Fracture Mechanics of Concrete and Concrete Structures -
High Performance, Fiber Reinforced Concrete, Special Loadings and Structural Applications- B. H. Oh, et al. (eds)

Ultra high strength fiber reinforced concrete using aramid fiber

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ABSTRACT: Ultra high strength fiber reinforced concretes were produced using aramid fibers having different shapes and sizes to investigate their fresh and mechanical properties after hardening, including compressive strength, as well as post-cracking strength from notched beams. These tests revealed that a small fiber diameter leads to low fluidity while fresh, inhibiting inclusion of fibers in an appreciable amount, while a short fiber length allows inclusion of a substantial amount of fibers, leading to excellent mechanical properties after hardening. Bundled fibers were found to be effective in improving the softening properties of concrete.

1 INTRODUCTION

In response to the increasing demand for a higher level and wider range of performances of concrete, in recent years, active research has been conducted to enhance the performance of concrete. One such example is ultrahigh strength fiber reinforced concrete (UFC) having excellent fluidity with a low water-binder ratio, which achieves an ultra high compressive strength exceeding 180 N/mm^2. It has been introduced into practical use, with recommendations for its design and construction (draft) being published by the Japan Society of Civil Engineers (JSCE 2004). High strength steel fibers are used for UFC covered by these recommendations to achieve high mechanical properties. To eliminate the possibility of steel fiber corrosion in case of cracking, these recommendations permit no cracking in UFC while in use. The use of organic fibers with high corrosion resistance instead of steel fibers has been investigated. However, it has been reported that the mechanical performances, such as flexural strength, of UFC made using organic fibers are substantially lower than those of UFC made using steel fibers (Kawaguchi 2008).

With this as a background, the authors focused on aramid fibers having high strength and high elastic modulus among other organic fibers as a substitute for steel fibers and investigated the mechanical properties of UFC made using aramid fibers.

Table 1. Mix proportion.

W/(C+SF)	Unit weight (kg/m^3)					
	W	C	SF	SP	S	Ad
0.19	182	987	228	386	494	49

W: Water, C: Cement, SF: Silica fume, SP: Silica powder
S: Sand, Ad: Superplasticizer

2 OUTLINE OF EXPERIMENT

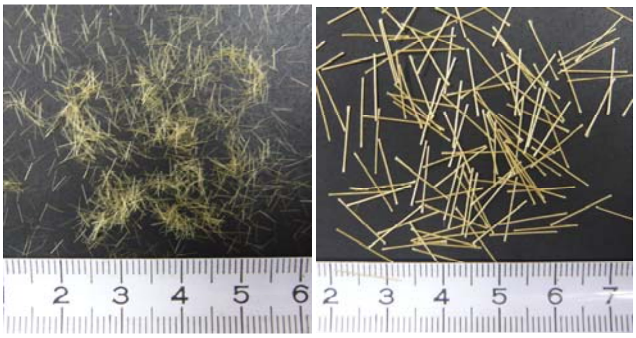
2.1 *Mix proportion and materials*

Table 1 gives the mix proportion of the mortar matrix used in this study, which are established referring to a past study (Richard 1995). The mix is not a concrete but mortal in a strict sense because the coarse aggregate is not included. Low-heat portland cement with a density of 3.21 g/cm^3 and silica fume with a density of 2.2 g/cm^3 are used as the binder, so that the water-binder ratio (W/(C+SF)) is 0.19 (the total chemical admixture dosage is included in the calculation as part of the water content). Silica powder with a density of 2.6 g/cm^3 and specific surface of 8,180 cm^2 is used as filler for the microstructure. Class 6 silica sand with a density of 2.6 g/cm^3 is used as fine aggregate. The chemical admixture is a polycarboxylate ether-based superplasticizer for ultrahigh strength concrete. Note that all of these materials are not specially developed for this study but available on the market.

2.2 *Fiber types and test parameters*

Aramid fibers having different diameters, lengths, and shapes (Fig. 1) are used in this study, and steel fibers are also used for comparison. The material properties of aramid fibers used in this study (copolyparaphenylene 3,4'-oxydiphenylene terephthalamide) are described as follows: density: 1.39 g/cm^3, tensile strength: 3,430 N/mm^2, and elastic modulus in tension: 72.5 kN/mm^2. As given in Table 2, six types of aramid fibers are used: one type 12 μm in diameter and 12 mm in length; other fibers 45 μm in diameter and 3, 6, 8, and 12 mm in length;

and one type with 267 fibers having a diameter of 12 μm, bundled with vinyl ester resin into sticks having an external diameter of 200 μm and a length of 12 mm . One type of steel fiber 0.2 mm in diameter and 15 mm in length with a tensile strength of 2,000 N/mm^2 is also used.



(a) Monofilament (b) Bundled fiber

Figure 1. Aramid fibers.

Table 2. Kind of fibers.

Name	Materials	Diameter(μm)	Length(mm)
12μ-6mm		12	6
3mm			3
6mm	Aramid	45	6
8mm			8
12mm			12
12mm-B		200	12
Steel	Steel	200	15

2.3 *Mixing*

A 10-liter Hobart mixer and a 10-liter omni-mixer are used for mixing as follows: place all mortar materials excepting half of cement in the Hobart mixer and mix. Add the remaining half of cement when the mixture is fluidized. Transfer the mortar mixture to the omni-mixer, add fibers, and mix.

The reason for using a Hobart mixer is because it is difficult to fluidize the materials in an omni-mixer, as it is incapable of applying sufficient shearing forces to materials in a powdery condition. The reason for adding cement in two steps is because it shortens the mixing time from a powdery state to a fluidized state when compared with addition of all cement at a time. The reason for using an omni-mixer for mixing fibers is because an omni-mixer is more efficient in mixing materials with a high viscosity than a Hobart mixer, particularly in uniformly dispersing fibers.

2.4 *Specimen fabrication*

Compression specimens 50 mm in diameter and 100 mm in height and bending specimens measuring 40 by 40 by 160 mm are used for this study. The concrete is placed in the molds and consolidated using a table vibrator. Note that concrete for bending specimens is allowed to flow into each mold from one end toward the other as shown in Figure.2. The table vibrator is not used for specimens containing steel fibers to prevent fiber segregation.

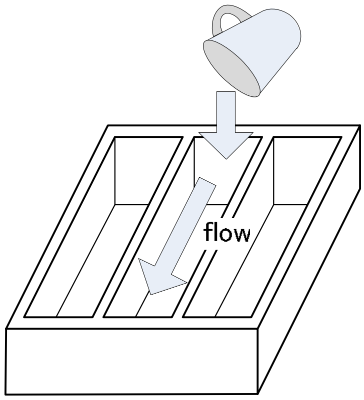


Figure 2. Placement of concrete.

2.5 *Curing methods*

The surfaces of specimens are plastic-wrapped immediately after placing and left to stand for two days in a thermostatic room at 20°C. After being demolded, specimens are water-cured with hot water or water at normal temperatures. Hot water curing is carried out for three days in water at a temperature of 90°C, whereas normal temperature water curing is carried out for 28 days in water at 20°C.

2.6 *Investigation items*

2.6.1 *Fiber content*

Assuming a target flow value (JIS R 5201, with no jigging) of 200 mm in consideration of the ease of placing, the maximum fiber content is determined for each type of aramid fiber. This is done by repeating the following steps: add fibers in a small quantity; take samples to measure the flow value; if more fibers are accommodated, promptly return the samples to the mixer; and add more fibers and mix. Note that a fiber content of 2% is adopted for steel fibers for reference without investigating the accommodated maximum.

2.6.2 *Compression test*

Compression tests are conducted on mixtures having maximum content of each fiber type determined as described in section 2.6.1. A testing machine with a capacity of 2,000 kN is used for loading via a spherically seated bearing block for 1,000 kN. Three specimens are used for each set of conditions.

2.6.3 *Bending test*

Three point loading tests are conducted on notched beams as shown in Figure. 3 having mixture proportions determined in section 3.1, similarly to section 2.6.2, to measure the load-crack opening displacement curves. These tests are carried out in accordance with the test method for the load displacement curve of fiber-reinforced concrete notched beams (JCI, 2003), but the specimen size is 40 by 40 by 160 mm (notch depth: 12 mm) because of the batch size. Three specimens are used for each set of conditions.

A manually operated mechanical jack is used for loading, while using a load cell with a capacity of 10 kN and clip gauges with an accuracy of 1/2,000 mm for monitoring the load and opening displacement, respectively.

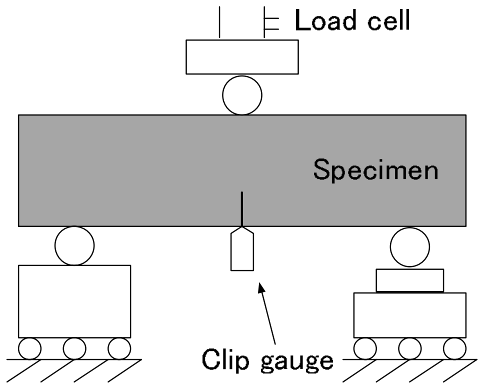


Figure 3. Bending test.

Table 3. Fiber content and flow value.

Name	Fiber cont. (%)	Flow value(mm)
12μ-6mm	1.0	119
3mm	2.0	273
	3.0	211
6mm	1.0	300<
	1.5	228
	2.0	187
8mm	1.25	201
12mm	0.5	300<
	1.0	202
12mm-B	1.0	256
	1.75	233
	2.0	185
Steel	2.0	270

2.6.4 *Tension softening curve*

Tension softening curves are estimated from the load-crack opening displacement relationships determined in section 2.6.3 by back analysis (JCI, 2003). Note that the average curve of three specimens tested under the same conditions is used for back analysis.

3 TEST RESULTS

3.1 *Fresh properties*

The average flow value of all batches of mortar before adding fibers was 270 mm. Table 3 gives the flow test results after adding fibers. Note that no flow value greater than 300 mm was measured, since a flow table with a diameter of 300 mm was used.

With a fiber diameter of 12 μm, a fiber content of 1% led to a flow as small as 119 mm. It was therefore found necessary to further reduce the fiber content to attain the target flow. Since such a limitation in the fiber content implies no improvement in the flexural and tensile properties of hardened concrete, subsequent tests on hardened concrete containing 12 μm fibers were cancelled.

With a fiber diameter of 45 μm, the flow decreased as the fiber length increased and as the fiber content increased. When the fiber length was 8 mm and 12 mm, the fiber content had to be limited to a level below 1.0% or 1.25% to ensure a flow of 200 mm, whereas a fiber content of 2% was attained when the fiber length was 3 mm, 6 mm, and bundled 12 mm. A fiber content of 3% was possible with a fiber length of 3 mm. Note that the water-binder ratio (W/B) was corrected from 0.19 to 0.21 for 12 mm-length fibers, as the fiber content cannot be increased with the low W/B.

Based on these results, the maximum fiber content was determined for each fiber type, with which specimens were fabricated. The selected fiber contents are indicated in Table 3. Note that a fiber content of 1.75% was selected for bundled 12 mm fibers, as a fiber content of 2% tended to lead to slight segregation.

Table 4. Compressive strength.

Name	Fiber Cont. (%)	Curing Temp. (°C)	Compressive. Strength (N/mm^2)
12μ-6mm	1.0	20	152
3mm	3.0	90	225
6mm	2.0		219
8mm	1.25		221
12mm	1.0		183
12mm-B	1.75		192
Steel	2.0		242

3.2 *Compressive strength*

Table 4 gives the results of compression tests. When comparing the strengths of specimens containing 3% of 3 mm fibers cured in water at 90°C and 20°C, the strength of hot water-cured specimens was higher by 70 N/mm^2, presumably because a higher curing temperature densified the microstructure of the mortar matrix to a greater extent.

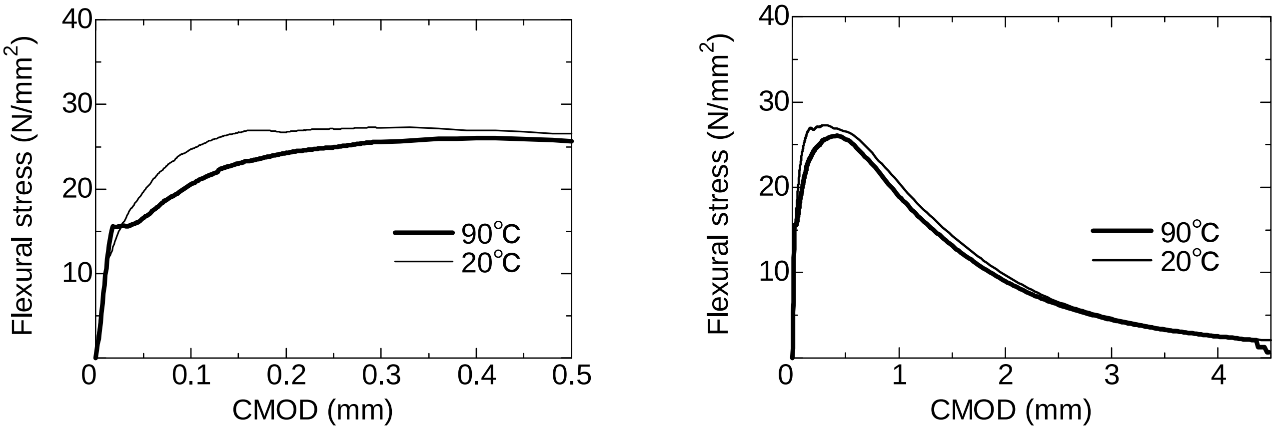
When comparing hot water-cured specimens containing aramid fibers, those having 3 mm, 6 mm, and 8 mm-long fibers similarly achieved a compressive strength of approximately 220 N/mm^2. On the other hand, those having 12 mm-long and 12 mm bundled fibers tended to attain a lower compressive strength of around 180 to 190 N/mm^2. The increase in the W/B to 0.21 may have affected the strength of specimens with a fiber length of 12 mm. The compressive strength of specimens made using steel fibers was around 240 N/mm^2, being higher than those of aramid fiber-reinforced specimens by around 10%.

3.3 *Flexural strength*

Figures 4 to 6 show the load-crack opening displacement curves obtained from three-point loading on notched beams (averages of three specimens). Note that the values on the vertical axis represent the loads converted into the flexural tensile stress of the ligament section.

Figure 4 compares the results of hot water and normal temperature water curing of specimens containing 3% fibers with a length of 3 mm. Little difference is observed between the curves, demonstrating that the difference in the curing method scarcely affects the flexural properties in contrast to the effect on compressive strength.

Figure 5 shows the results of different lengths of monofilament-type fibers. It should be noted that the fiber content varies depending on the fiber length as shown in Table 3. While little difference is found in the cracking strengths of specimens containing fibers with a length of 8 mm or less, those of specimens containing fibers 12 mm in length are lower. Similarly, the maximum strengths after cracking of specimens containing 3 mm fibers (fiber content:



(a) Initial part (b) Whole

Figure 4. Load-CMOD curves with different curing temperature.

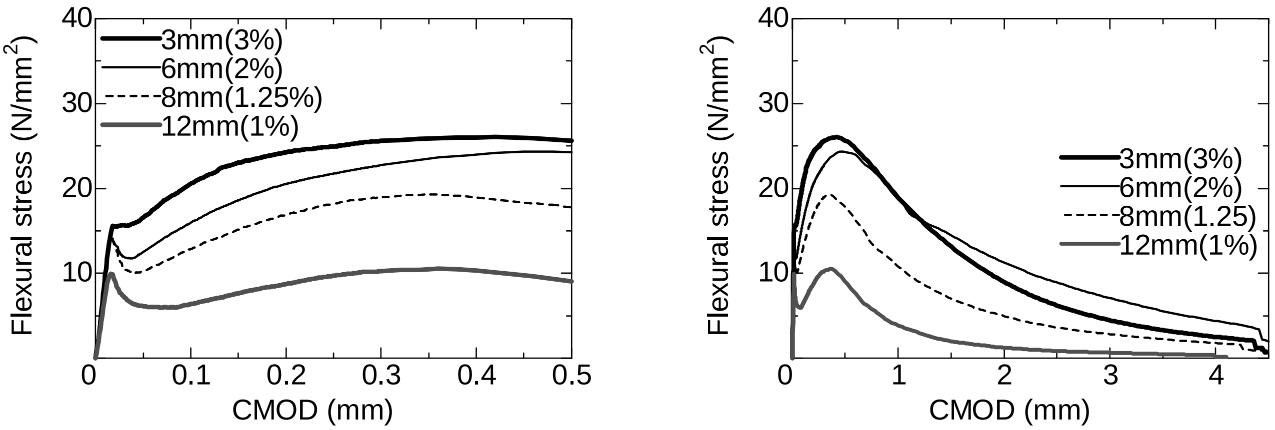


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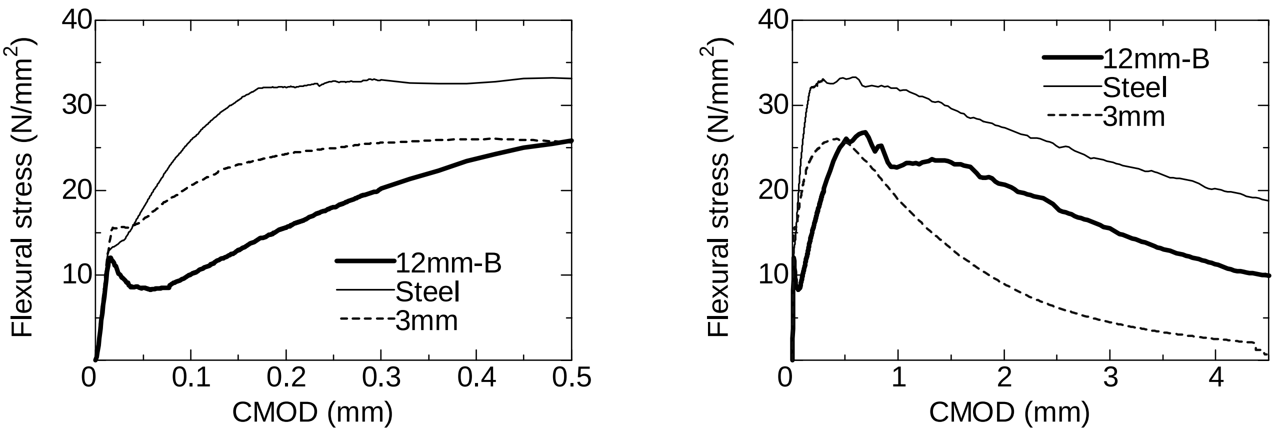
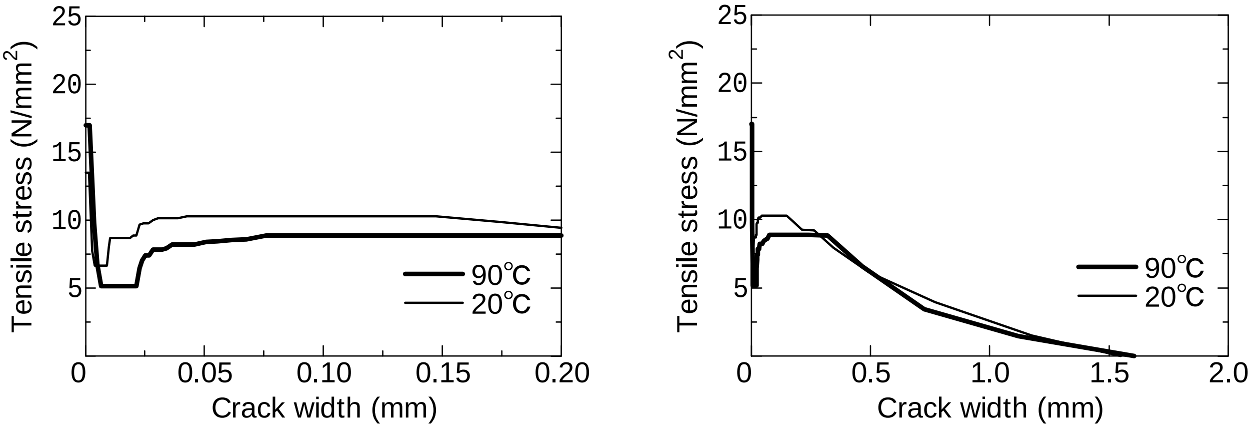
Figure 5. Load-CMOD curves with different length of fibers.



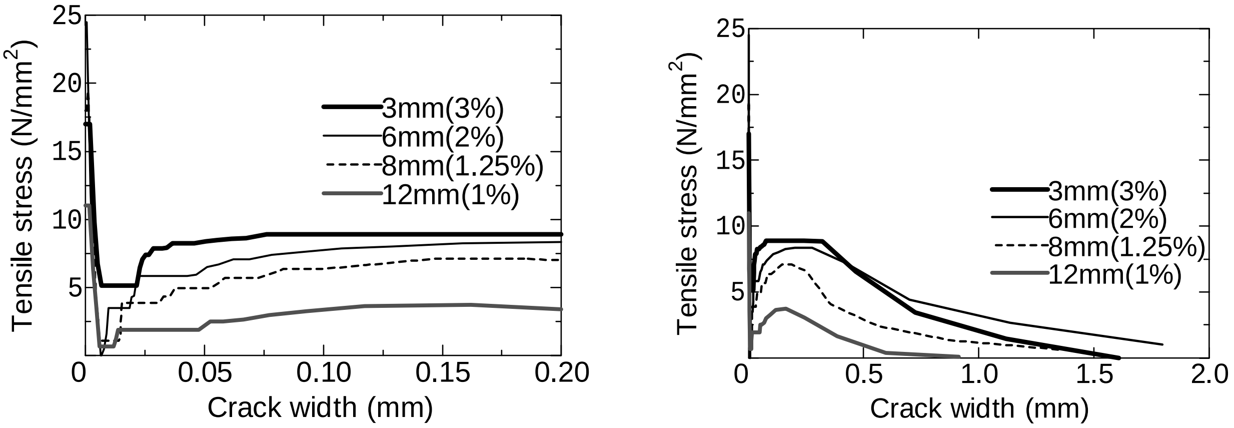
(a) Initial part (b) Whole

Figure 6. Load-CMOD curves with different kind of fiber.



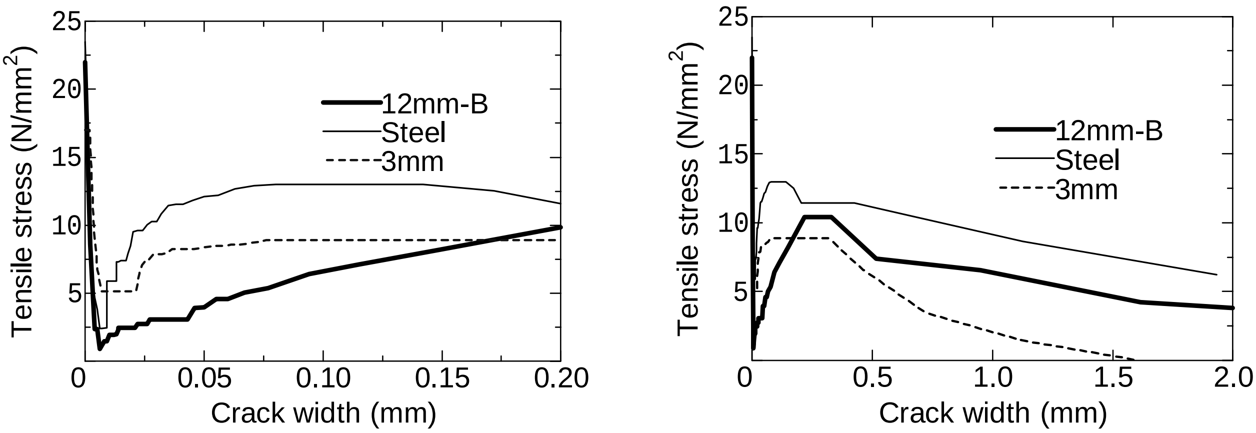
(a) Initial part (b) Whole

Figure 7. Tension softening curves with different curing temperature.



(a) Initial part (b) Whole

Figure 8. Tension softening curves with different length of fibers.



(a) Initial part (b) Whole

Figure 9. Tension softening curves with different kind of fiber.

3%) and 6 mm fibers (2%) scarcely differ from each other, whereas the strengths are lower with a fiber length of 8 mm and even lower with 12 mm. It should be noted that, for all specimens excluding those containing 3 mm fibers, the stress shows a temporary drop after cracking and subsequent upward trend toward the maximum stress supported by the bridging effect, which develops with the increases in the opening displacement.

Accordingly, when using monofilament-type fibers to increase the flexural strength of UFC, it is found effective to incorporate a large amount of fibers 3 mm or 6 mm in length. It should also be noted that 3 mm fibers with a fiber content of 3% are deemed superior in terms of flexural properties, as "6 mm – 2%" fibers show a temporary stress reduction immediately after cracking.

Figure 6 compares the bundled aramid fibers and steel fibers. The results of 3 mm fibers are also shown for comparison. These results reveal that concrete containing steel fibers is superior from all aspects of the post-cracking stiffness, strength, and absorbed energy after the strength point.

In regard to bundled aramid fibers, their stiffness after cracking is found to be particularly low. This is presumably because bundles cause the bond stress between the fibers and mortar to be higher than in the case of steel fibers with the same tensile stress, leading to a greater amount of fiber dislocation at crack faces.

The maximum strength of specimens containing bundled aramid fibers is similar to those of specimens containing 3 mm (3%) and 6 mm (2%) fibers, being approximately 75% of that of specimens containing steel fibers.

The rate of stress reduction after the maximum strength (the softening gradient of the curve) of bundled aramid fibers is moderate when compared with that of 3 mm fibers, being similar to that of steel fibers. This can be attributed to the long size of bundled fibers, which retains the bridging effect even in a stage of large displacement, while 3 mm fibers slip out of mortar in an earlier stage with a small displacement.

3.4 *Tension softening curve*

Figures 7 to 9 show the tension-softening curves determined by back analysis from the flexural stress (load)-opening displacement curves shown in Figures. 4 to 6. All softening curves reach 15 to 20 N/mm^2 at the initiation point of softening (corresponding to the tensile strength of the matrix), followed by a rapid reduction. The stress then increases as the bridging effect develops with the increase in the opening displacement (crack width), reaching the maximum strength, and enters the softening phase. The effects of the curing method, fiber length, and fiber type on the tension-softening curves are similar to those on the flexural stress-opening displacement curves reported in the previous section. However, tension-softening curves more clearly express the processes of tensile failure of UFC than the flexural stress-opening displacement curves, including softening associated with matrix cracking, stress increases due to the bridging effect of fibers, the maximum point of bridging stress, and softening.

4 CONCLUSIONS

In this study, compression tests and three point bending tests were conducted on cylindrical and notched beam specimens of ultrahigh strength fiber-reinforced concrete (UFC) containing aramid fibers. Their tension-softening curves were calculated by back analysis from the bending test results. The results obtained from this study are summarized as follows:

(1) When the fiber contents by volume are the same, fibers with a diameter of 12 μm lead to a smaller flow value than those with a diameter of 45 μm, being difficult to include in concrete in an appreciable amount.

(2) When comparing the mechanical properties of UFCs containing fibers 45 μm in diameter and 3 to 12 mm in length, with the fiber content being maximized within the required flow range, those having 3% of 3 mm fibers and 2% of 6 mm fibers are found to be most effective.

(3) Curing in 90°C hot water and 20°C water leads to different compressive strengths of UFC but scarcely affects its flexural and tension softening properties.

(4) Though the stiffness of UFC containing bundled fibers is low immediately after cracking, its maximum bridged stress is comparable to those of UFCs containing 3 mm and 6 mm fibers, being around 75% of that of UFC containing steel fibers.

In this study, a possibility of achieving strength and ductility comparable to concrete containing steel fibers was suggested by the use of aramid fibers. However, further improvements are required before putting aramid fiber-reinforced concrete into practical use.

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