive forces and end anchorage of fibers each other with concrete matrix to prevent the flow especially in the J-ring when passing through the reinforcement. Following the opposite trend, the longest fiber mix was observed more flowable than other types of fiber and takes less time to spread as referred to Fig. 4 (b). However, the flowing time of 5D fiber through j-ring has taken around 6-7 times higher than slump flow to exceed 500mm circle of plywood.

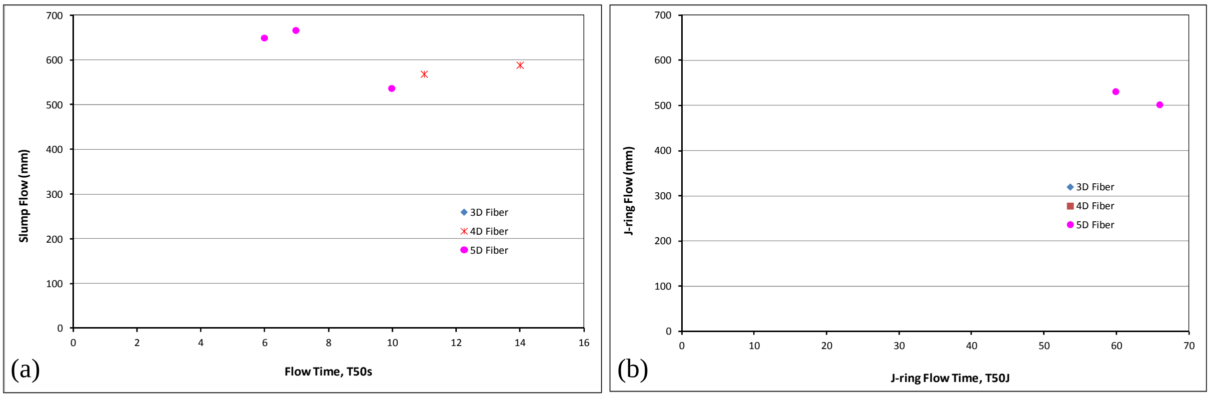

Fig.4 (a) Slump flow versus T_{50s} (b) J-ring flow versus T_{50j}

3.2 Strength properties of UHPFRC

The influence of varying fiber type and content of compressive strength gain is investigated for manufacturing UHPFRC. The compressive strength of all 100x200mm cylinders is determined at days 7, 28, 56 and 90. The results given are the mean of three identical test specimens at each time step and results are shown in the graph according to the fiber type and volume-fraction. In general, it was found that the compressive strength obtained from the UHPFRC test results range from 100MPa to 160MPa for different fiber types and fiber volume- fraction. Besides, it was identified that the strength of UHPFRC is highly time dependent and that the strength of UHPFRC may regress over time due to restraint of shrinkage by the fibers.

Compressive strength of UHPFRC with curing age for different types and volume-fraction of fibers are shown in Fig.5 (a) and Fig.5 (b). It is important to notice that from Fig. 5(a) in general compressive strength of UHPFRC gradually increase up to a peak around 160MPa at 56 days for 4D fiber before regressing slightly at day 90 for all types and volume fraction of fiber. The difference of strength between fiber types with the same volume fraction is relatively small, exceptional observed for 0% and 1% fiber mixes. Moreover, the rate of gain compressive strength was observed with increasing fiber amount for each curing day and each fiber type; however the gain of strength shows the highest value with 3% fiber volume fraction at 56 days period. This behavior could be attributed to the combined effect of 4D fiber in resisting the crack development and mixture with 4D fiber is more homogeneous leads to increase the strength compared to 3D and 5D fibers. On the other hand, decreasing the strength at 90 days suggest that the increased shrinkage effect with higher fiber volumes results in increased cracks lead to a decrease in strength.

The compressive strength compare separately as a normalized stress with the different fiber type is illustrated in Fig.5(c) and Fig.5 (d). The fiber of 3D is considered as reference strength, and then 4D and 5D fiber strength were compared with the reference fiber type. While the compressive strength up to an age of 56 days increased with increasing fiber volume, by day 90 the lowest fiber volumes have the greatest compressive strength for all fiber types. This trend suggests that the increased restraint to shrinkage provided by the higher fiber volumes result in increasing micro-cracking which leads to a greater reduction in strength.

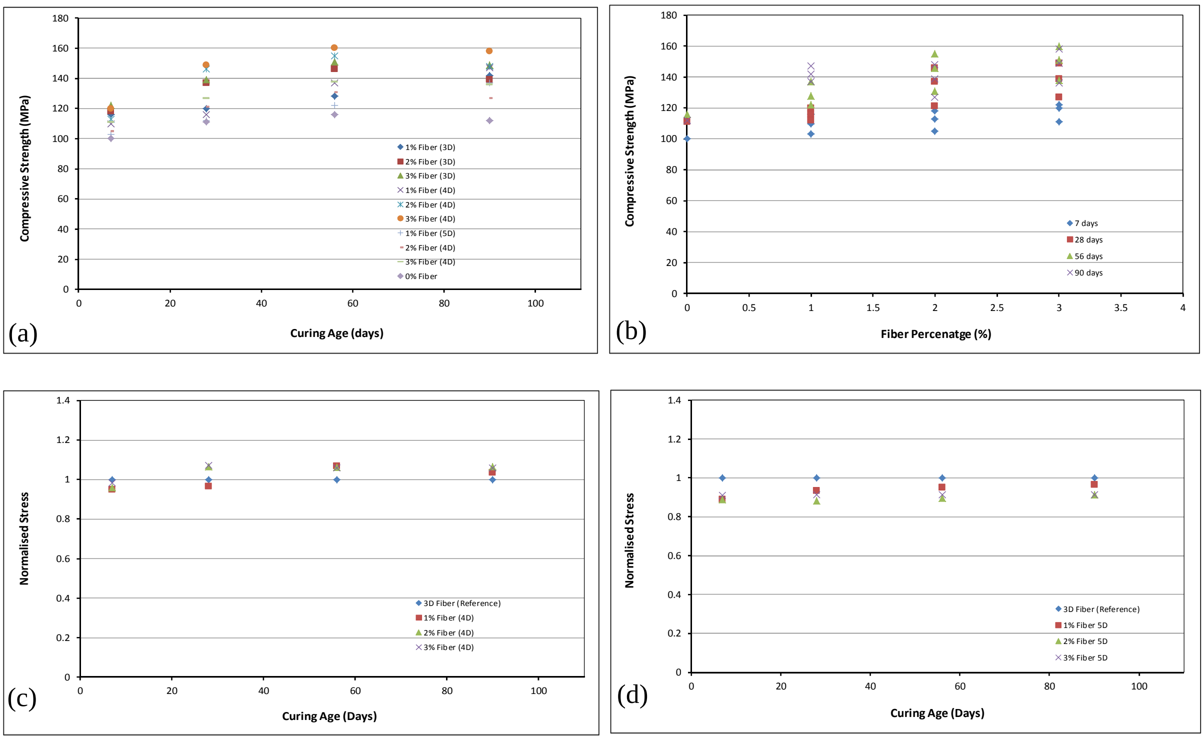

Fig.5 Compressive strength versus (a) curing age (b) fiber percentage, Fig.5 Normalized stress versus (c) curing age (d) curing age

4. Conclusions

UHPFRC has the highest potential for the construction industry because of its high compressive strength and flow properties. The manufacturing of UPFRC from the local available conventional aggregates could be an alternative way in the construction industry. Major outcomes of this study are:

1) The contribution of different fiber type and amount on the strength and workability properties of UHPFRC is distinctly proven through experimental investigation.

2) It is possible to produce UHPFRC with compressive strengths in the range of 130–160MPa with varying fiber type and volume-fraction by using conventional natural and manufactured fine aggregates.

3) It was observed that 2% and 1% fiber volume-fraction exhibits quiet similar flow for all fiber type mixes, indicating that the influence of fiber addition in this range has negligible effects on the measurement of fresh properties of UHPFRC. Consequently, 3% fiber volume-fraction shows the lowest flow, especially the 3D fiber type which can be easily identified from other fiber flow.

4) Further experimental large-scale of experimental work is required in the structural level to understand fully of UHPFRC members with fiber type and volume-fraction including flexural and time-dependent behavior under various loading conditions (such as sustained loads) and environmental exposures (such as freeze thaw, temperature, heat treatment).

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