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- Technical Paper -

FLEXURAL PERFORMANCE AND CRACKING BEHAVIOR OF REINFORCED STRAIN-HARDENING CEMENT COMPOSITE BEAMS

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ABSTRACT

This paper describes the test results of concrete and strain-hardening cement composite (SHCC) beams reinforced with normal and high strength bars to evaluate the effect of bar strength and cement composites' ductility on the flexural performance and cracking behavior of flexure-dominant beams. The test results indicate that the superior mitigation of cracking damage is observed for reinforced SHCC beams compared to those of reinforced concrete beams. Crack-damage mitigation in the SHCC beams is also effective in the case of SHCC beam reinforced with 800MPa high strength bars.

Keywords: strain-hardening cement composite (SHCC), flexural performance, cracking behavior, ductility

1. INTRODUCTION

The social needs to reduce a term of construction and lengthen the service life of reinforced concrete (RC) structures have increased the demands for improving the performance of both the concrete and reinforcing steel bars. Besides, practical advantages of high strength steel include a reduction of congestion in heavily reinforced members and savings in the cost of labour. These demands have led to a number of researches on various high performance concrete. Recently, a high performance concrete with 80MPa of compressive strength, high density, and low permeability was used in the foundations of Burj Khalifa in Dubai. Currently, Korean Concrete Institute (KCI) 2007 design code for structural concrete [1] permits the design using steel reinforcement with a yield strength defined as the stress corresponding to a strain of 0.0035, but not to exceed 550MPa. Now, the code has been revising and it is considered to permit the using of higher strength steel reinforcement.

As Nawy [2] reported, the limits on yield strength are mainly related to the control of crack widths at service loads. Crack width is a function of steel strain and stress. Therefore, the stress in the steel reinforcement will always need to be limited to some extent to prevent cracking from affecting serviceability of the structure. However with recent development of ductile and high performance fibre-reinforced cement-based composites shown in Fig. 1, such as strain-hardening cement composite (SHCC), engineered cementitious composite (ECC), and ductile fibre-reinforced cement composite (DFRCC), the KCI 2007 limit of 550MPa on the steel reinforcement yield strength are believed to be unnecessarily conservative for new designs.

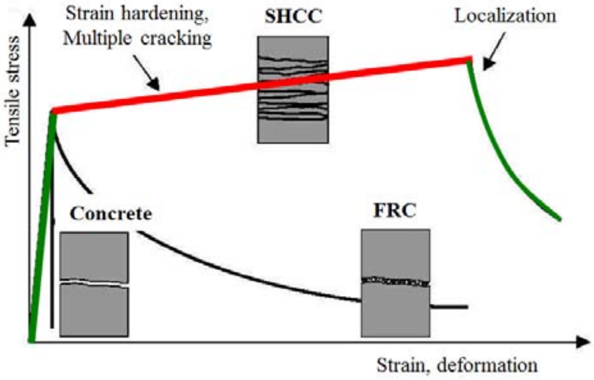

Fig. 1 Definition of SHCC material

Yun et al. [3] investigated the effect of high-performance steel as reinforcement steel bar on the tension response and cracking behavior of concrete and SHCC tension members. They reported that SHCC material's ductility and crack-damage mitigation capacity led to significant increase in the tension stiffening and cracking behavior of tension members with normal strength as well as high strength reinforcement.

The purpose of this study is to evaluate the effect of steel bar strength and cement composite type on the flexural performance and cracking behavior of flexure-dominant beams. Also this study explores the application of 800MPa high strength steel and SHCC material for improving flexural performance and mitigating the crack-damage of flexural members.

2. EXPERIMENTAL PROGRAM

2.1 Test Specimens

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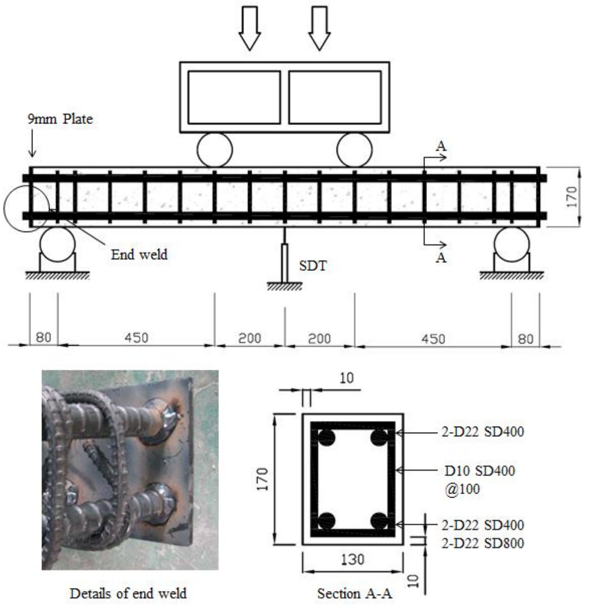
The experimental program consisted of four beam tests. Fig. 2 shows the configuration and reinforcement details of test beams.

The yield strength of two deformed steel bars reinforced in tensile zone were 400 and 800MPa with nominal diameter of 22mm (D22) and two 400MPa deformed steel bars with nominal diameter of 22mm were placed in compressive zone. All the specimens have the same configuration and dimension. The beam is rectangular cross-section with a width of 130mm, a height of 170mm and a net span length of 1300mm. All the specimens were designed with 70MPa of concrete compressive strength. The summary of the test specimens is given in Table 1. Steel plate was welded at each end of all the bars for the anchorage of the bars, as shown in Fig. 2. All beams were tested as simply supported beams under four-point loading. Vertical load was applied through 500 kN hydraulic actuator mounted to the strong frame. The controlled displacement rate was 0.02 mm/min. Crack formations were visually observed and, at specified and yield loads, crack number and widths were microscopically measured over 800 mm central zone of the beam's tensile face. To measure the whole vertical deflection at the center of tensile face Strain Displacement Transducer (SDT) was installed.

2.2 Mechanical Properties of Reinforcing Bar

Tension coupons for the normal and high strength reinforcing bars were made and tested according to KS B 0802, and the stress-strain relationship are shown in Fig.3.

High strength reinforcing bar experienced linear behavior until a stress level of approximately 600MPa, followed by a negligibly small reduction in the elastic modulus up to 800MPa, and then nonlinear behavior to a maximum tensile strength 1,236MPa at 5% strain. The yield strength of high strength bar, based on KS B 0802 0.2% off set method, was 772MPa. The yield strength at Normal strength reinforcing bar's yield strength was 401MPa (according to KS B 0802).



Details of end weld

Section A-A

Fig. 2 Section of reinforcement details of beams (dimensions in mm)

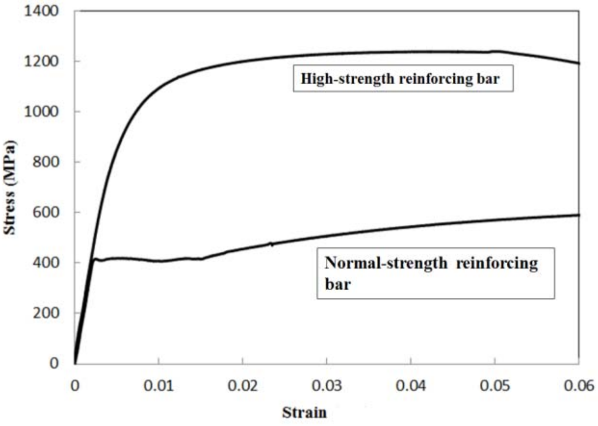


Fig. 3 Stress-strain relationship of steel

Table 1. Specimen test matrix

Beam	Section (mm x mm)	Length (mm)	Composite types	Compressive strength (MPa)	Yield strength (MPa)
HTB–CON 70	130x170	1460	Concrete	70	800
NTB-CON 70	130x170	1460	Concrete	70	400
HTB-PE70	130x170	1460	SHCC	70	800
NTB-PE70	130x170	1460	SHCC	70	400

Table 2. Mix proportions of concrete and SHCC

	Material (kg/m^3)				Fiber Volume rate (%)	Super -plasticizer (kg/m^3)	Methyl cellulose (kg/m^3)
	Water	Cement	Sand	Aggregate			
Concrete	160	550	738	933	-	-	-
SHCC	384	1218	512	-	1.5	13	0.52

2.3 Mechanical Properties of Cement Composite

The compressive tests for cylindrical specimens with 100mm diameter and 200mm height were carried out according to ASTM C 39. The four-point loading flexural tests were carried out for prisms with the dimension of 100 x 100 x 400 mm according to the requirements of ASTM C78. To evaluate the tensile performance of SHCC material, direct tension tests for dumbbell-shaped specimens were conducted according to the recommendation of the Japan Society of Civil Engineers (JSCE-E-51). Two SDT were mounted on the two sides of the tensile specimen for measuring tensile strain as well as test control.

The mix compositions of the SHCC and plain concrete used in this study are given in Table 2 (all the mix proportions use the dry weight of the ingredients). PE fibers as reinforcing fiber in SHCC materials were used. PE fibers have an elastic modulus of 75GPa and a tensile strength of 2,500MPa. Total fiber volume fraction in the SHCC materials is 1.5%. The compressive strengths of concrete and SHCC are 63MPa and 70MPa, respectively.

Fig. 4(a) shows the uniaxial tensile responses of five SHCC dumbbell-shaped specimens. An elastic response is observed up to the first-crack load. After the first crack, the tensile stress increases with an increase in strain with multiple cracks develop up to the peak stress.

Fig. 4(b) shows the flexural stress-deflection curves of three SHCC prisms. For conventional concrete, brittle fracture occurs soon after the first-crack load. However, SHCC material shows a ductile post-cracking behavior after the first-crack load.

SHCC material has higher tensile strength and bending strength due to the bridging action of short reinforcing fibers. Average tensile strength and bending strength of SHCC material are 6.26MPa and 14.38MPa, respectively.

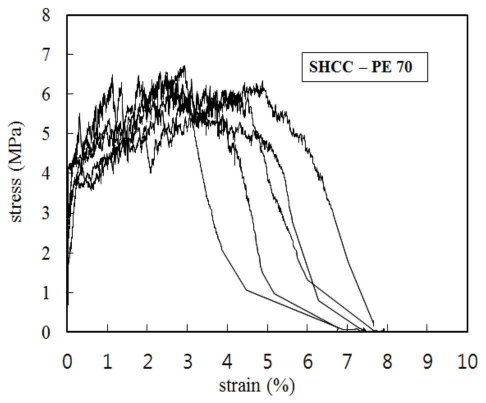
3. TEST RESULT AND DISCUSSIONS

3.1 Observed Behavior of Beam Specimens

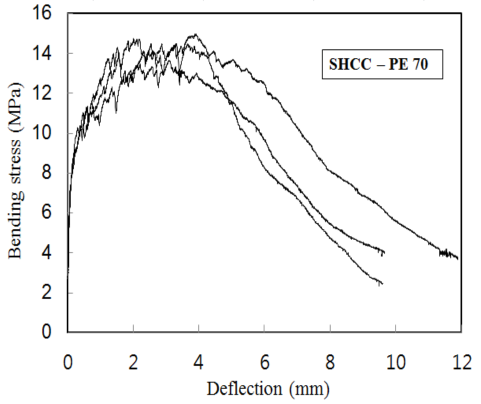
In this study, according to Pack and Paulay(1975) suggestion[4], the yielding and ultimate strength was defined. A triliear load-deflection relationship shown in Fig 5 is defined by the points of cracking, yielding and ultimate.

Fig. 6 shows load-displacement relationship of test beams. As expected, the SHCC beams increases the flexural stiffness after the crack load compared to RC beams. HTB-PE70 beam specimen showed 3.46 times higher displacement at ultimate load than HTB-CON70 beam specimen. NTB-PE70 beam specimen showed 7.24 times higher than HTB-CON70 beam specimen.

HTB-PE70 beams specimen had a 48% higher yielding strength than NTB-PE70. HTB-CON70 beams specimen had a 25% higher yielding strength than NTB-CON70.



(a) Direct tensile behavior



(b) Flexural behavior

Fig. 4 Mechanical properties of SHCC

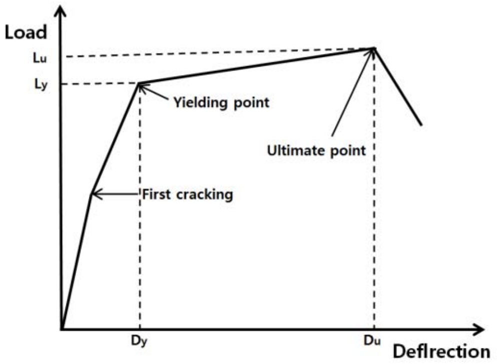


Fig. 5 Define of yielding and ultimate strength

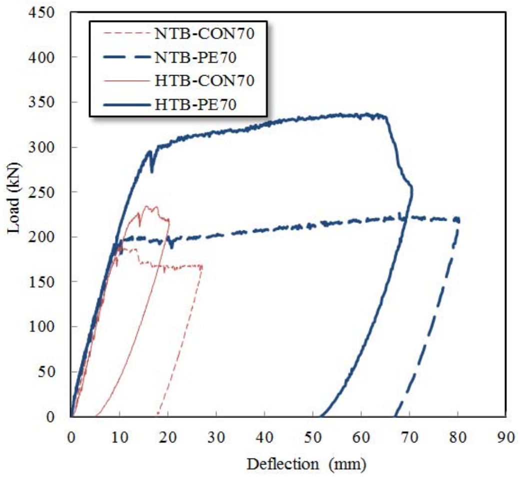


Fig. 6 Load-deflection relationship

Significant differences between conventional RC beams and SHCC beams can be noted from Fig. 6. It is clear that SHCC material can improve ductility of flexure-dominant beams. Specifically, it may be concluded that high strength steel reinforced SHCC beam can improve more effectively flexural performance than concrete beam reinforced with high strength steel bar because of the high tensile ductility and damage mitigating capacity of SHCC material.

Fig. 7 shows the cracking patterns of concrete and SHCC beams with normal and high strength reinforcing bar at yield load. In the conventional RC beams, a few wide cracks developed. However, in the SHCC beams, a large number of fine cracks developed. And SHCC specimens with high-strength reinforcing bars appear large number of fine cracks developed, due to high strain of reinforcing bars and high ductility of SHCC material.

The large number of fine cracks developed means that the stress is distributed. In case of SHCC, beams specimen appear that ductile behavior with crack distributed, while concrete beams show brittle behavior and fracture due to concentration of stress at a few wide cracks. It is concluded that the application of SHCC material to flexure-dominant members may prevents the penetration of aggressive substances into the cement-based composite or reinforcing bars and could improve the durability of RC members.

3.2 Cracking Behavior of Beams

Localized crack widths were captured with a photo microscope over the 800 mm in the center of the tensile face of the beams at predetermined loading stages. Table 3 and Fig. 8 (a) and (b) show that the tensile strength and strain capacity of SHCC matrial have a significant effect on the crack width of the beams. They also show that the number of cracks in the SHCC beams increases, and the average width of cracks decreases compared with the conventional RC beams.

Fig. 8 (a) represents effect of SHCC material on number of cracks at pre-decided loading stages. Also, the number of cracks is increased at SHCC specimens steadily. However concrete beams sustain steady number of cracks after 80 kN.

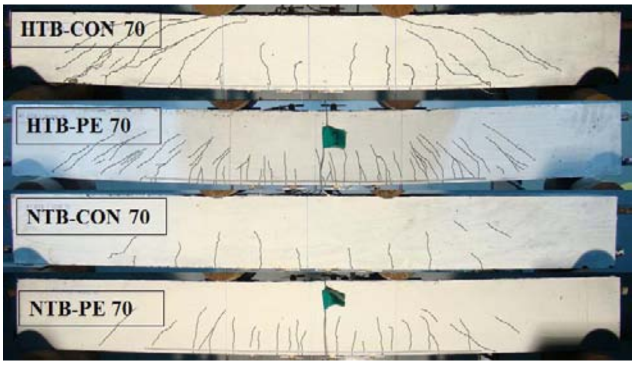
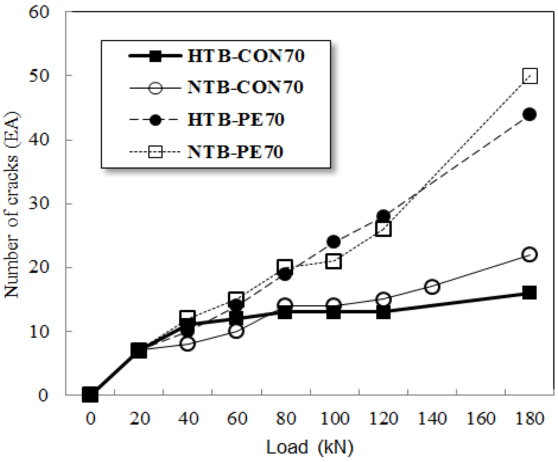
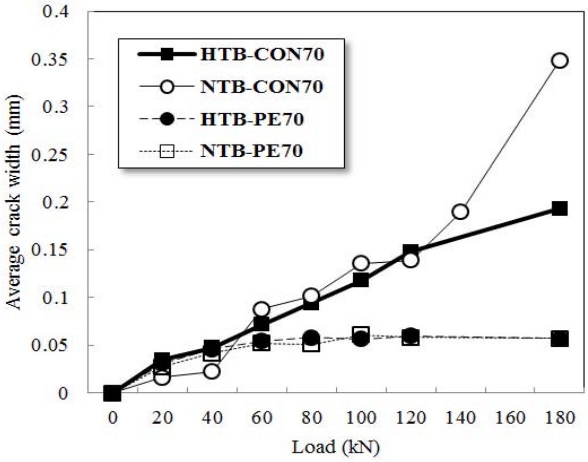


Fig. 7 Crack pattern of specimens



(a) Effect of SHCC on number of cracks



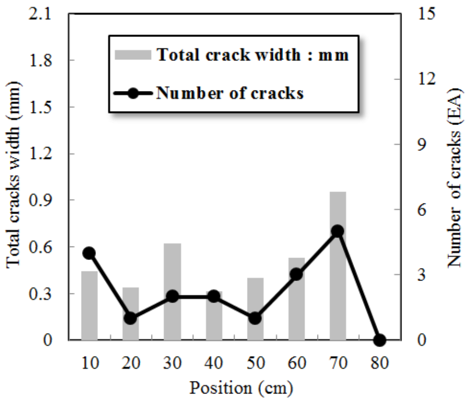
(b) Effect of SHCC on average crack width

Fig. 8 Effect of SHCC on cracks

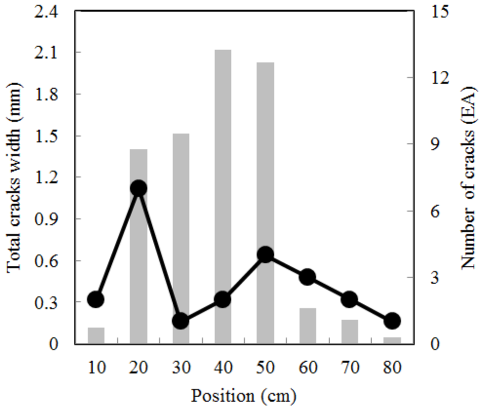
Table 3. Cracking behavior of beam specimens

Specimen	Load							
	40 kN		80 kN		120 kN		180 kN	
	No. (EA)	Ave-W (mm)	No. (EA)	Ave-W (mm)	No. (EA)	Ave-W (mm)	No. (EA)	Ave-W (mm)
HTB-CON70	11	0.048	13	0.094	13	0.148	16	0.193
NTB-CON70	8	0.023	14	0.101	15	0.139	22	0.348
HTB-PE70	10	0.046	19	0.058	28	0.060	44	0.057
NTB-PE70	12	0.042	20	0.051	26	0.058	50	0.057

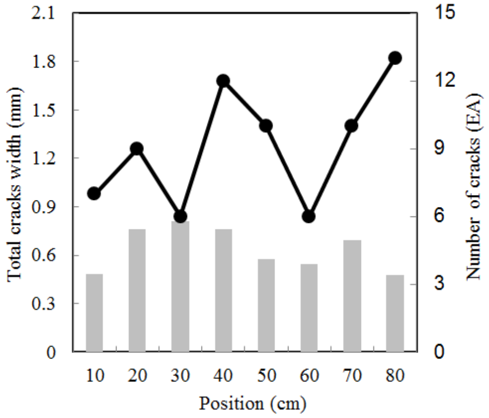
No.: Number of cracks, Ave-W: Average crack width



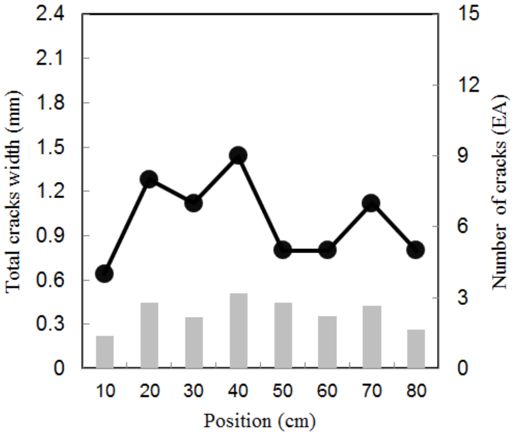
(a) HTB-CON70



(b) NTB-CON70



(c) HTB-PE70



(d) NTB-PE70

Fig 9. Crack distribution of beams at yielding load

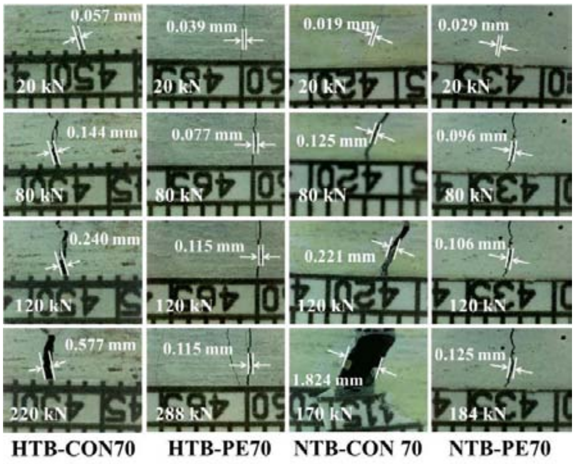


Fig 10. Variation of crack width of specimens

Fig. 8 (b) shows the average crack width according to each loading stage. In case of concrete specimens, average crack width has increased consistently. SHCC specimens, on the other hand, maintain a constant width after 60 kN.

Fig. 9 (a) through (d) shows the cracks in the SHCC and RC beam specimens at yielding strength. SHCC beams are distributed widely along the tensile region compared with the conventional RC beams. As expected, crack damage of the SHCC beams mitigate due to the reinforced fiber bridge action.

In Fig. 10, the variation of crack width of specimens is a reference for checking the position of the cracks. Two series (concrete and SHCC) of pictures indicate a significant difference in the cracking behavior of the beam specimens. From Fig. 10, it can be concluded that the reducing the crack width in the SHCC beam specimens is due to multiple fine cracks in this material. These results show that replacement of concrete by SHCC is effective for the initial crack tendency, reducing the restrained tensile stress and increasing the durability.

4. CONCLUSIONS

This study investigated the flexural performance and cracking behavior of RC and SHCC beams with high and normal strength reinforcing bars. For this purpose, four beams including a conventional RC beams were designed and tested. The results of the investigation can be summarized as follows.

(a) RC beam with high-strength reinforcing bar did not exercise sufficient strength. In contrast SHCC beam with high-strength reinforcing bar exercise sufficient strength.

(b) The conventional RC beams failed with a few wide cracks. For the SHCC beam, major cracks diffused into multiple fine cracks by material properties of SHCC.

(c) The present investigation shows the potential of high-strength structure materials used of high-strength reinforcing bars with SHCC.

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