JOURNAL OF THE KOREAN SOCIETY OF AGRICULTURAL ENGINEERS DEC. 2004, pp.55-67

JOURNAL OF THE KOREAN SOCIETY
OF AGRICULTURAL ENGINEERS,
Vol. 46, No. 7

Engineering Properties of Steel Fiber Reinforced High Performance Concrete

Kim, Young Ik* · Sung, Chan Yong**

Abstract

In this paper, the flowability, strengths, impact resistance and sulfuric acid resistance of steel fiber reinforced high performance concrete (SFHPC) for the steel fiber content and fly ash and blast furnace slag as admixtures were presented. For evaluating flowability particularly, tests of slump flow, box-type passing ability and L-type filling ability were performed. The slump flow of SFHPC was some decreased with increase of the steel fiber content. At the box-type passing ability, the difference of box height of SFHPC is greatly increased with increasing the fiber content. The L-type filling ability of SFHPC was not excellent above 0.75% of the steel fiber content. Also, the compressive strength of SFHPC was decreased with increase of the steel fiber content, but the flexural strength of SFHPC was much higher than that of the concrete without the steel fiber. At the impact resistance, drop number of SFHPC for reaching final fracture was increased with increase of the fiber content. Also, the drop number for reaching initial fracture of 1mm was increased with increase of the fiber content. At the sulfuric acid resistance, 4-week weight change of SFHPC with the steel fiber was almost similarity that of HPC without the steel fiber and was in the range of 73.6 to 81.5.

Keywords : High performance concrete, Steel fiber, Flowability, Filling ability, Strengths, Impact resistance, Sulfuric acid resistance

---

I. Introduction

For many decades, concrete has been largely used as a construction material, whether in moderate aggressive environments, or in strongly aggressive environments. This is due to the fact that it possesses excellent water resistance, can be moulded in a variety of shape and sizes, and for being cheaper and more easily available in the field. Besides the aspects mentioned above, the

---

* Institute of Agricultural Science, College of Agriculture and Life Sciences, Chungnam National University

** Professor, Department of Rural Infrastructure Engineering, College of Agriculture and Life Sciences, Chungnam National University

** Corresponding author. Tel.: +82-42-821-5798, Fax.: +82-42-825-5791
E-mail address: cysung@cnu.ac.kr

use of concrete as structural material is favored by its mechanical properties, mainly compressive strength, a very significant parameter for design engineers and for those who perform quality control. This property is highly important for characterizing the material, serving as reference for its classification. Accordingly, nowadays, high performance concretes (HPC) are extensively applied in construction projects. This new advanced concrete has been transferred from laboratory research to practical application; and it already occupies a noticeable share of the market.1),6),7)

Based on the latest developments in concrete technology, HPC is characterized by a superior level of properties: workability, strength and durability. These advantages provided large-scale cost savings in many construction projects. HPC could be defined as concrete that satisfy 3 conditions of high-strength, high -durability and high-workability. In access method, HPC of high strength concrete (HSC) organized its inter microstructure by water-cement ratio lower than 40% is studied in the United States of America. But, in Japans, HPC of high flow concrete (HFC) can flow and compact in a mold or formwork under its own weight without the need for vibration is studied.2),3),10)

Also, as a result of the rapid developments in concrete technology, concretes of strength over 100 MPa can be easily produced using ordinary materials and applying conventional mix design methods. The main concern about high strength concrete is its increasing brittleness while its strength is being increased. The higher concrete strength is, the lower concrete ductility is. This inverse relation between strength and ductility is a serious drawback when using high strength concrete is of concern. A compromise between these two convicting properties of concrete can be obtained by adding steel fiber. Therefore, it becomes a more significant problem to improve the ductility of concrete. Steel fiber reinforcement greatly increases the energy absorption and ductility of concrete.4),5)

Therefore, this study is performed to evaluate effect on steel fiber of HPC that tamping does not need. To evaluate properties of steel fiber reinforced high performance concrete (SFHPC), it is analyzed flowability and workability by slump flow, Box-type passing ability and L-type filling ability before is hardened and mechanical properties by compressive strength, flexural strength, impact resistance and sulfuric acid resistance in hardened concrete.

Ⅱ. Experimental Program

1. Material

The cementitious materials used in this study were ordinary Portland cement (PC) specified KS F 5201, fly ash (FA) and blast furnace slag (BS). The chemical compositions of cement, FA, BS are shown in Table 1. The coarse aggregate used was crushed granite with nominal sizes of 5 and 20 mm. The specific gravity of the coarse aggregate was 2.64. Also, natural river sand, with a fineness modulus of 2.35 from the Geumgang river in Daejeon, was used as fine aggregate. The steel fiber used was hooked fiber with a length of 35mm and an aspect ratio of 65. A naphthalene-based superplasticizer was used to achieve the required workability of the concrete mixes.

Table 1 Chemical compositions and physical properties of PC, FA and BS

Item	PC	FA	BS
Chemical compositions (%)			
SiO_2	21.09	59.9	32.3
Al_2O_3	4.84	25.2	14.8
K_2O	1.13	-	-
Fe_2O_3	2.39	6.04	3.40
Na_2O	0.29	0.41	-
MgO	3.32	0.59	7.73
CaO	68.35	7.50	48.48
SO_3	3.09	0.09	3.89
Ig. loss	-	5.09	0.18
Physical properties			
Bulk density (kg/m^3)	3.12	2.39	2.90
Specific surface (Blain)(cm^2/g)	3,100	3,152	4,665
Color	Gray	Gray	White

2. Mix Proportions and Manufacture

Mix proportions were designed so that invest practical utilizing of industry product, flowability, filling ability, early and long term strength and acid resistance of HPC containing 10 and 20% of FA and BA of binder weight. Also, the steel fiber of 35 mm was used for crack control, increase of flexural rigidity and durability. The steel fiber was used by 0%, 2.5%, 0.5%, 0.75%, 1.0% weight ratio of total binder (C+FA of BS). The superplasticizer and water-cement ratio for reaching target slump with fiber content increase are increased. Meanwhile, superplasticizer was used by 1.5~1.7% to reduce water-cement ratio and improves fluidity, and mix proportions are shown in Table 2.

Specimens were prepared according to the Korean Standard Testing Methods, KS F 2405 (Specimen preparation methods for strength measure of concrete). All the specimens were demolded after cured at 20±1 ℃ for one day, and cured again at 20±1 ℃ for 28 days.

3. Test Method

가. Flowing and filling test

As a first step, the properties of fresh concrete other than slump were evaluated, since in this case the slump value is not relevant being the concrete very fluid. Therefore, the attention was focused on the measurement of the slump flow, which is the mean diameter of the "cake" of concrete obtained after releasing of a standard slump cone. Then, the elapsed time to gain the mean diameter of 500 mm (t_{500}) and the elapsed

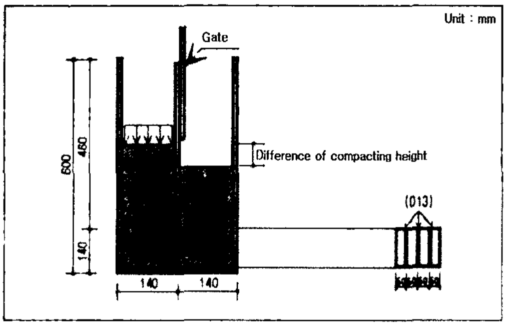


Fig. 1 Box-type test apparatus

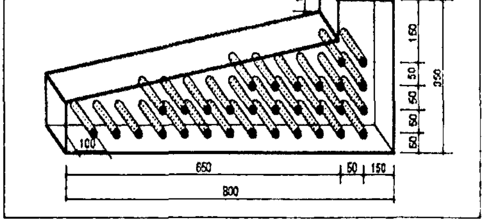


Fig. 2 L-type test apparatus

Table 2 Mix proportions of SFHPC

Mix types		G_V	S_R	kg/m^3								SF	SP
				C	FA	BS	C+F	C+B	W/B (%)	Sand	Gravel	(Vol)	(%)
SFHPC -10	(HPC-10)	50	47	486	54	-	540	-	0.35	825	760	0	1.5
	SPF-a	50	47	486	54	-	540	-	0.35	821	758	0.25	1.5
		50	47	486	54	-	540	-	0.36	817	755	0.5	1.6
		50	47	486	54	-	540	-	0.36	815	751	0.75	1.6
		50	47	486	54	-	540	-	0.37	813	748	1.0	1.7
	(HPC-10)	50	47	504	-	56	-	560	0.35	825	760	0	1.5
	SPB-a	50	47	504	-	56	-	560	0.35	821	758	0.25	1.5
		50	47	504	-	56	-	560	0.36	817	755	0.5	1.6
		50	47	504	-	56	-	560	0.36	815	751	0.75	1.6
		50	47	504	-	56	-	560	0.37	813	748	1.0	1.7
SFHPC -20	(HPC-20)	50	47	420	105	-	525	-	0.35	840	730	0	1.5
	SPF-b	50	47	420	105	-	525	-	0.35	837	728	0.25	1.6
		50	47	420	105	-	525	-	0.36	833	726	0.5	1.6
		50	47	420	105	-	525	-	0.36	830	722	0.75	1.7
		50	47	420	105	-	525	-	0.36	825	720	1.0	1.7
	(HPC-20)	50	47	425	-	110	-	535	0.35	840	730	0	1.5
	SPB-b	50	47	425	-	110	-	535	0.35	837	728	0.25	1.6
		50	47	425	-	110	-	535	0.36	833	726	0.5	1.6
		50	47	425	-	110	-	535	0.36	830	722	0.75	1.7
		50	47	425	-	110	-	535	0.36	825	720	1.0	1.7

* G_V: Volume ratio of coarse aggregate, S_r: Volume ratio of fine aggregate
* W/B: Water/(C+FA or BS)
* SFHPC-10: Steel fiber reinforced high performance concrete (FA and BS: 10%)
* SFHPC-20: Steel fiber reinforced high performance concrete (FA and BS: 20%)
* SPF-a, b: Steel fiber reinforced high performance concrete (FA: 10% and 20%)
* SPB-a, b: Steel fiber reinforced high performance concrete (BS: 10% and 20%)

time to gain the final configuration (t_{fin}) were recorded.

The ability of the concrete of compacting itself under its own weight was evaluated by means of the Box-type and L-type filling ability test with vertical and horizontal bars as shown in Fig. 1 and Fig. 2.1),3)

나. Strength

The compressive and flexural strength tests were carried out according to the KS F 2405 (Compressive strength test method for concrete), KS F 2408 (Flexural strength test method for concrete), respectively. The sizes of specimens were ø10×20 mm and 60×60×240 mm.

다. Impact resistance

The impact resistance was measured drop number of final and initial fracture of 1 mm, dropping a steel of 2 kg weight in height of 50 cm according to the KS F 2221 (Test method of impact for building boards).

라. Sulfuric acid resistance

Based on a primary test for selecting the concentration of sulfuric acid solution, a 5% sulfuric acid solution was chosen. The specimens were weighted once a week in such a way that the specimens were brushed softly under water with an iron brush to remove loose surface debris before weighting.

마. SEM and XRD

The scanning electron microphotographs were taken with a Hitachi S-2350 SEM equipped with an energy dispersive X-ray and with 20kV accelerating voltage. High vacuum evaporation was the method used for producing a thin gold film to make the specimen surface electrically conductive. The XRD experiments were carried out in a X-ray powder diffract meter with detector using CuK α radiation. The intensities were calculated from the maximum of diffraction after discounting the background.

Ⅲ. Results and Discussion

1. Slump Flow

Table. 3 shows the relationship between slump flow and steel fiber content(0, 0.25, 0.5, 0.75, 1%). As the steel fiber content increases, slump flow of SFHPC was decreased as shown in Table 3. But, values of slump flow at all mix types (SPF-a, SPF-b, SPB-a, SPB-b) were showed above 60 cm. On the other hand, reaching velocity of 50 cm slump flow as shown in Table 3 was greatly decreased with increase steel fiber content. It should be noted that the flow velocity of high performance concrete was considerably reduced with the increase of steel fiber content due to increasing viscosity between cement paste and steel fiber. In addition, slump flow and 50 cm slump flow of SPF-b and SPB-b was much higher than that of SPF-a and SPB-a. For these main reasons, it is believed that is increased flowability due to ball bearing effect and resegration by using fly ash and blast furnace slag of cementitious materials.

2. Box Passing Ability

Fig. 3 and Table 3 show the relationship between box height difference and the steel fiber content. Box height difference of SFHPC with the steel fiber between the left and right of the box was much higher than that of HPC without the steel fiber. In addition, Box height difference of SPF-a and SPB-a with increase the steel fiber content was increased, and was approximately ranged from 3 to 11 and 3 to 10 as shown in Fig. 3 and Table 3, respectively. Though the slump flow of SPF-a and SPB-a with the steel fiber were almost similarity that of HPC without the steel fiber, it should be noted that Box height difference of SPF-a and SPB-a with the steel fiber in filling ability test were much higher than that of HPC without the steel fiber due to matrix of 35 mm steel fiber and cement paste. Also, Box height difference of SPF-b and SPB-b was almost similarity that of SPF-a and SPB-a.

Table 3 Rheology test results of SFHPC

Type	Steel fiber content (%)	Slump flow		Difference of box height (cm)	L-type filling ability
		Length (cm)	50 cm reach velocity (cm/s)		
SPF-a	0.00	65*66	5.6	3	Excellent
	0.25	65*65	5.4	3	Excellent
	0.50	64*64	4.5	5	Excellent
	0.75	63*64	3.5	7	Good
	1.00	62*62	2.7	11	Plain
SPB-a	0.00	65*65	5.7	3	Excellent
	0.25	64*65	5.6	3	Excellent
	0.50	63*62	4.7	5	Excellent
	0.75	62*62	3.5	7	Good
	1.00	62*62	2.9	10	Plain
SPF-b	0.00	65*66	5.9	2	Excellent
	0.25	65*66	5.7	2	Excellent
	0.50	64*65	4.9	4	Excellent
	0.75	63*63	3.9	6	Good
	1.00	63*62	3.1	9	Good
SPB-b	0.00	66*67	6.0	2	Excellent
	0.25	66*65	5.7	2	Excellent
	0.50	66*65	4.9	5	Excellent
	0.75	65*66	3.8	6	Good
	1.00	64*63	3.0	9	Good

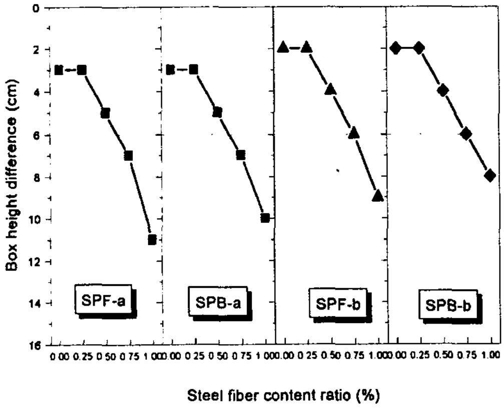


Fig. 3 Difference of box height for SF

3. L-type Filling Ability

The ability of the concrete of compacting itself under its own weight was evaluated by means of the L-type filling ability with horizontal steel bars. The results obtained are reported in Table 3. The L-type filling ability of SFHPC with the steel fiber showed satisfactory, but not excellent above 0.75% steel fiber content, results in terms of mobility in narrow sections. Nevertheless, for producing the thin precast elements, this workability level resulted adequate, due to the absence of reinforcing steel bars inside the formwork.

4. Compressive Strength

The results of the compressive strength tests at 7, 28 and 91 days of curing are summarized in Table 4. At 7 days of curing, the compressive strength of SPF-a and SPB-a with the steel fiber was decreased by about 6 to 24% and 4 to 11% than that of HPC-10 without the steel fiber. In addition, the compressive strength of SFHPC-10 with increase the steel fiber content is decreased. The lower compressive strength of SFHPC-10 prepared with the steel fiber might be due to the insufficient dispersing of the fiber in the concrete during mixing. As a result, the compressive strength of concrete is reduced. For sufficient dispersing of the steel fiber, a special concrete mixing procedure is required.[4),5)] Also, the compressive strength of SPB-a was higher than that of SPF-a. At 28 days of curing, the compressive strength of SPF-a and SPB-a with the steel fiber was decreased by approximately 2 to 15% and 2 to 14% than that of HPC-10

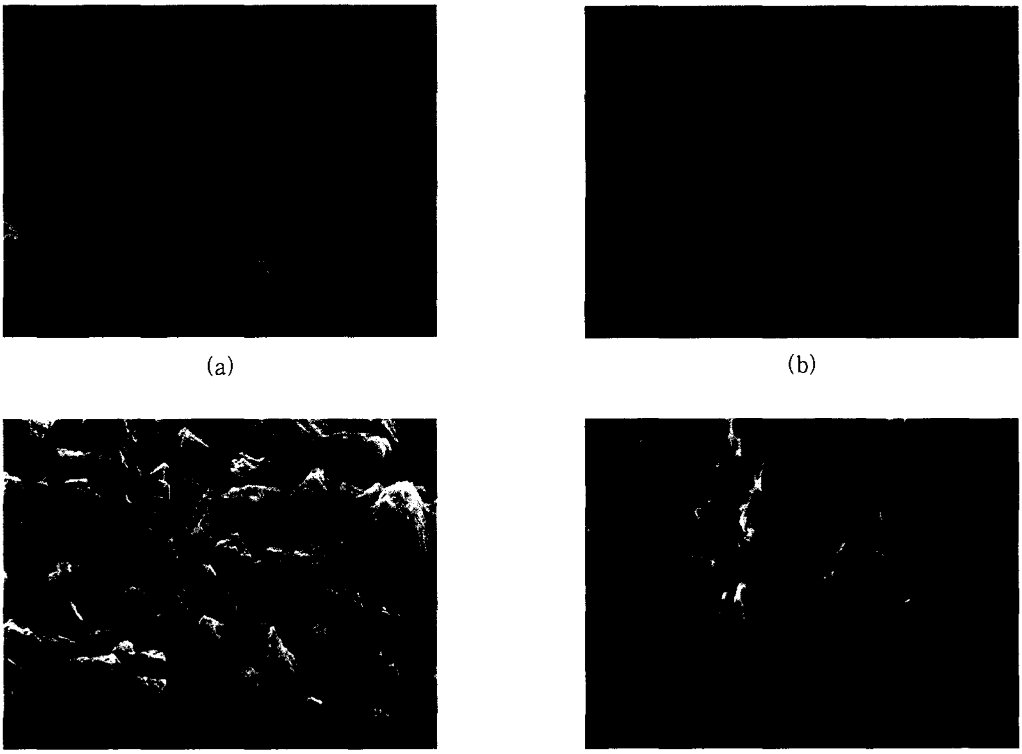
Table 4 Strengths and impact resistance of SFHPC

Type	SF (%)	Strength						Fracture drop number	
		Compressive			Flexural				
		Age (days)						Initial (1mm)	Final
		7	28	91	7	28	91		
SPF-a	0.00	33.3	41.4	48.2	5.4	7.7	8.4	1	3
	0.25	31.4	40.7	47.9	6.1	8.4	9.4	4	13
	0.50	28.3	39.0	46.1	7.2	9.2	10.7	12	22
	0.75	27.2	37.8	44.4	7.4	9.6	11.2	17	38
	1.00	25.2	35.1	43.0	7.8	10.7	11.9	24	47
SPB-a	0.00	34.5	43.0	49.0	6.4	8.7	9.0	1	4
	0.25	33.1	42.2	48.6	7.4	9.0	9.6	6	15
	0.50	32.4	40.7	47.4	7.6	9.6	10.9	12	27
	0.75	31.5	38.9	45.2	8.0	10.1	11.3	19	43
	1.00	30.7	36.9	42.9	8.9	11.0	12.3	27	52
SPF-b	0.00	27.0	36.2	47.7	5.1	7.4	7.9	1	1
	0.25	26.0	33.8	46.0	5.2	7.7	8.7	4	10
	0.50	22.6	31.0	45.2	5.5	8.4	9.8	6	19
	0.75	21.0	28.0	43.7	6.2	8.8	10.6	12	28
	1.00	20.2	27.3	39.0	6.7	9.2	12.2	17	37
SPB-b	0.00	32.9	42.0	47.3	5.5	7.4	7.9	1	3
	0.25	31.7	39.6	46.6	5.9	8.3	8.9	3	11
	0.50	30.4	37.9	44.9	6.3	8.9	9.4	8	21
	0.75	28.6	35.3	41.3	6.9	9.2	10.3	14	30
	1.00	25.0	33.4	38.0	7.4	10.3	11.1	19	43

without the steel fiber. Regardless of the steel fiber content, the compressive strength in all mix types was easily achieved over 35 MPa. Fig. 4(a) and (b) show two images obtained by scanning electron microscopy observations on SPF-a and SPB-a samples at 28 days of curing. At 91 days of curing, the compressive strength of SPF-a and SFPB-a with the steel fiber was decreased by approximately 1 to 11% and 1 to 12% than that of HPC without the steel fiber. Regardless of the steel fiber content, the compressive strength in all mix types was easily achieved high strength above 42 MPa. Fig. 4(c) and (d) show two images obtained by scanning electron microscopy observations on SPF-a and SPB-a samples at 91 days of curing. Meanwhile, compressive strength of SPF-b and SPB-b was some lower than that of SPF-a and SPB-a at 7, 28, and 91 days of curing, as shown in Table 4.

5. Flexural Strength

The results of the flexural strength tests at 7, 28 and 91 days of curing are summarized in Table 4. At 7 days of curing, the flexural strength of SPF-a and SFPB-a with the steel fiber was increased by approximately 13 to 44% and 16 to 39% than that of HPC-10 without the steel fiber. In addition, the flexural strength of SFHPC-10 with increase the steel fiber content is greatly



(a) (b)

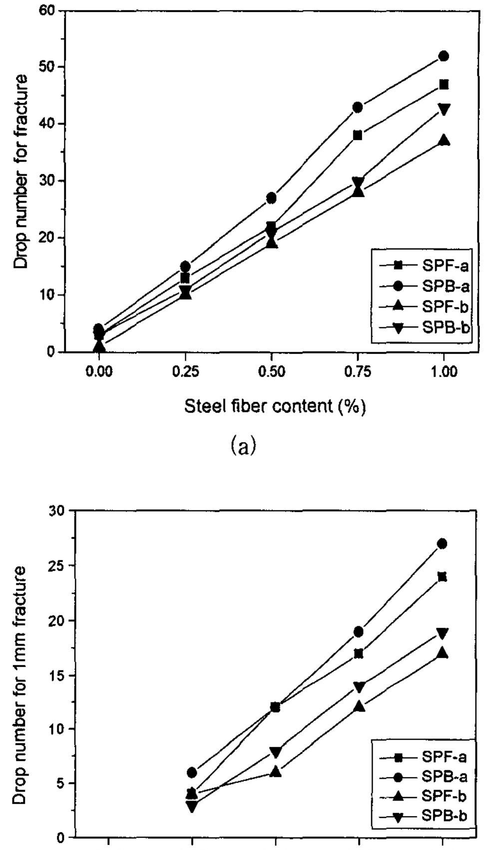
(c) (d)

Fig. 4 Images by SEM of SPF-a and SPB-a at 28 and 91 days of curing.

increased. The higher flexural strength of the SFHPC-10 prepared with the steel fiber might be due to increasing of the bond strength between the steel fiber and cement paste. As a result, the flexural strength of concrete is increased.[8] At 28 days of curing, the flexural strength of SPF-a and SFPB-a with the steel fiber was increased by approximately 9 to 39% and 3 to 26% than that of HPC-10 without steel fiber. Regardless of the steel fiber content, the flexural strength in all mix types was presented above 8 MPa. At 91 days of curing, the flexural strength of SPF-a and SFPB-a with the steel fiber was decreased by 12 to 42% and 7 to 37% than that of HPC-10 without steel fiber. Meanwhile, the flexural strength of SPF-b and SPB-b was some lower than that of SPF-a and SPB-a at 7, 28, and 91 days of curing as results of the compressive strength, as shown in Table 4.

6. Impact Resistance

The impact resistance performance of the SFHPC with the steel fiber content is shown in Fig. 5 and Table 4. Drop number for reaching final fracture of SPF-a and SPB-a with the steel fiber were in the range of 13 to 52 and it was greatly increased than that of HPC-10 without the steel fiber(3 to 5) as shown in Fig. 5(a). Drop number for reaching final fracture was increased with increase of fiber content. Also, Drop number for reaching initial fracture of 1 mm of SPF-a and SPB-a with the steel fiber were in the range of 4~27 s shown in Fig. 5(b). Fig. 6(a) and (b) show fracture state after reaching final fracture of SPF-a with 0% and 0.5% fiber content. Also, Drop number for reaching final fracture of SPF-b and SPB-b with the steel fiber were in the range of 10 to 43 and it was greatly increased than that of HPC-20 without the steel fiber(1 to 3) as shown in Fig. 5(a) and Table 4.

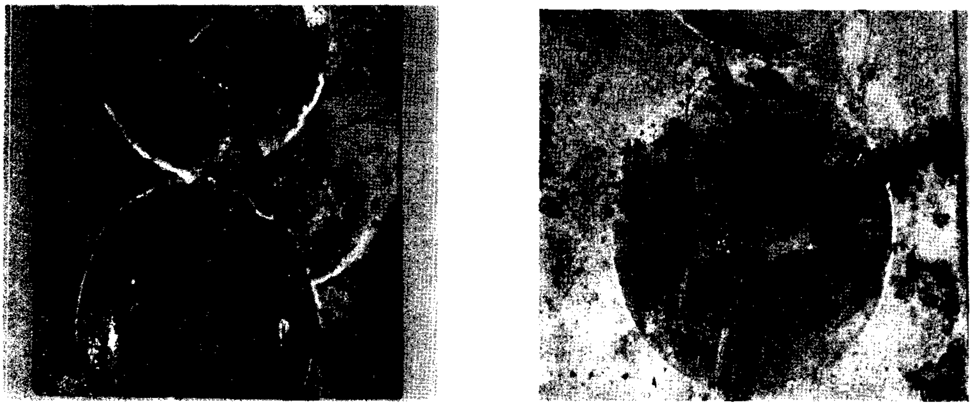


(a)

(b)

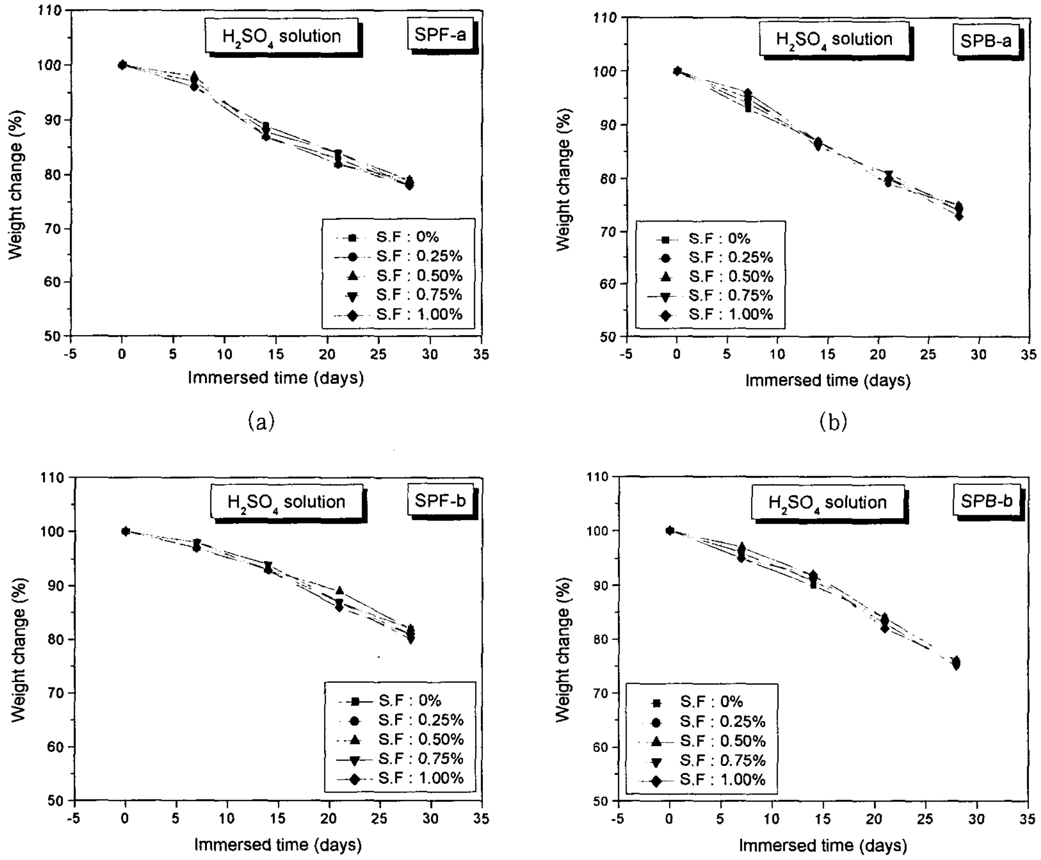
Fig. 5 Relationship between SF content and drop number for reaching final fracture and fracture of 1 mm

This indicates that the SFHPC with the steel fiber has a great ability to absorb kinetic energy because of effect of the steel fiber. The initiation and propagation of cracks during an impact event were restrained by effect of the steel fiber. The SFHPC with the steel fiber could still withstand impact stress and absorb more kinetic energy



(a) SF (content: 0%) (b) SF (content: 0.5%)

Fig. 6 Fracture state after reaching final fracture of SPF-a with SF content (0% and 0.5%)



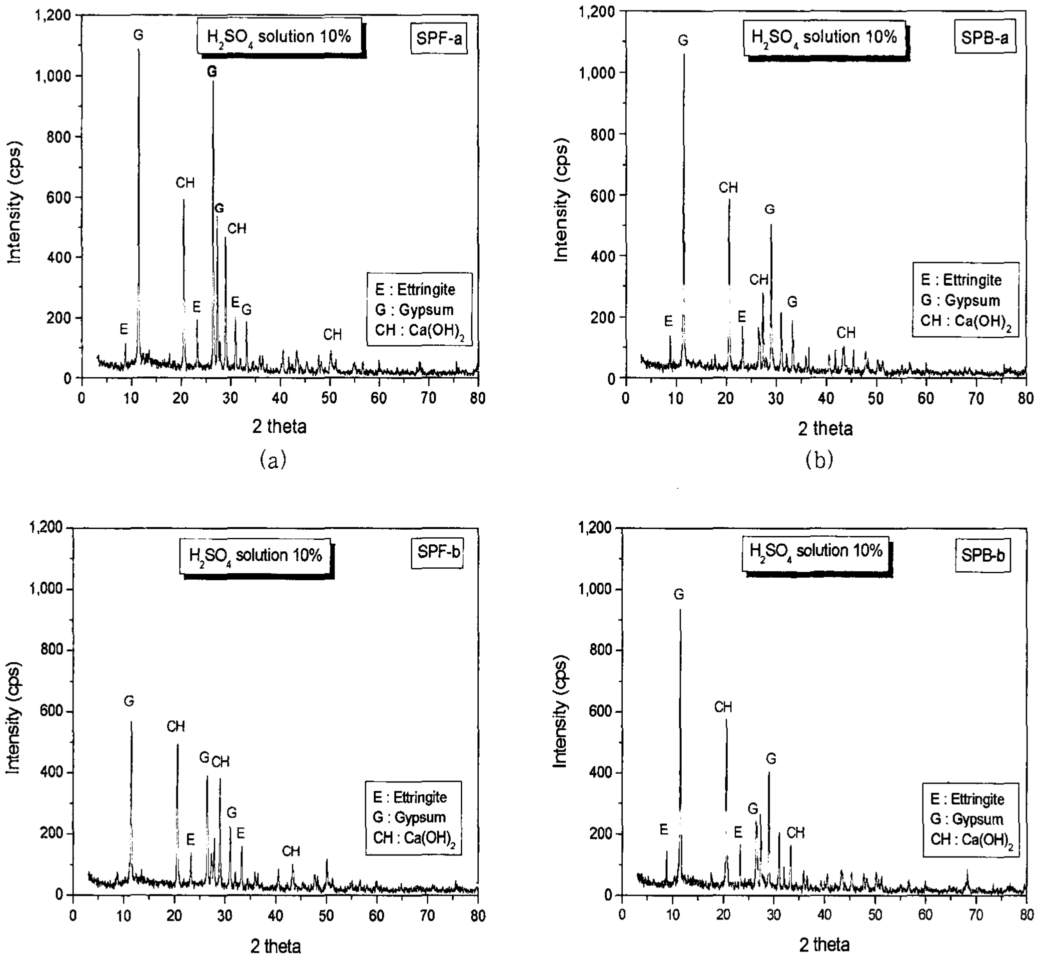
(a) (b)

(c) (d)

Fig. 7 Weight change of SFHPC-10 and SFHPC-20 during 4-week after sulfuric acid without leading to concrete damage after the initial cracking. The final damage pattern of SFHPC with the steel fiber was multiple cracking without complete rupture.

7. Sulfuric Acid Resistance

Sulfuric acid is particularly aggressive, because in addition to the sulfate attack of the aluminates phase, acid attack on $Ca(OH)_2$ and C-S-H takes place. As shown in Fig. 7, the 4-week weight change in 5% sulfuric acid solution were in the range of 78.3 to 78.6, 73.6 to 75.8, 80.5 to 81.5 and 75.5 to 76.8 for SPF-a, SPB-a, SPF-b and SPB-b with the steel fiber, respectively. Also, weight change of SFHPC with the steel fiber was almost similarity that of HPC without the steel fiber. Fig. 8 represents the XRD patterns for cement paste of SPF-a, SPB-a, SPF-b, and SPB-b after 4-week sulfuric acid



(a)
(b)
(c)
(d)

Fig. 8 XRD patterns of SPF and SPB after 4-week sulfuric acid attack

attack.[9] A large amount of $CaSO_4 \cdot 0.6H_2O$ is formed in the central part of specimens of all mix types as seen in this Fig. 8 and the rice like substance in Fig. 9. Fig. 9 shows the SEM micrographs of SPF-a after 4-week in 5% sulfuric acid attack. A considerable quantity of plate like, rice-shaped substance is seen in the central parts of SPF-a after sulfuric acid attack. This means that the central parts of specimens of all mix types were corroded. Fig. 10 shows SPB-b specimens brushed softly under water with an iron brush to remove loose surface debris before weighing after 1-week sulfuric acid attack.

Fig. 9 SEM of SPF-a after 4-week sulfuric acid attack

Fig. 10 Specimen of SPB-b after 1-week sulfuric acid attack

Ⅳ. Conclusions

This study was performed to develop the flowability, strengths, impact resistance and sulfuric acid resistance of steel fiber reinforced high performance concrete (SFHPC) for the steel fiber content and fly ash and blast furnace slag as admixtures. For evaluating flowability, strengths and sulfuric acid resistance, tests of slump flow, box-type passing ability, L-type filling ability, compressive strength, flexural strength, impact resistance and sulfuric acid resistance were performed. The following conclusions were drawn;

Slump flow of SFHPC with the steel fiber was decreased with increase the steel fiber content and values of slump flow at all mix types (SPF-a, SPF-b, SPB-a, SPB-b) was showed above 60 cm. But, reaching velocity of 50 cm slump flow was rapidly decreased with increase steel fiber content. Box height difference of SFHPC with the steel fiber between the left and right of the box was much higher than that of HPC without the steel fiber. In addition, Box height difference of SFHPC with increase the steel fiber content was increased. The L-type filling ability of SFHPC with the steel fiber showed satisfactory, but not excellent above 0.75% steel fiber content, results in terms of mobility in narrow sections.

The compressive strength of SFHPC with increase the steel fiber content was decreased and the compressive strength in all mix types was easily achieved over 35 MPa at 91 days of curing, regardless of the steel fiber content. The flexural strength of SFHPC with increase the steel fiber content is greatly increased and the higher flexural strength of SFHPC prepared with the steel fiber might be due to increasing of the bond strength between the steel fiber and cement paste.

Drop number for reaching final fracture of SFHPC with the steel fiber was in the range of 10 to 52 and it was greatly increased than that of HPC without the steel fiber(1 to 3). Drop number SFHPC of for reaching final fracture was increased with increase of fiber content. Also, Drop number for reaching initial fracture of 1mm of SFHPC with the steel fiber was in the range of 3~27.

In sulfuric acid resistance, 4-week weight change of SFHPC with the steel fiber was almost similarity that of HPC without the steel fiber and was in the range of 74.5 to 82.6%

References

1. Adriano Papo and Luciano Piani, 2004, Effect of various superplasticizer on the rheological properties of Portland cement pastes, *Cement and Concrete Research* 34 : 2,097-2,101.
2. David, W. A., A. W. Saak and H. M. Jennings, 1999, The influence of mixing on the rheology of fresh cement paste, *Cement and Concrete Research* 29 : 1,491-1,496.
3. Domone, P. L. and H. W. Chai, 1996, Design and testing of self-compacting concrete, in Proceedings of RILEM International Conference on Production Methods and Methods and Workability of Fresh Concrete, *E&FN Spon*, London : 223-236.
4. Elzeldin, A. S. and P. N. Balaguru, 1992, Normal and high strength fiber reinforced concrete under compression, *Journal of Materials in Civil Engineering* 4(4) : 415-429.
5. Jianming Gao., Wei Sun and Morino. Keiji., 1997, Mechanical properties of steel fiber reinforced, high-strength, lightweight concrete, *Cement and Concrete Composites* 19(4) : 307-313.
6. Khatri, R. P. and V. Sirivivatnanon, 1995, Effect of different supplementary cementitious materials on mechanical properties of high performance concrete, *Cement and Concrete Research* 25(1) : 209-220.
7. Cengiz. O and L. Turanli, 2004, Compressive evaluation of steel mech, steel fiber and high-performance polypropylene fibre reinforced shotcrete in panel test, *Cement and Concrete Research* 34 : 1,357-1,364.
8. Peter Robins, Simon Austin, Jim Chandler and Peter Jones, 2001, Flexural strain and crack width measurement of steel-fibre-reinforced concrete by optical grid and electrical gauge methods, *Cement and Concrete Research* 31 : 719-729.
9. Paulo. J. M and E. K. Kimberly, 2003, Time to failure concrete exposed to serve sulfate attack, *Cement and Concrete Research* 33 : 987-993.
10. Sung, C. Y. and R. N. Swamy, 1997, Experimental study on engineering properties of lightweight aggregate concrete, *Journal of the Korean Society of Agricultural Engineer* 39(1) : 75-82. (in korean)