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TENSILE BEHAVIOR OF ULTRA HIGH PERFORMANCE HYBRID FIBER REINFORCED CEMENT-BASED COMPOSITES

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Abstract: In this paper, a material design concept based on Hybrid Fiber Reinforced Cement-based Composites (HFRCC) is applied to Ultra High Performance Concrete (UHPC) so that a multi-level-reinforcement system for cracking will enhance the peak stress after crack initiation (i.e. tensile strength) and tensile strain capacity (i.e. strain at the peak stress, or ductility). UHP-HFRCC is created by means of the multi-level-reinforcement system, in which micro-fibers and macro-fibers are blended and work together for preventing crack extension in UHPC. The aim of this research is to investigate the effect of blending two different fibers in UHP-HFRCC on tensile strength and tensile strain capacity. Lastly, all results are compared with previous ones reported by other researchers to reveal the present results far exceed previous ones.

1 INTRODUCTION

Concrete is one of the most widely used materials in structures around the world. Advanced concrete technologies have recently focused especially on developing Ultra High Performance Concrete (UHPC) and High Performance Fiber Reinforced Cementitious Composites (HPFRCC). UHPC has high compressive strength (150-200MPa) [1] and also great durability due to its excellent environmental resistance. However, UHPC leads to ultra high compressive strength that results in an explosive failure in compression, and a very brittle failure in tension [2]. To improve such a poor property, UHP-Fiber Reinforced Cementitious Composites (UHP-FRC) have been developed. Fibers are added not to improve the peak tensile strength itself but mainly to control the cracking, that is to change the behavior of the cracked material by bridging of fibers across the cracks. The tensile strength of UHP-FRC has been reported in the range of about 8MPa to 15MPa [2] and strain capacity, i.e. strain value at the peak stress in uniaxial tension tests have been reported in the range from 0.06% to 0.46% [3-4]. On the other hand, HPFRCC is defined as a ductile material which shows strain hardening behavior and multiple cracking [3]. In HPFRCC under uniaxial tensile stress, the stress level ascends as the tensile strain increases, even after the first crack initiates. As a result, the strain capacity becomes very large. Wille et al. [2] and Park et al. [4] reported the reason of difficulties in obtaining strain capacity larger than 0.5%, as well as tensile strength higher than 15MPa. The reasons are as follows: first, there is a limit in the amount of fiber volume contents that can be mixed, especially for deformed steel macro-fiber (HDR) with an aspect ratio more than 80 and length longer than 30mm. Second, the bond strength of short micro-fiber is much lower than that of HDR, although a much larger amount (4.0-6.0vol.%) of fibers can be added without serious reduction in workability.

Our idea for solving the difficulties mentioned above is to apply a material design concept of Hybrid Fiber Reinforced Cement-based Composites (HFRCC) so that a multi-level-reinforcement system (Fig.1) will enhance the peak stress after crack initiation (i.e. tensile strength) and strain capacity (ductility). UHP-HFRCC is created by means of the multi-level-reinforcement system for preventing crack extension in UHPC, in which short micro-fiber and long macro-fiber are blended and work together.

Rossi [5] reported a concept of UHP-HFRCC, in which two or three different types of fibers are blended in UHPC matrices. For example, long and short fibers, or smooth and hooked steel fibers were blended accounting for 6.0vol.% to 11.0vol.%. The main difficulty caused by a large amount of fiber in the application of UHP-HFRCC was the high material cost and poor workability.

Kawamata et al. [6] studied the reinforcing mechanism of HFRCC. While they used steel cord as the macro-fiber and polyethylene fiber as the micro-fiber, they revealed the effectiveness of the multi-level-reinforcement system for enhancing the ductility. Markovic [7] investigated optimum combinations of various types of steel fibers. Although he reported the flexural and tensile behavior of HFRCC, no information about tensile strain capacity was provided. Thus, very little information is available regarding the tensile stress-strain response of UHP-HFRCC. Table 1 summarizes the key properties of UHP-FRCCs reported in previous studies.

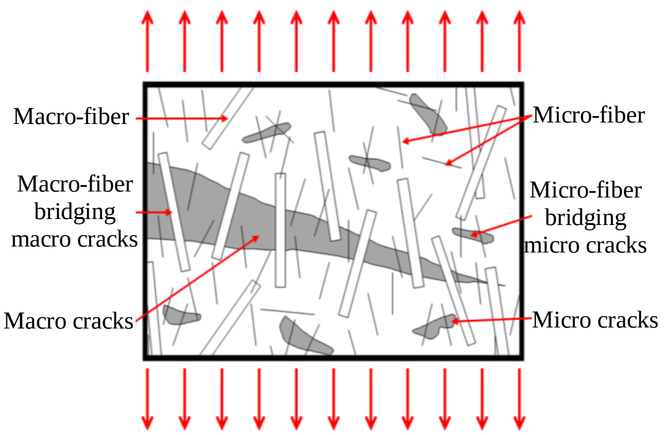


Fig.1 Fiber bridging by hybridization of micro-fiber and macro-fiber (multi-level-reinforcement system) on crack surface

The aim of this research is to investigate the effect of blending the two different fibers on tensile strength and tensile strain capacity of UHP-HFRCC. A series of experiments are carried out and results are compared with data shown in Table 1.

2 MATERIALS

UHP-HFRCC mixture was developed in our laboratory by optimizing several constituent material's parameters, leading to a compressive strength of 182MPa, which additionally exhibits self consolidating properties providing good workability. Commercial Silica Fume Cement (SFC) was used, in which low-heat cement (82wt.%) and silica fume (18wt.%) were blended. The density and blaine fineness of SFC were 3.01g/cm^3 and 6,555cm^2/g, respectively. As aggregates, well-graded very fine natural silica sand with the average particle size of 0.212mm was used and wollastonite ($CaSiO_3$) was also substituted. The density of wollastonite was 2.9g/cm^3. Superplasticizer and anti-foaming agents were employed for reducing water dosage and air content. The steel fibers used in this study were OL fiber of 6mm as the micro-fiber and HDR fiber of 30mm as the macro-fiber. The properties of fibers are shown in Table 2. The volume content of OL fiber was maintained as 1.0vol.% for keeping the workability available, while the volume content of HDR fiber was varied at 0.5vol.%, 1.0vol.%, 1.5vol.% and 2.0vol.%. Table 3 provides the mixtures for UHP-HFRCC used in this study.

3 EXPERIMENTAL PROGRAM

The experimental study was carried out for investigating the influence of volume content of macro-fiber HDR on the mechanical behavior of four mixtures in Table 3. After de-molding, the specimens were cured in a steam chamber for 24 hours. The steam curing condition was as follows: temperature increased at a rate of 15ºC per hour up to 90ºC, where it was kept for 24 hours; then gradually cooled down to 20ºC.

Table 1 Tensile properties of UHP-FRCCs

Notation	Fiber				σ_{pc} (MPa)	ε_{pc} (%)	Reference
	Type	l_f (mm)	d_f (mm)	V_f (%)			
Ceracem	Mono	20.0	0.30	Smooth 2.5	9.7	0.25	Jungwirth et al. [8]
Ductal	Mono	13.0	0.20	Smooth 2.0	12.0	0.30	Chanvillard et al. [9]
RPC	Mono	12.0	0.15	Smooth 2.4	7.8	n/a	Behloul et al. [1]
HPFRCC	Mono	30.0	0.30	Smooth 2.0	12.0	0.46	Sujiravorakul et al. [10]
*S-UHPFRC	Mono	13.0	0.20	Smooth 2.5	14.2	0.24	Wille et al. [2]
UHPFRC1	Mono	10.0	0.20	Smooth 6.0	9.65	0.07	Wuest et al. [11]
UHPFRC2	Mono	13.0	0.16	Smooth 4.0	12.6	0.27	Wuest et al. [11]
MSCC	Hybrid	25.0	0.30	Hooked 2.0	15.0	n/a	Rossi et al. [5]
		5.0	0.25	Smooth 5.0			
CARDIFRC	Hybrid	13.0	0.16	Smooth 5.0	13.5	0.06	Benson et al. [12]
		6.0	0.16	Smooth 1.0			
CEMTEC multiscale	Hybrid	Three fiber-types	Three fiber-types	Total 11.0	20.0	0.2	Boulay et al. [13]

Note: In all series, a heat treatment up to 90 ºC was carried out, *: normal curing condition, n/a: not available

Table 2 Properties of different fibers used in this study

Notation	Form	Specific gravity (g/cm^3)	Length (mm)	Diameter (μm)	Aspect ratio (L/D)	Tensile strengh (MPa)	Young's modulus (GPa)
OL6	Straight	7.85	6	160	37.5	2000～	206
HDR	Hooked	7.85	30	380	78.9	3000	206

Table 3 Mixtures for UHP-HFRCC and results

Notation	B	S/B	Wo/B	W/B	SP/B	D/B	OL6 (vol.%)	HDR (vol.%)	σ_{pc} (MPa)	ε_{pc} (%)
OL1H0.5	100.0	35.0	13.0	14.3	1.7	0.02	1.0	0.5	11.9	0.073
OL1H1.0								1.0	12.4	0.086
OL1H1.5								1.5	16.1	1.06
OL1H2.0								2.0	20.1	0.89

Note: B:binder, A:aggregate, S:sand, Wo:wollastonite, SP:superplasticizer, D: antifoaming agent

After the steam curing, specimens were stored in a curing room at 20ºC and about 95%RH until the time of the loading tests. The geometrical dimension of `dumbbell type` specimens tested in this study followed the recommendations of the Japan Society of Civil Engineers (2007) for HPFRCC composites. The uniaxial tensile load was applied with an Instron testing machine of 30kN capacity, and the supporting condition was 'fix-fix'. Each test was controlled by the loading head's displacement at a velocity of 0.5mm/min. Average extension was measured over the central gauge length (80mm) by means of two LVDTs which were placed on the both sides of mounting frames and firmly clamped onto the specimens.

4 RESULT AND DISCUSSION

4.1 Tensile Behavior of UHP-HFRCC

Mean curves of each mixture are shown in Fig.2, which were calculated by averaging the stress values of each curve at the same strain level. All series investigated exhibited strain softening or strain hardening without brittle behavior. OL1H0.5 series showed strain softening but not strain hardening behavior. In addition, few multiple cracks were observed. This phenomenon was also observed in OL1H1.0 series. Strain hardening behavior, including multiple cracking, was clearly observed for investigated UHP-HFRCC in OL1H1.5 and OL1H2.0, both of which contain fibers of total volume fractions exceeding 2.5vol.%. Since the volume content of OL fiber was kept constant as 1.0vol.% in this study, it was verified that at least 1.5vol.% of HDR fibers are required for obtaining strain hardening behavior and multiple cracking.

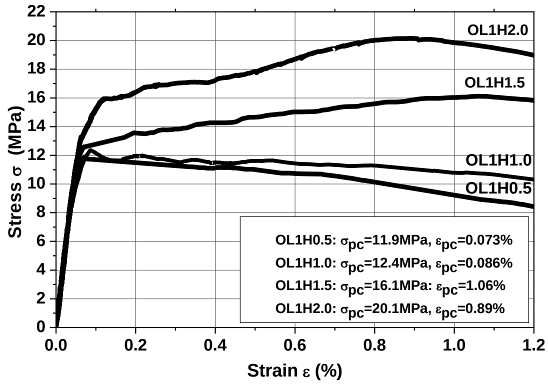
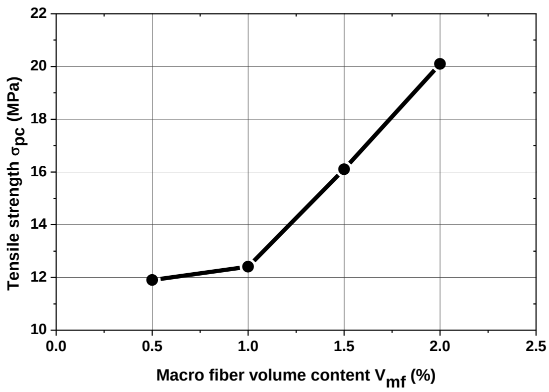
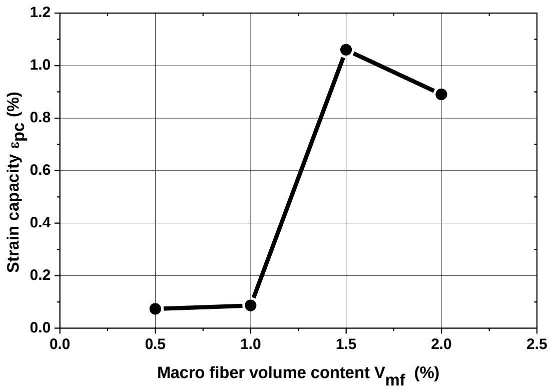


Fig.2 Tensile behavior of UHP-HFRCC developed in this study

Figure 3 summarizes the results obtained for UHP-HFRCC. Fig.3(a) showed that the peak stress, σ_{pc}, gradually increased as macro-fiber volume content: V_{mf} increased in all series, though the increasing rate drastically changed when the value of V_{mf} exceeded 1.0vol.%. As for values of the strain capacity: ε_{pc}, they were not much different in both cases of OL1H0.5 and OL1H1.0 series and were 0.073% and 0.086%, respectively (Fig.3(b)). On the other hand, in both cases of OL1H1.5 and OL1H2.0 series, the values of ε_{pc} notably increased, though the values did not proportionally increase as V_{mf} increased over 1.5vol.%.



(a) tensile strength



(b) strain capacity

Fig.3 Influence of macro-fiber volume content on tensile strength (a) and strain capacity (b)

It is worthwhile to notice that there was a remarkable difference between two values of the strain capacity when V_{mf} was below 1.0vol.% or over 1.5vol.%, though such a remarkable difference was not recognized for the tensile strength. According to Fig. 2, the stress levels of the first crack initiation are almost the same for the four series. After the first crack initiation, however, strain softening behavior starts in OL1H0.5 and OL1H1.0 series but strain hardening behavior starts in OL1H1.5 and OL1H2.0 series. This is due to the multi-level-reinforcement system to control crack initiation and propagation in UHP-HFRCC with two different types of fibers. A large quantity of thin and short OL fibers are densely dispersed in the matrix, which usually increases the crack initiation strength. However, because of the relatively low bond strength and shorter length, OL fibers can't work well for bridging crack surfaces on the macro-level. On the contrary, HDR fiber, which has a high bond strength and a longer length, increased stress transfer performance even after the first crack is initiated. During the process of pull-out from the crack surface, HDR fiber resists mechanically by the bending and yielding of the hooked part. Therefore the amount of the HDR fiber was very important to control macro crack propagation and to enhance the strain hardening behavior, while OL fiber reinforces the matrix by increasing stiffness, strength and crack resistance on the micro-level. Thus, in OL1H0.5 and OL1H1.0 series, the amount of HDR fibers might be insufficient to control macro crack propagation for leading the strain hardening behavior after the first crack initiation.

According to the experimental results obtained in the present study, tensile strength can be increased by increasing the volume content of HDR fibers exceeding 1.0vol.% on the condition that the matrix of high strength mortar is reinforced with short and thin micro-fibers of at least 1.0vol.%. As for the strain capacity, it is concluded that HDR fibers exceeding 1.5vol.% on the same condition mentioned above are required for achieving UHP-HFRCC based on the multi-level-reinforcement system (Fig.1).

4.2 Comparison with Results Reported by Other Researchers

Figures 4 and 5 show the tensile properties of all series of UHP-HFRCC obtained in this study, which are compared with tensile test results of UHP-FRCs reported by previous studies shown in Table 1. As a result, OL1H1.5 series containing total fiber volume content of 2.5vol.% resulted in a tensile strength of 16.1MPa in association with a strain capacity of 1.06%. The strain value is 2 to 17 times larger than those obtained in previous studies. UHP-HFRCC shows a noticeable increase of tensile strength, σ_{pc}, as the fiber volume content increased. Although this phenomenon is observed not only in this study but also in previous studies, the increasing rates of these two groups are remarkably different from each other and previous studies required higher volume contents of fiber. As for the strain capacity, ε_{pc}, UHP-HFRCC shows a noticeable enhancement as the total fiber volume content

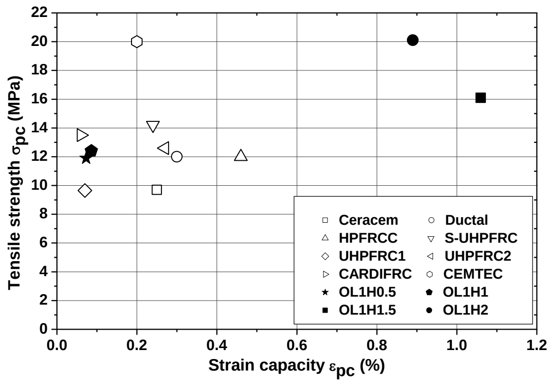
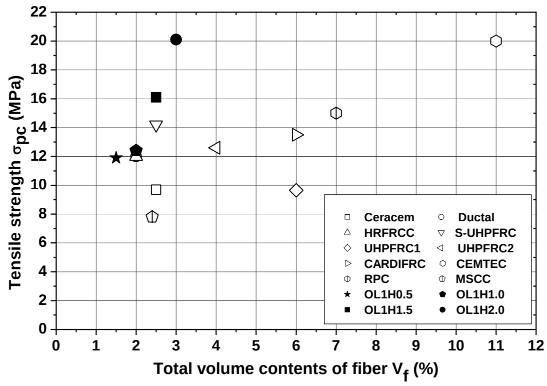
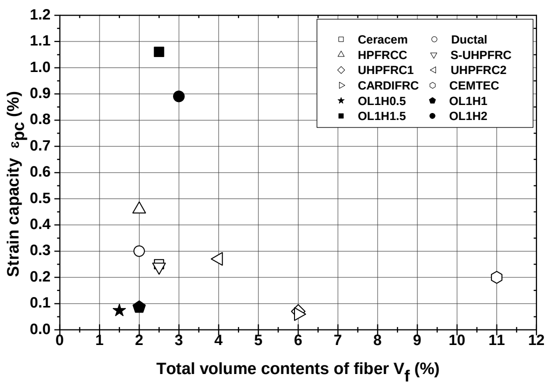


Fig.4 Tensile behavior of UHP-HFRCC developed in this study in comparison to results reported by other researchers



(a) Tensile strength



(b) Strain capacity

Fig.5 Influence of total fiber volume contents on tensile properties of UHP-HFRCC.
(a) Tensile strength, (b) Strain capacity

approaches 2.5vol.%,. On the other hand, values of the strain capacity obtained in previous studies do not increase proportionally to the fiber volume content.

5 SUMMARY AND CONCLUSIONS

This study investigated applicability of a material design concept based on the multi-level-reinforcement system to development of UHP-HFRCC, and influence of blending micro- and macro-fibers on tensile mechanical properties of UHP-HFRCC. The following conclusions were obtained:

1. Applying the multi-level-reinforcement system to UHPC is an affordable approach to develop UHP-HFRCC.
2. Increasing the volume content of HDR fibers was confirmed to improve tensile strength and strain capacity of UHP- HFRCC.
3. This study clearly showed that UHP-HFRCC achieves much higher tensile strain capacity than that reported in previous studies.

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