MECHANICAL PROPERTIES OF ULTRA-HIGH-PERFORMANCE HYBRID FIBRE-REINFORCED CEMENT-BASED COMPOSITES

Sukmin Kwon (1), Tomoya Nishiwaki (1), Takatune Kikuta (2) and Hirozo Mihashi (1)

(1) Tohoku University, Sendai, Japan

(2) Nippon Institute of Technology, Saitama, Japan

Abstract

In this study, the influence of volume contents of mesofibre and macrofibre on the tensile behaviour of ultra-high-performance hybrid fibre-reinforced cement-based composites (UHP-HFRCC) was experimentally investigated. It was shown that the tensile behaviour of UHP-HFRCC is dominantly affected by the volume content of macrofibre rather than that of mesofibre. However, it was also shown that mechanical performance such as tensile strength, tensile strain capacity (ductility) and energy absorption capacity are not simply affected by the volume content of the macrofibre; The balance of volume contents between mesofibre and macrofibre is very important to enhance the mechanical performance under tension.

Résumé

Dans cet article on étudie expérimentalement l'influence de la teneur volumique en fibres et microfibres sur le comportement en traction de composites cimentaires fibrés hybrides à ultra-hautes performances (CCFHUP). On montre que le comportement en traction des CCFHUP est principalement affecté par la teneur en macrofibres, plus que par celle en microfibres. Cependant, on montre aussi que la résistance en traction, la capacité de déformation en traction (ductilité) et la capacité d'absorption d'énergie ne sont pas seulement influencées par la teneur en macrofibres, mais que l'équilibre des teneurs en microfibres et macrofibres est très important pour améliorer le comportement en traction du CCFHUP.

1. INTRODUCTION

Ultra-high-performance fibre-reinforced cement-based composites (UHP-FRCC), which have the potential to be a ductile material that shows pseudo-strain-hardening behaviour and multiple cracking after the occurrence of the first crack under uniaxial tensile stress, have been focused on by many researchers because of its unique mechanical performance. Nonetheless, by simply adding one type of fibre in ultra-high-performance concrete (UHPC), it is still difficult to obtain high strain capacity (ductility) as well as high tensile strength

Table 1: Composition of matrix mixture by weight ratio and compressive strength

Cement*	Water	Sand	Wollastonite	Superplasticizer	Anti-foaming agents	Compressive strength (MPa)
1.0	0.143	0.35	0.13	0.017	0.0002	182

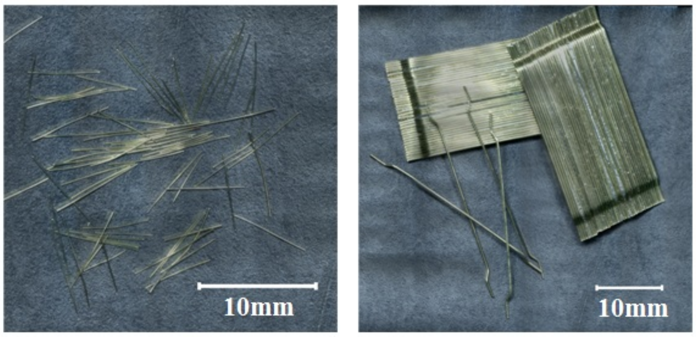
Note: *Silicafume premixed low heat cement (Mitsubishi materials Co.).

because a high volume content of fibre causes workability problems and high cost. As one possible solution to these problems, some researchers used a hybrid system which is the application of fibres of different geometries in UHPC. It hereby, a multi-level reinforcement system is created, and it is called UHP-hybrid fibre reinforced cement-based composites (UHP-HFRCC) [1]. However, current researches on UHP-HFRCC have been focused on enhancing tensile performance such as strain capacity, tensile strength as well as energy absorption capacity which required a large amount of fibres, i.e. 6-11% by volume [2, 3, 4]. Thus, it results in high cost and poor workability. Indeed, after the first crack initiation, the mechanical response of UHP-HFRCC changes from elastic stage to microcracking stage or mesocracking stage, because of the bridging action performed by microfibre or mesofibre. Then, the beneficial effects of macrofibre become evident only after this stage by arresting and delaying the growth of macrocrack [1, 5]. Kwon et al. [1] reported mono-fibre composites which use only macrofibres exhibit larger scatter and lower tensile performance than hybrid-fibre composites. Fantilli et al. [6] showed that the volume content of macrofibre for achieving strain hardening and multiple cracking in UHP-HFRCC could be reduced with hybrid-fibre composites. However, very little information is available regarding the influence of the mix proportion of volume contents of microfibre or mesofibre and macrofibre on the mechanical performance of UHP-HFRCC. The objective of this study is to investigate the mechanical perfromance of UHP-HFRCC under tension by changing the mix proportion of volume contents of mesofibre and macrofibre. The specific objective is to investigate the effect of blending of two different types of fibres: straight, short fibres (mesofibres) and hooked, long fibres (macrofibres).

2. EXPERIMENTAL PROGRAM

2.1 Materials

An UHP–HFRCC mixture based on a multi-level reinforcement concept was developed by optimizing the parameters of several constituent materials (Kwon et al. [1]); the mixture shown in Table 1 has a compressive strength of 182 MPa and exhibits good workability. We used commercial silica fume cement (SFC), in which low-heat cement (82 wt.%) and silica fume (18 wt.%) were pre-mixed. The density and blaine fineness of SFC were 3.01 g/cm^3 and 6,555 cm^2/g, respectively. As aggregates, well-graded very fine natural silica sand with an average particle size of 0.212 mm was used and wollastonite ($CaSiO_3$) was also substituted. The density of silica sand and wollastonite were 2.9 g/cm^3 and 2.9 g/cm^3, respectively. Polycarboxylate-based superplasticizer and anti-foaming agents were employed for reducing water dosage and air content.



Mesofibre (S-fibre) Macrofibre (H-fibre)
Figure 1: Different type of fibres used in this study.

Table 2 - Properties of different fibres used in this study

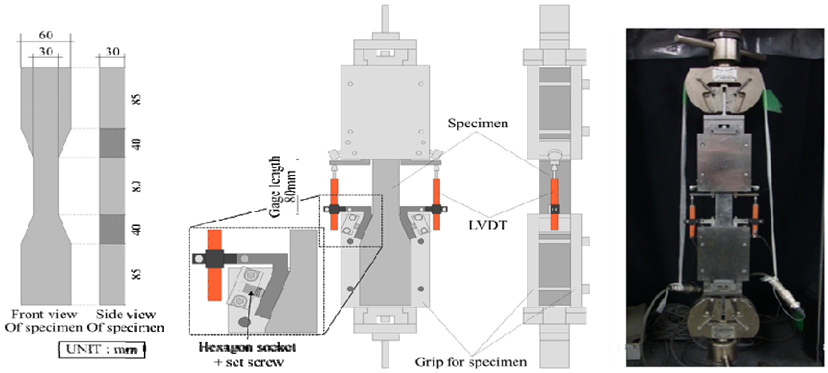
Notation	Form	Specific gravity (g/cm[3])	Length (mm)	Diameter (mm)	Aspect ratio (L/D)	Tensile strength (MPa)	Young's modulus (Gpa)
S	Straight	7.85	6.0	0.16	37.5	2000~	206
H	Hooked	7.85	30.0	0.38	78.9	3000	206

Table 3 - Test series

Notation	V_{sf} (%)	V_{hf} (%)	V_f (%)	χ_f
S0H0.5	0.0	0.5	0.5	0.4
S0H1.0	0.0	1.0	1.0	0.8
S0H1.5	0.0	1.5	1.5	1.2
S1H0.5	1.0	0.5	1.5	0.8
S1H1.0	1.0	1.0	2.0	1.2
S1H1.5	1.0	1.5	2.5	1.6
S2H0.5	2.0	0.5	2.5	1.2
S2H1.0	2.0	1.0	3.0	1.6
S2H1.5	2.0	1.5	3.5	2.0
S3H0.5	3.0	0.5	3.5	1.6
S3H1.0	3.0	1.0	4.0	2.0
S3H1.5	3.0	1.5	4.5	2.4

Note: V_{sf} : volume content of S-fibre, V_{hf} : volume content of H-fibre, V_f: total volume content of fibre, χ_f : fibre factor

As shown in Fig. 1, the steel fibre used as the mesofibre in this study was straight steel fibre with a length of 6 mm (hereafter, "S-fibre"); the macrofibre was long and with hooked ends with a length of 30 mm (hereafter, "H-fibre"). The diameter of the mesofibre was 0.16 mm and that of the macrofibre was 0.38 mm. The properties of the fibres are shown in Table 2. The volume content of S-fibre was changed as V_{sf} = 0.0%, 1.0%, 2.0%, 3.0%, each of which are described as S0, S1, S2 and S3. On the other hand, the volume content of H-fibre was changed as V_{hf}= 0.5%, 1.0% and 1.5%, each of which are described as H0.5, H1.0 and H1.5. Table 3 shows as overview of the UHP-HFRCC mixtures adopted in this study.



(a) Specimen geometry properties. (b) Equipment for mounting. (c) Test setup for uniaxial tension.
Figure 2: Geometrical properties of dog-bone specimen and test setup for uniaxial tension.

2.2 Specimen preparation and curing

An Omni-type laboratory mixer of 5.0 litres capacity was used for mixing. Cement, sand, and wollastonite were first dry-mixed for 60 s. Water was pre-mixed with polycarboxylate-based superplasticizer. Then anti-foaming agents were added and mixed for another 360 s. The S-fibres were dispersed into the mortar and then mixed for another 90 s. The H-fibres were finally added and mixed for another 210 s. Table flow tests were conducted for each batch to measure the fresh property which followed the recommendations of Japan industrial standards (JIS R 5201) [7]. The filling method of UHP-HFRCC to produce the specimens was fixed in the same way for each series, by keeping the pouring position of three parts to make two layers in the mould. Zhou et al. [8] reported that fibre orientation was not changed if the filling method was the same even though the type of fibre and the volume content were changed. Based on their experimental findings, the influence of the fibre orientation on mechanical performance was not discussed in the present study. Dog-bone specimens were cast in plastic moulds. The geometry of the dog-bone specimens, which followed the recommendations of the Japan society of civil engineers (JSCE) [9] for high-performance fibre-reinforced cement-based composites, is illustrated in Fig. 2(a). Figure 2(a) shows that the smallest section of the specimen was 30×30 mm^2. In principle, 4-6 specimens were used for each test series. After de-moulding, the specimens were cured in a steam chamber for 24 h. The steam curing condition was as follows: the temperature increased at a rate of 15ºC per hour up to 90ºC, and it was kept at this level for 24 h. Then the temperature was gradually lowered to 20ºC. After the steam curing, the specimens were stored in a curing room at 20ºC and about 95% relative humidity (RH) until the time the test were carried out.

2. 3 Test set-up and procedure

The uniaxial tension tests were conducted according to the recommendations of the Japan Society of Civil Engineers (JSCE) [9]. Equipment for mounting the dog-bone-type specimen on the loading machine and the test set-up for uniaxial tension are shown in Figs. 2(b) and (c), respectively. The average extension was measured over the central gauge length of 80 mm using two linear variable-differential transformers (LVDT) that were placed on both sides of the mounting frames and firmly clamped onto the specimen, as shown in Fig. 2(b). The uniaxial tensile load was applied with an universal testing machine with 30 kN capacity and the supporting condition for the specimen was “fix–fix.” Each test was controlled by the displacement of the loading head at a displacement rate of 0.5 mm/min.

3. EVALUATION PROCEDURES

3.1 Fiber factors related to workability

Fibre volume content and aspect ratio (the ratio of length to diameter) are known to affect the workability of FRCC, so that an increase in these values leads to a decrease in workability. Assuming that fibres have the same surface conditions, the fibre factor, χ_f can be selected as a parameter to evaluate in advance whether the workability of a mix is adequate or not. The fibre factor is defined by Equation (1):

$$\chi_f = V_f \times \ell_f / d_f \tag{1}$$

where χ_f is the fibre factor, V_f is the fibre volume content, ℓ_f is the fibre length, and d_f is the fibre diameter. Obviously, an increase in χ_f increases the risk of fibre clumping during the mixing process and decreases workability. Note that a value of $\chi_f \approx 2.5$ was suggested by Markovic [10] as an upper limit for the straight steel fibre used in his study. Naaman and Wille [11] and Wille and Naaman [12] investigated the workability of UHP–FRCC with different fibre volume contents, and suggested $\chi_f \approx 2.0$ as the upper limit. In this study, χ_f was calculated for each of S-fibre and H-fibre. Then, both values were summed up (Table 3).

3.2 Mechanical properties

σ_{pc} is the maximum post-cracking stress, or tensile strength. The strain value at the tensile strength is defined as the strain capacity ε_{pc}. "Pseudo-strain-hardening" means that the tensile stress increases up to the tensile strength σ_{pc} even after the first crack occurs on the crack-initiation stress σ_{cc}. According to Naaman [13], high-performance fibre-reinforced cement-based composites should satisfy Equation (2), that is the condition formulated for the pseudo-strain-hardening property, and to obtain multiple cracking.

$$\sigma_{pc} \geq \sigma_{cc} \tag{2}$$

Load-displacement relations were recorded in a data-acquisition system. From these digital data, we determined the mechanical properties of UHP–HFRCC, i.e., the crack-initiation stress, σ_{cc}, the tensile strength, σ_{pc}, and the strain capacity, ε_{pc}. By comparing two values of σ_{cc}, and σ_{pc}, we assessed whether the condition for the pseudo-strain-hardening property described in Equation (2) was satisfied or not.

3.3 Energy-absorption capacity

Energy-absorption capacity is defined as the dissipated energy per unit volume (kJ/m^3) of composites because of cracking in the matrix and the frictional bonding and yielding of steel fibres in the specimen. In this study, the energy-absorption capacity, g, of UHP–HFRCC was determined by Equation (3), which is equivalent to the area under the stress–strain curve starting from zero up to the strain capacity, ε_{pc}. The energy absorption during the strain-softening phase was not discussed in this study.

$$g = \int_0^{\varepsilon_{pc}} \sigma(\varepsilon) d\varepsilon \tag{3}$$

Table 4 - Experimental results of table flow test and mechanical properties

Notation	Flow (mm)	*Ave. value of* σ_{pc} (MPa)	*Variation of* σ_{pc} (MPa)	*Ave. value of* ε_{pc} (%)	*Ave. value of g* (kJ/m^3)	*Number of specimes (ea.)*
S0H0.5	280 × 280	13.04	2.95	0.056	3.65	5
S0H1.0	275 × 270	11.70	1.65	0.11	9.74	6
S0H1.5	260 × 260	12.97	0.91	0.63	71.49	6
S1H0.5	275 × 280	14.16	0.99	0.19	20.09	6
S1H1.0	270 × 260	13.31	1.10	0.36	38.33	6
S1H1.5	220 × 220	16.59	0.53	1.01	145.20	6
S2H0.5	250 × 250	14.17	0.71	0.228	27.87	4
S2H1.0	240 × 250	14.79	2.68	0.748	98.50	6
S2H1.5	230 × 230	14.53	4.77	0.502	69.49	5
S3H0.5	235 × 235	10.50	1.57	0.163	13.35	6
S3H1.0	220 × 220	13.81	2.19	0.26	30.97	6
S3H1.5	210 × 210	14.36	4.50	0.58	69.54	6

Note: σ_{pc}: tensile strength, ε_{pc}:strain capacity, *g*:energy absorption.

4. EXPERIMENTAL RESULTS AND DISCUSSION

4.1 Fresh property

The results of the table flow test are shown in Table 4. While the calculated values of the fibre factor χ_f range from 0.8 to 2.4 in this study, the experimental results of the table flow test are inversely proportional to the value of χ_f and the workability was sufficient. Practically, the fibre factor can be a useful parameter to estimate the workability.

4.2 Stress–strain curves

The tensile stress-strain curves of all test series are illustrated in Fig. 3. According to Figs. 3(a)-(l), the stress levels at crack initiation were almost the same for all series except S3H0.5 and S3H1.5, in these cases the scatter was large. Unstable descending branches right after the first peak were observed in S0H0.5 and S0H1.0 series and also in several specimens of S1H0.5 series, though they were not observed in other series with S-fibres.

Strain-softening as well as strain-hardening behaviour was observed in the tests (Fig. 3) The result shows that it is difficult to achieve the strain-hardening behaviour if the volume content of H-fibre is less than 1.0 % in case of mono-fibre reinforced cement-based composites. However, it is clearly shown that adding at least 2 % S-fibres can be achieved strain-hardening behaviour even with H-fibre of 1 %. This is a result of the multi-level reinforcement system which controls crack initiation and propagation in UHP-HFRCC by means of a synergy effect of S-fibre and H-fibre. S0 series with H-fibre of less than 1.0 % showed strain-softening behaviour (Fig. 3(a), (b)). In those series, crack localization occurred right after the peak stress. This phenomenon was also observed in S1 series (Fig. 3 (d), (e)), S2 series (Fig. 3(g)) and S3 series (Fig. 3(j)), although a few multiple cracks were observed in some specimens. The results show that increasing V_{sf} from 1.0 % to 3.0 % of S-fibre does not lead to strain hardening behaviour at V_{hf} = 0.5% of H-fibre. Strain-hardening behaviour, together with multiple cracking, was clearly observed in all series with H-fibre of 1.5% (Fig. 3(c), (f), (i) and (l)), and S2 series and S3 series with H-fibre of 1% (Fig. 3(h) and (k)). It is worthwhile to notice that hybrid-fibre series containing S-fibre of V_{sf} = 1.0% showed lower

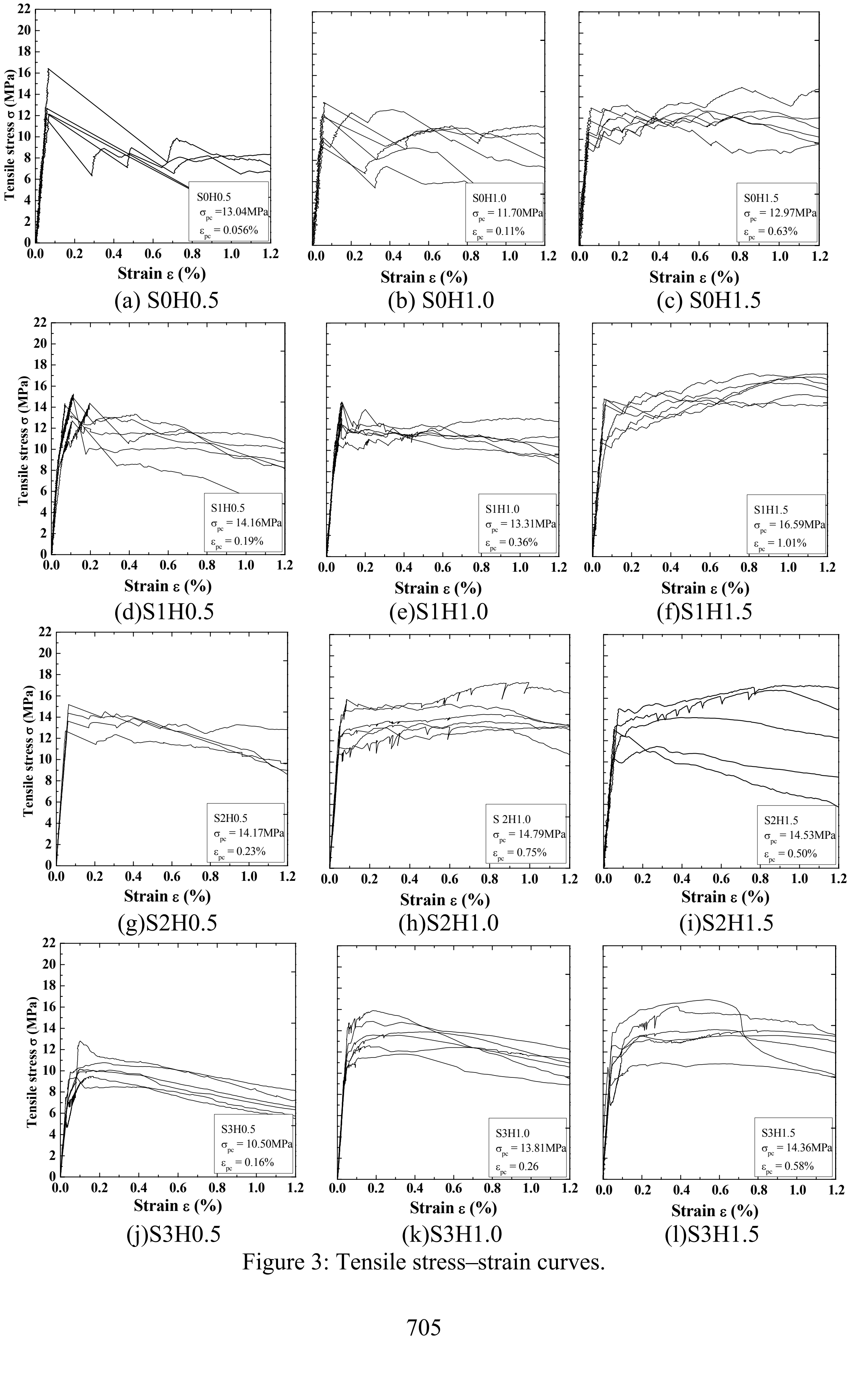
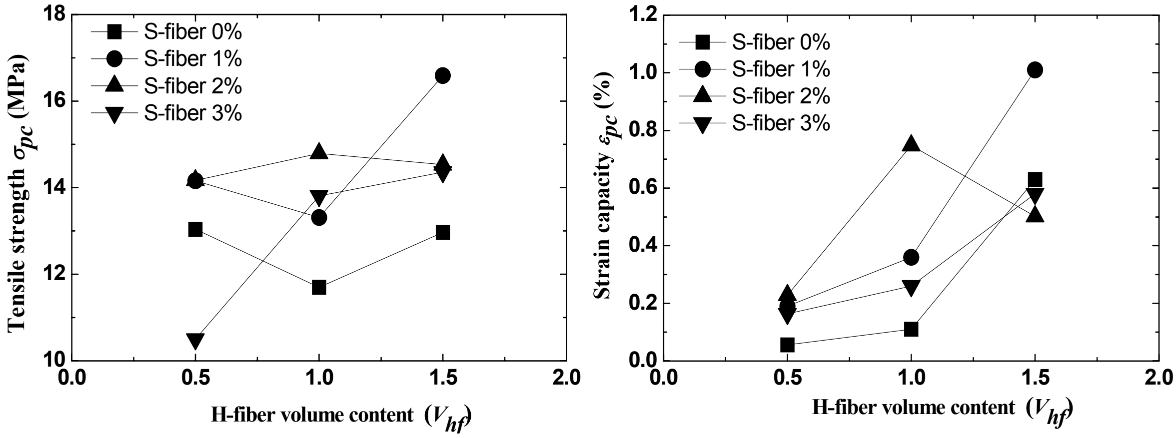


Figure 3: Tensile stress–strain curves.



(a)Tensile strength (b)Strain capacity

Figure 4 : Influence of H-fibre volume content on tensile strength and strain capacity.

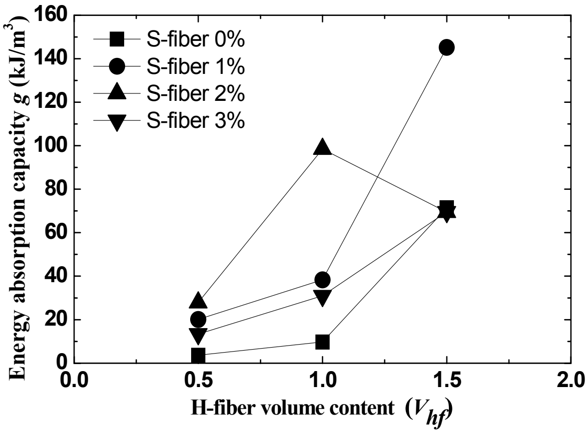


Figure 5 : Influence of H-fibre volume content on energy absorption capacity.

scatter than mono-fibre series which only contained H-fibres. In addition, these hybrid-fibre series containing S-fibre of 1% showed that the tensile performance was dramatically enhanced at V_{hf} = 1.5 (i.e. S1H1.5 series). It was also shown that too much fibre contents caused the larger scatter in such cases as S2H1.5 and S3H1.5.

4.3 Mechanical properties

The results of the mechanical properties are shown in Table 4. Figures 4 and 5 summarize the mechanical properties obtained for UHP-HFRCC as a function of H-fibre volume content. Figure 4 (a) shows that the tensile strength, σ_{pc}, increased as the volume content of H- fibre (V_{hf}) increased, except for S0H1.0, S1H1.0 and S2H1.5. Especially values of σ_{pc} notably increased from S1H1.0 series to S1H1.5 series and from S3H0.5 series to S3H1.0 series. On the other hand, the values of σ_{pc} in case of S0H1.0 and S0H1.5 series are obviously lower than those of other hybrid-fibre series in which both of S-fibre and H-fibre are contained. With respect to the strain capacity, ε_{pc}, Fig. 4 (b) shows that ε_{pc} increased as the volume content of H-fibre (V_{hf}) increased, except S2H1.5. The gradual increasing tendency of the strain capacity of UHP-HFRCC as V_{hf} increased from 0.5 % to 1.0 % was not much different from that of mono-fibre reinforced UHP (i.e. S0H0.5 and S0H1.0 series) as shown in Fig. 4

(b) except S2H1.0 series in which ε_{pc} increases notably from S1H0.5 to S1H1.0. Values of ε_{pc} in S1H1.5 and S0H1.5 series clearly increased as V_{hf} increased from 1.0 % to 1.5 %, though the value of S2H1.5 series decreased remarkably from S2H1.0 series. The highest values both of σ_{pc} and ε_{pc} among all series were obtained in S1H1.5 series. The results show that the balance of volume contents between S-fibre and H-fibre is very important to enhance the mechanical performance of UHP-HFRCC under tension and this is also an evidence of the synergy effect of S-fibre and H-fibre.

Figure 5 illustrates the influence of H-fibre volume content on energy absorption capacity. Tendencies of these results are quite similar to those of strain capacity, ε_{pc}, shown in Fig. 4(b). The values of energy absorption *g* were not much different between those in cases of V_{hf} = 0.5 % and 1.0 %, except S2H1.0. The energy absorption *g* was 98.50 kJ/m^3 in S2H1.0 series (Fig. 5) but only 69.49 kJ/m^3 in S2H1.5, though V_{hf} increased from 1.0% to 1.5%. On the other hand, the value of ε_{pc} significantly increased in S1H1.5 series and the highest value of all series was obtained (145.20 kJ/m^3). With respect to the influence of total volume content of fibres on mechanical performance, tensile strength, strain capacity and energy absorption capacity S1H1.5 performed better than those of S2H1.5 and S3H1.5. Furthermore, the strain capacity and the energy absorption capacity of S2H1.0 were much higher than those of S2H1.5, though the tensile strength of S2H1.0 is only somewhat higher than that of S2H1.5.

The results clearly show that neither the increase of the total volume content of fibre nor the volume content of H-fibre always results in as increase of the mechanical properties of UHP-HFRCC under tension. A large quantity of thin and short S-fibre can be dispersed densely in the matrix, which increases the pull-out resistance due to the additional bond stress caused by snubbing friction [14]. However, because of its relatively low bond strength and shorter length, S-fibres do not adequately bridge crack surfaces on the macro-level even when a large amount of fibres is presented. In constrast, H-fibre, which has high bond strength due to the geometry and a longer length, increases stress-transfer performance even after the micro- or meso-cracks initiation. During the pull-out process from the crack surface, H-fibres resist mechanically because of the bending and yielding of the hooked part. Therefore, increasing the amount of H-fibre is more effective than S-fibre for increasing the tensile strength and enhancing strain-hardening behaviour. However, Yoshida [15] reported that too high volume contents of H-fibre negatively applied tensile strengh and tensile strain. According to her numerical results, too small distance between H-fibres creates a kind of material defects. It can be the same for S-fibre, too. Hence a range of optimal volume contents of S-fibre and H-fibre might be exsisting to enhance the mechanical performance of UHP-HFRCC under tension.

5. CONCLUSIONS

In this paper the influence of volume contents of mesofibre (S-fibre) and macrofibre (H-fibre) on mechanical performance of UHP-HFRCC under tension is discussed. The following conclusions can be drawn:

Tensile stress-strain curves of UHP-HFRCC are dominantly dependent on the volume content of macrofibre rather than that of mesofibre.

Increasing volume contents of fibre does not always enhance the mechanical performance of UHP-HFRCC, even with a smaller amount of volume content of macrofibre, it can be possible to achieve a higher mechanical performance by means of a synergy effect of meso- and macrofibres.

The balance of volume contents of mesofibre and macrofibre is very important to achieve a better mechanical performance of UHP-HFRCC under tension.

REFERENCES

[1] Kwon, S., Nishiwaki, T., Kikuta, T. and Mihashi, H. 'Tensile Behavior of Ultra High Performance Hybrid Fiber Reinforced Cement-Based Composites', Proceedings of an International Conference, Framcos-8, Toledo, Spain, March, (2013) pp.1309-1314.

[2] Rossi, P., 'High Performance Multimodal Fiber Reinforced Cement Composite (HPMFRCC): The LCPC Experience', *ACI Mater. J.*, **94**(6), (1997) pp.478-483.

[3] Benson, S.D.P. and Karihaloo, B.L., 'CARDIFRC-Development and Mechanical Properties. Part Ⅲ: Uniaxial Tensile Response and Other Mechanical Properties', *Magazine of Concrete Research*, **57**(8), (2005) pp. 433-443.

[4] Boulay, C., Rossi, P., and Tailhan, J.-L., 'Uniaxial Tensile Test on a New Cement Composite Having a Hardening Behaviour', 6th RILEM Symposium in Fiber-Reinforced Concretes (FRC), BEFIB 2004, Varenna, Italy, (2004) pp.61-68.

[5] Fantilli, A.P., Mihashi, H., Naganuma, T. and Nishiwaki, T., 'Tailoring SHCC Made of Steel Cords and Plastic Fibers', High Performance Fiber Reinforced Cement Composites 6, (2012) pp.11-18

[6] Fantilli, A.P., Kwon, S., Mihashi H. and Nishiwaki T., 'Tensile Behavior of Ultra High Performance Hybrid Fiber Reinforced Cement-Based Composites', Proceedings of an International Conference, Framcos-8, Toledo, Spain, March, (2013) pp.1267-1275.

[7] JIS R 5201, 'Physical testing method for cement, Japan Industrial standards', 2007. (In Japanese)

[8] Zhou B. and Uchida Y., 'Fiber Orientation in Ultra High Performance Fiber Reinforced Concrete and Its Visualization', Proceedings of an International Conference , Framcos-8, Toledo, Spain, March, (2013) pp.228-235.

[9] Japan Society of Civil Engineers, Recommendations for Design and Construction of HPFRCC with Multiple Fine Cracks. (http://www.jsce.or.jp/committee/concret e/e/hpfrcc_JSCE.pdf) (2008).

[10] Markovic, I., 'High-Performance Hybrid-Fibre Concrete Development and Utilisation', Ph.D. thesis, Delft University Press, Delft, The Netherlands, (2006) pp.82-92.

[11] Naaman, A.E. and Wille, K., 'Some Correlation between High Packing Density, Ultra-high Performance, Flowability, and Fiber Reinforcement of a Concrete Matrix', In: BAC 2010-2nd Iberian Congress on Self Compaction Concrete, University of Minho-Guimaraes, Portugal, July, (2010) pp.1-2.

[12] Wille, K. and Naaman, A.E., 'Fracture Energy of UHPFRC Under Direct Tensile Loading', FraMCoS-7 International Conference, Jeju, Korea, (2010) pp.65-72.

[13] Naaman, A.E. and Reinhardt, H.W., 'Characterization of High Performance Fiber Reinforced Cement Composites', Proceedings of 2nd International Workshop on HPFRCC, Chapter 41. in High Performance Fiber Reinforced Cement Composites: HPFRCC 2, A.E. Naaman and H.W. Reinhardt, Editors, RILEM, No. 31, E. & FN Spon, London, (1996) pp.1-24.

[14] Mihashi, H. and Kohno, Y., 'Toughening Mechanism of Hybrid Fiber Reinforced Cement Composites', Preceedings of the 6th International Confrernce on Fracture Mechanics of Concrete and Concrete Structures, Catania, Italy, Vol.3, 2007, pp.1329-1339.

[15] Yoshida, R. 'Experimental study on Material Design of Hybrid FRCC with High Strength and Toughness', Master's Thesis of Tohoku University, 2013 (In Japanese).