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Development of High-Strength Fiber Reinforced Concrete for Highly Durable Bridge Structures

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ABSTRACT

As one way to construct the highly durable and long lifetime concrete structures, it is considered that steel rebars and PC tendons are reduced in concrete structures. This paper describes development of high-strength fiber reinforced concrete (HSFRC), which is developed mainly to increase shear strength of the concrete. Not only does this HSFRC possess high shear strength due to high compressive strength and fiber reinforced, but it don't also require peculiar curing methods and materials. The result of the examination, it was shown that it is possible to make HSFRC possess the specified workability, compressive strength of proportioning, 80-100 N/mm^2, and high shear strength.

Keywords. Steel Fiber, High-Strength Concrete, Shear Strength, Flexural Strength, Flexural Toughness

INTRODUCTION

It is possible to thin down and lighten concrete member by increasing concrete's strength. High-strength concrete is the highly durable material due to its solidity. As one way to construct the more highly durable and longer lifetime concrete structures, it is considered that steel reinforcements are reduced in concrete structures. Steel reinforcements can be corroded. It is considered that such a design becomes feasible if the concrete's performance on tensile and shear stress is improved.

Ultra high strength fiber reinforced concrete (UFC) has become a practical proposition as a material that can be used to produce structures without steel reinforcements by raising the concrete's own tensile strength, and it is being introduced for applications such as road bridges. UFC is a cementitious material with high compressive strength of over 180 N/mm^2 and providing high tensile strength and toughness by large number of steel fibers. However, UFC generally has the following characteristics: 1) Requirement to use particular materials, 2) Special curing requirements, and 3) Autogenous shrinkage is larger than normal concrete due to include no coase aggregate.

This paper describes the development of high strength fiber reinforced concrete (HSFRC) with f'_{ck} in the 80-100 N/mm^2 range. The objective was mainly to increase the shear strength, with the aim of producing a concrete requiring less steel for use in the construction of prestressed concrete bridge superstructures. In addition to increasing compressive strength of the concrete and using fiber reinforcement to improve shear strength, another development objective was to increase versatility by producing HSFRC that does not requiring special materials or special curing methods.

EXPERIMENTAL OVERVIEW

Short Fiber. Table 1 shows materials of HSFRC. The experiment used readily available steel fibers, which have excellent mechanical characteristics. SF1 is the most generally steel fiber, which is hooked at each end. SF2 is same shape as SF1, but having higher tensile strength and a smaller fiber diameter. As maximum size of coarse aggregates (Gmax) is 20 mm, and fibers' length of both SF1 and SF2 is 30 mm. In contrast, SF3 has a smaller fiber length, 22 mm, and also a smaller fiber diameter. Namely, this fiber has a larger aspect ratio.

Concrete Proportion. Table 2 shows the proportion of the concrete without short fibers in it (hereafter Base Concrete or Base). The water-binder ratio (W/B) is 30 % and 25 %. Binders are ordinary portland cement with W/B of 30% and ordinary portland cement and silica fume with W/B of 25 %. Unit water content (W) was 175 kg/m^3. This is the maximum value for ordinary concrete stipulated in the Standard Specifications for Concrete Structure (JSCE),. Unit volume of coarse aggregates (Vg) was taken to be 0.350 or 0.330 m^3/m^3 with fiber content (Vf) of 0 vol%, and was reduced with increase in Vf. Minimum value of Vg was 0.200 m^3/m^3. Air content was adjusted to 3.5 % ± 0.5 %. Slump was at least 18 cm,

Table 1. Materials

Material	Characteristics	Symbol	
Ordinary portland cement	Density: 3.15 g/cm^3, specific surface area: 3360 cm^2/g	C	B
Silica fume	Density: 2.25 g/cm^3, specific surface area: 16.2 m^2/g	SF	
Sand	Density: 2.59 g/cm^3, absorption: 2.56 %, F.M. 2.01	S1	S
Crushed sand (hard sandstone)	Density: 2.62 g/cm^3, absorption: 1.47 %, F.M. 2.93	S2	
Crushed stone (hard sandstone)	Density: 2.65 g/cm^3, absorption: 0.82 %, F.M. 6.58	G	
High-range water-reducing admixture	Polycarboxylate-based	SP	
Steel fiber	Density: 7.85 g/cm^3, diameter: 0.62 mm, length: 30 mm, aspect ratio: 48, tensile strength: 1100 N/mm^2	SF1	
	Density: 7.83 g/cm^3, diameter: 0.38 mm, length: 30 mm, aspect ratio: 79, tensile strength: 2610-3190 N/mm^2	SF2	
	Density: 7.86 g/cm^3, diameter: 0.2 mm, length: 22 mm, aspect ratio: 110, tensile strength: >2000 N/mm^2	SF3	

Table 2. Mixed Proportion (Base Concrete)

W/B (%)	s/a (%)	Air (%)	SF/B (%)	Vg (m^3/m^3)	Unit content (kg/m^3)					
					W	B		S		G
						C	SF	S1	S2	
30	42.1	3.5 ± 0.5	0	0.350	175	583	0	264	401	928
25	41.0		10	0.330	175	630	70	237	360	875

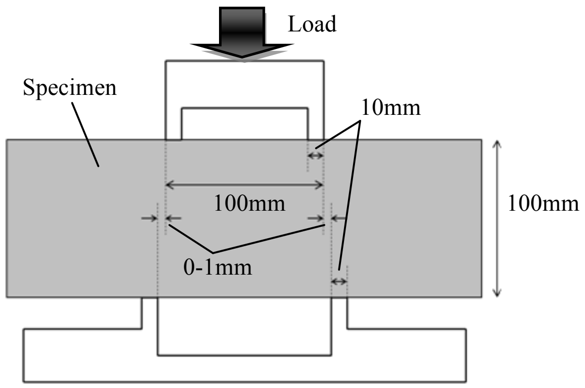

Figure 1. Overview of shear strength test

adjusted to be within a range where no segregation occurred.

Test Method. A biaxial forced action mixer with a capacity 0.1 m^3 was used for mixing concrete. Properties of flesh concrete was evaluated through the slump test (JIS A 1101). The mechanical properties of concrete were evaluated through compressive strength (JIS A 1108), young's modulus (JIS A 1149), flexural strength (JSCE-G552) and shear strength (JSCE-G553). The specimens had forms stripped 1 day after casting, and were then cured in 20 °C water until day 28 before strength testing. Figure 1 shows the overview of test method for shear strength.

RESULTS AND DISCCUTION

Properties of Flesh Concrete. Figure 2 shows relationships between Vf, Vg and slump. In addition, calculated values with the manual have been shown in this figure. For SF1 and SF2 with Vf in the range 0.5-1.0 vol%, setting Vg to the calculated value according to the manual enabled a slump of 18 cm. When using SF3, however, even with Vf in the range 0.5-0.75 %, the largest slump was about 16 cm. By increasing W to 185 kg/m^3, an 18 cm slump was obtained with Vf of 0.5 vol%. To ensure a slump of 18 cm under conditions of 1.0 vol% for SF3 and 1.5vol% for SF2, it was necessary to increase W to 200 kg/m^3. Since short fibers and coarse aggregates tend to segregate even if the amount of SP is increased to an excessive amount, it was confirmed that there are appropriate mixed proportion for obtaining the specified slump with each type of short fiber and values of Vf.

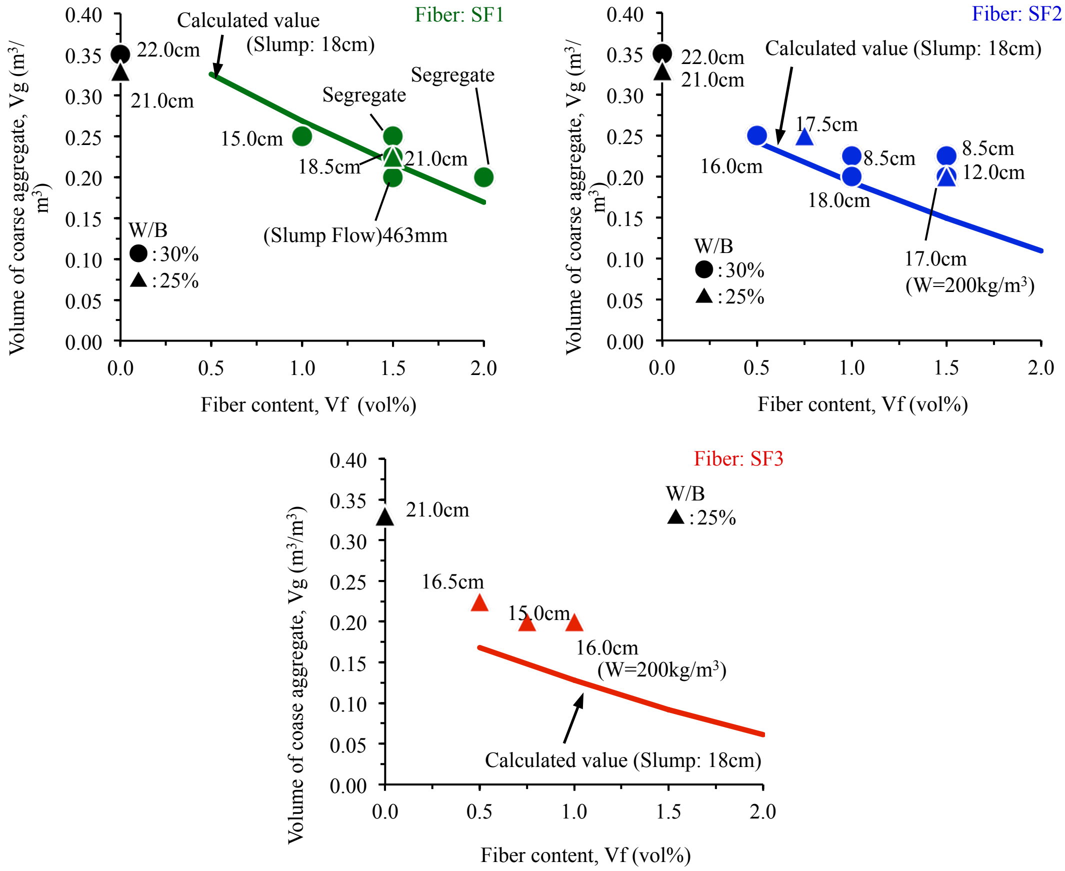

Figure 2. Relationships between Vf, Vg and slump

Compressive Strength. Figure 3 shows the relationship between Vf and compressive strength ratio. Here, compressive strength ratio represents compressive strength of fiber reinforced concrete divided by compressive strength of Base Concrete under the same W/B. The compressive strength of Base Concrete was 94 N/mm^2 with W/B of 30 % and 129 N/mm^2 with W/B of 25 %. Regardless of the type of short fibers and the short fiber content, compressive strength ratio was approximately 1. When an appropriate mixed proportion is selected, steel fibers have very little effect on compressive strength.

Young's Modulus. Figure 4 shows the relationship between compressive strength and young's modulus. The broken lines in the figure indicate the Young's modulus for Base Concrete, and 0.9 times the same figure. Since, for the purposes of this experiment, Vg was reduced as Vf increased, the Young's modulus of the concrete tended to decline. Tests by the authors revealed that this tendency was particularly noticeable if PVA fibers were used. However, as can be seen from Figure 4, in the current experiment Young's modulus only declined slightly when Vg was reduced. This is assumed to be due to the stiffness of the steel fibers used.

Flexural Strength. Figure 5 shows the relationship between Vf and flexural strength ratio. Here, flexural strength ratio represents the flexural strength of fiber reinforced concrete divided by the flexural strength of Base Concrete under the same W/B. The flexural strength

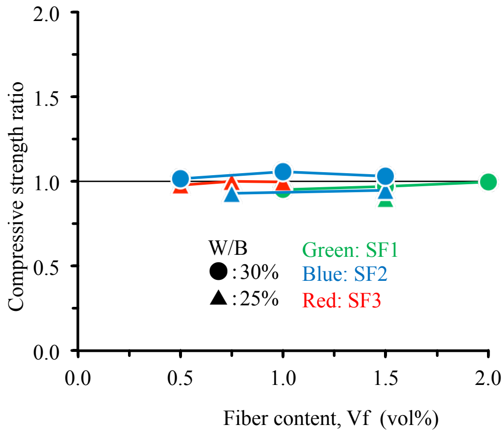

Figure 3. Relationship between Vf and compressive strength ratio

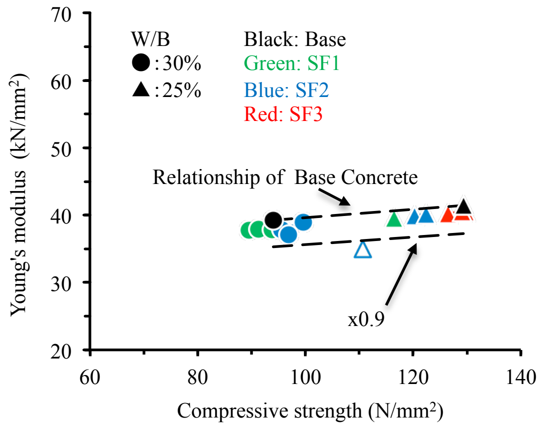

Figure 4. Relationship between compressive strength and young's modulus

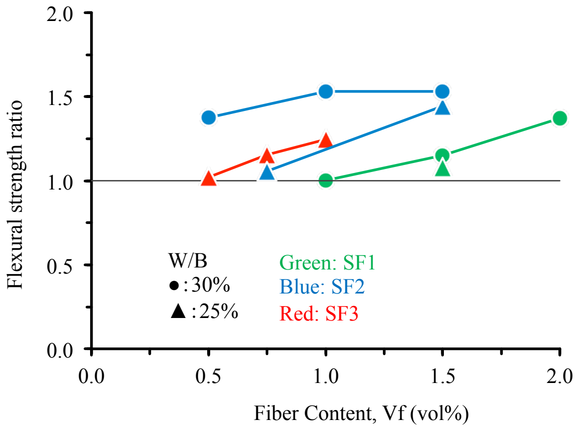

Figure 5. Relationship between Vf and flexural strength ratio

of Base Concrete was 8.12 N/mm^2 with W/B of 30% and 10.7 N/mm^2 with W/B of 25%. Each fiber was pulled out at flexural failure.

From the figure, it can be seen that there is a value of Vf where flexural strength begins to increase. This value is varying according to the type of short fiber and the water-binder ratio. Specifically, an increase in flexural strength with increase of Vf can be observed when Vf is at least 1.0 vol% for SF1, at least 0-0.5 vol% (W/B of 30 %) or 1.0 vol% (W/B of 25 %) for SF2, and at least 0.5 vol% for SF3. With SF3, the fiber length of 22 mm is short considering that Gmax is 20 mm, but this is still likely to provide sufficient reinforcement.

Figure 6 shows an example of the load-deflection curve in flexural strength test. The load at which flexural cracking occurs is virtually the same as for concrete without short fibers in the mix, but subsequent behavior is significantly influenced by the type of short fibers and by the value of Vf. After cracking occurs, load recovery is observed with increase in deflection due to fiber bridging effect, and the greater the value of Vf, the greater the increase in the load after cracking, exceeding the load at which cracking occurs. As flexural strength is the value for the maximum load on the load-deflection curve, flexural strength is observed to increase with increase in Vf, as described above.

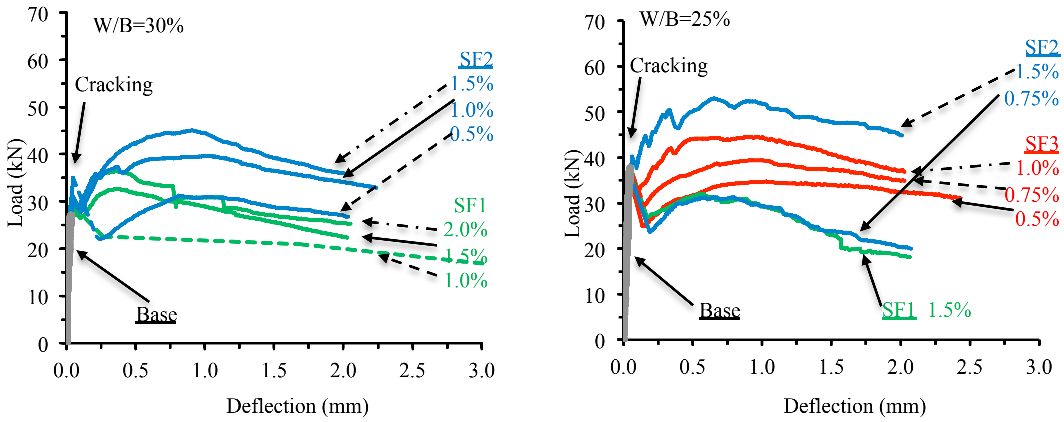

Figure 6. Example of the load-deflection curve in the flexural strength test

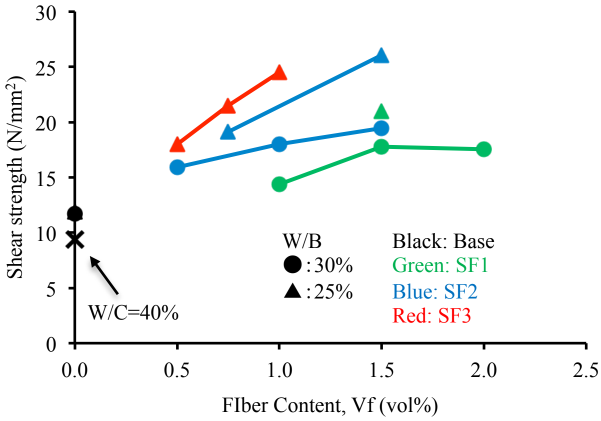

Figure 7. Relationship between Vf and shear strength

Shear Strength. Figure 7 shows the relationship between Vf and shear strength. It was observed that no fiber was ruptured at shear failure. For reference, the shear strength of early-strength concrete (water-cement ratio is 40 %) that is used for PC bridge superstructures generally has been shown in this figure. When short fibers are not added to the mix, reducing W/B to increase strength produces an increase in shear strength of about 20 %. With W/B of 30 % and 25 %, the increase in shear strength was small, and of a similar level. There was a difference in compressive strength of about 35 N/mm^2, but it was discovered that a difference of this extent had only a small effect on shear strength. However, when short fibers are added, shear strength was significantly different, and there was a large increase in shear strength due to the short fibers with a small W/B. Increasing the value of Vf also raised the shear strength, but when SF1 mixed, shear strength reached a maximum at Vf of 1.5vol% with W/B of 30 %. When SF2 or SF3 mixed, shear strength increased linearly up to Vf of 0.5-1.0 vol% or 1.5 vol%, but the proportion was greater with W/B of 25 %, and it was discovered that shear strength of at least double that of Base Concrete could be obtained when Vf was 1.5 vol% (SF2) or 1.0 vol% (SF3).

Relationship between the Type of Short Fibers and Mechanical Properties of HSFRC. Figure 5 and Figure 7 show that for identical values of Vf, reinforcement increases with larger aspect ratio of the fibers. Consequently, in order to consider aspect

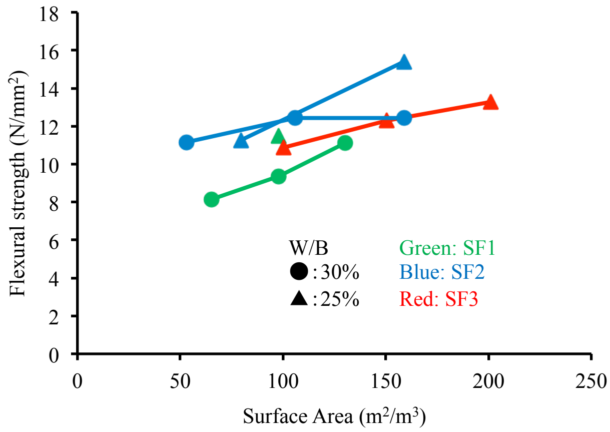

Figure 8. Relationship between Surface Area and flexural strength

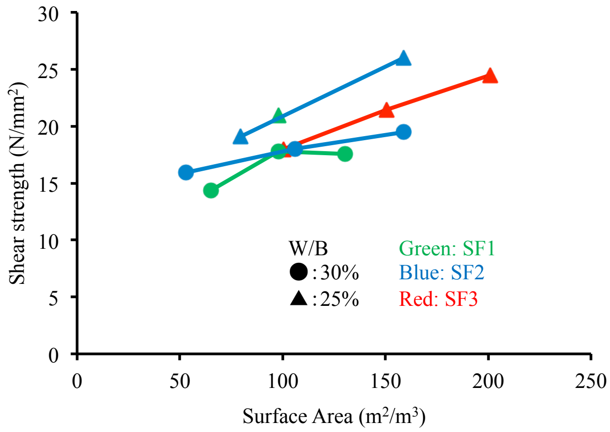

Figure 9. Relationship between Surface Area and shear strength

ratio and Vf in conjunction, the data was arranged in terms of the total surface area of short fibers in 1 m^3 of concrete (hereafter "Surface Area"). Figure 8 shows the relationship between Surface Area and flexural strength, and figure 9 shows the relationship between Surface Aria and shear strength.

From Figure 8 it can be seen that flexural strength increases with Surface Area. For an arbitrary value of Surface Area, flexural strength was biggest with SF2 and smallest with SF1. The flexural strength with SF2 may be greater than that with SF1 because of the greater tensile strength of the fibers. Also, the SF1 and SF2 fibers are hooked so that they bond well to the matrix, but those in SF3 are not modified in any way to increase bonding to the surface. This sort of difference in mechanical adhesion between the concrete and fibers may well affect the resulting flexural strength. Examining SF1 and SF2 shows that W/B has a smaller effect than the type of short fibers.

From Figure 9 it can be seen that shear strength increases with surface area. Examining SF1 and SF2 reveals the opposite situation from that with flexural strength, as there is a correlation between Surface Area and shear strength for each value of W/B irrespective of the type of short fibers. However, if SF3 is used with W/B of 25 %, shear strength is smaller than that with SF1 and SF2 for any values of Surface Area. Similarly to the situation with flexural strength in Figure 8, it is presumed that the absence of modifications to increase mechanical adhesion has an effect on shear strength.

CONCLUSIONS

The findings obtained in this experiment are summarized as follows:

(1) Provided that an appropriate mixed proportion is selected, High Strength Fiber Reinforced Concrete is able to obtain about 18cm slump with unit water content of 175 kg/m^3 and volume of unit coarse aggregates content of over 0.200 m^3/m^3.

(2) Steel fibers content has only a small impact on compressive strength and young's modulus, and has a big impact on flexural strength.

(3) Under the compressive strength range of this experiment, SF3 fiber which length is short considering that maximum size of coarse aggregates is still likely to provide sufficient reinforcement.

(4) There was a large increase in shear strength due to the steel fibers with a small water-binder ratio.

(5) Examining the influence of the total surface area of steel fibers in 1 m^3 of concrete, flexural strength and shear strength increase with the surface area of fibers. Moreover, the type of steel fibers has a significant influence on flexural strength, and the water-binder ratio has a significant influence on shear strength.

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