Flexural Performance and Cracking Behavior of Expansive SHCC Beams

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SUMMARY:
Recently, demand of high-rise buildings and long span bridge is on the increase. Therefore structure materials are required to be more strength than before. In the case of RC structure used the high-strength reinforcing bars occur problem about earthquake resistance due to weakness ductility and brittle fracture. This paper describes a method to replace concrete with strain-hardening cement-based composite (SHCC) in order to mitigate cracking and improve the ductility of the reinforced concrete (RC) members. Specifically, this paper study the structural application of SHCC which mitigate crack damage and improve ductility in RC beam with high-strength reinforcing bars. The results of tests on four simply supported beams are described. Due to the effects of type of SHCC used and strength of reinforcing bars, crack width and numbers from first-crack load to ultimate flexural load and the load-deflection relationship of beams are investigated. The results indicate that considerable reduction in the crack width was observed for SHCC beam, and amount of increase strength of SHCC beam is bigger than concrete beam according to use of high-strength reinforcing bars. In used same strength reinforcing bars, SHCC increased the strain-hardening. It is concluded that the application of SHCC to RC members may prevents the penetration of aggressive substances into the cement-based composite or reinforcing bars and could improve the ductility of RC members.

Keywords: Strain-hardening cement composit, High strength steel bar, expansive admixture, crack mitigation

1. INTRODUCTION

Recently, growing interest in high-rise buildings and large scale structures has led to a marked increase of interest in high strength structural materials. Compared to more common materials, high strength materials have the advantage of smaller beam and column cross sections, better constructability, and reduced structural weight, thus making it possible to reduce construction time and cost. With this background, continuous research has been conducted on high strength reinforced concrete materials. In the case of reinforcing steel bars, high strength steel bars with yield strength greater than 700 MPa have been developed. The use of high strength steel bars has the advantage of requiring less material for construction and a reduced section, thus resulting in lower material costs and better constructability due to increased bar space. However, the use of high strength steel bars in structural elements has been limited. The design criteria of the Korean Concrete Institute (KCI), enacted in 2007, defines the yield strength of reinforcing steel bars as the stress level that gives a 0.0035 strain, and not exceeding 550 MPa. The design criteria of the United States and Europe also limit the yield strength of reinforcing bars as 550MPa and 600 MPa respectively. These criteria are based on concerns about safety and durability. With high strength reinforcing bars, the yield strain exceeds the ultimate strain of concrete, cracks may occur before the bars themselves reach their yield point, resulting in brittle fracturing of the concrete. As such, the high strength properties of the reinforcing bars may not be fully utilized. Moreover, in the case of beams and slabs under vertical load, excessive strains on the tension side may aggravate crack width, leading to durability issues such as corrosion.

Recently, much research is being conducted on cement composites with high tensile strength, ductility, and resistance to sudden brittle fractures. Strain-hardening Cement-based Composites (SHCC) made by mixing reinforcing fibers into existing cement composites have high crack mitigation properties, tensile strength, and ductility because of the bridge actions of the fibers. However, SHCCs may develop shrinkage because of the added fibers and such shrinkages lead to a reduction in strength. However, such shrinkages can be compensated by substituting part of the cement with an expansion additive.

This study aims to determine the issues of excessive cracks and brittle fractures found on concrete beams reinforced with high strength steel bars and evaluate the improved ductility and crack mitigation properties after replacing the concrete with expansive SHCC by performing bending tests on simple beams made of such materials.

2. EXPERIMENTAL PROGRAM

2.1 Test Specimen

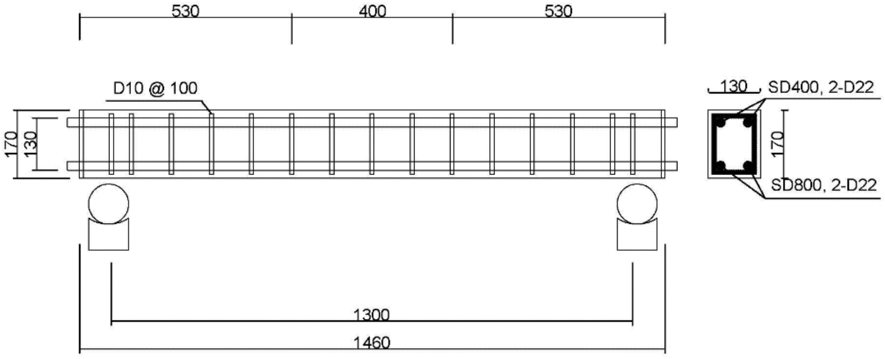


Figure 1. Specimen Configuration

To evaluate the ductility and crack mitigation properties of the expansive SHCC beam reinforced with high strength steel bars, structural beams with a 130 x 170mm section area and support distance of 1300mm were fabricated. The top compression side was reinforced with two(2) D22 deformed steel bars of 400 MPa yield strength. The lower tension side was reinforced with two(2) D22 deformed steel bars with a high yield strength at 800 MPa. Shear reinforcement was accomplished with deformed steel bars of D10 and 400 MPa yield strength, placed at 100mm intervals. The test was planned with the type of composite-concrete materials and the yield strength of reinforcing bars as the test variables. The list of test specimens is as shown on Table 1.

In this study, Polyethylene (PE) fiber manufactured by D of Japan was used as a reinforcing element, and domestically produced Calcium Sulfoaluminate (CSA) Type K was used as the expansive admixture. Table 2 shows the mixing formula for the SHCC. The water-binder ratio was 30%. Design compression strength was 70 MPa. The fiber mixing ratio was 1.5%. The expansive ingredient was 10%, as determined by a previous study. The properties of the PE fiber are as shown in Table 3.

Table 1. Specimen test matrix

Beam	Cross section (mm)	Length (mm)	Composit Types	Compressive strength (MPa)	Yeild Strength (MPa)
HTB-CON70	130×170	1460	Concrete	70	800
HTB-EXPE70			Expansive SHCC		
NTB-CON70			Concrete		400
NTB-EXPE70			Expansive SHCC		

Table 2. Mix proportions of concrete and SHCC

	Material (kg/m3)					Fiber Volume rate (%)	Super -plasticizer (kg/m3)	Methyl cellulose (kg/m3)
	Water	Cement	Sand	Aggregate	Expansive admixture			
Concrete	160	550	738	933	-	-	-	-
Expansive SHCC	384	1096	512	-	122	1.5	13	0.52

Table 3. Properties of PE fiber

Fiber	Specific gravity (kg/m^3)	Length (mm)	Diamiter (μm)	Aspect (l/d)	Tensile strength (MPa)	Elastic modulus (MPa)
PE	0.97	12	12	1	2,500	75

Table 4. Properties of expansive admixture

Mechanical property		Chemical composition(%)						
Specific gravity (kg/m3)	Fineness (cm2/g)	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	F-CaO
2.8	2,000	1	15	2	55	2	31	16

2.2 Test Procedure

To evaluate the mechanical properties of the steel bars, test specimens were made according to KS B 0801. Tests were performed according to KS B 0802 with a UTM with 200 KN capacity. To evaluate the properties of concrete and SHCC, test specimens were made for compression, bending and tensile testing. For the compression test, round specimens of Φ100 × 200mm were tested with a 200 KN capacity USM according to KS F 2405. Bending tests were performed by applying loads, using the displacement control method, at four(4) points on the 100 x 100 x 400 mm specimen with a 200 KN capacity USM. Displacement sensors were attached on both sides to measure the center deflection. Tensile strength tests were conducted according to the direct tensile test method of the Japanese Society of Civil Engineering, JSCE-E-531. The test piece was loaded at a rate of 0.5 mm per minute using the displacement control method and SDT's were attached on both sides to determine the center deformation.

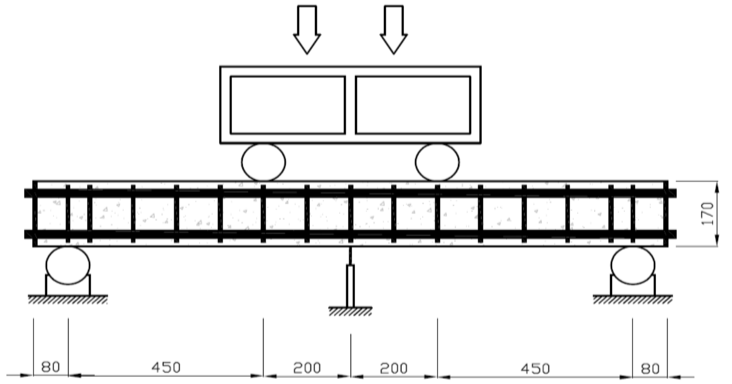


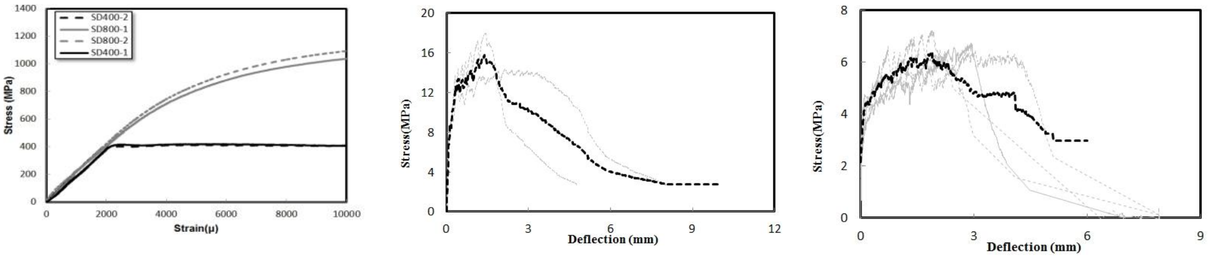
Figure 2. Details of the test

To evaluate the bending properties of a simple beam made of composite-concrete reinforced with high strength steel bars, a 500KN capacity actuator fixed to a reaction frame was used to load the beam at a rate of 0.2mm per minute using the displacement control method. SDT's were installed at the center and underside of the load points to measure the deflection. Testing continued until deflection reached 80 mm, the limit for this test. The center area of the beam spanning 800mm was inspected with a microscope, and the number of cracks and width at each load level was recorded. The details of the test beam installation are as shown in Figure 2.

3. MATERIALS TEST RESULTS

3.1 Reinforcing Steel Bars

To evaluate the performance of steel bars as a tension element, tensile strength tests were performed with normal strength steel bars of 400 MPa yield strength and high strength steel bars of 800 MPa yield strength. Test results are as shown on Figure 3. While the SD400 specimens had a clear yield point at 401.13 MPa, on average the SD800 specimens did not seem to have a clear yield point at all. Hence, the yield point was deduced from the load at the 0.2% offset point as suggested by KS B 0802, giving an average value of 772.14 MPa.



(a) Stress-strain relationship of steel

(b) Flexural behavior of expansive SHCC

(c) Direct tensile behavior of expansive SHCC

Figure 3. Mechanical properties of materials

3.2 Cement Composite

To evaluate the material properties of concrete and expansive SHCC, compression, tension and bending tests were performed. Average compression strengths were 63.1 MPa and 78.48 MPa respectively, demonstrating that SHCC has higher strength. Figures 3(b) & (c) show the results of the tensile strength tests of SHCC, where each test specimen shows similar ductile behavior due to the bridge action of the fibers added in the cement composites. Average bending strength was 15.52 MPa and average tensile strength was 6.11 MPa, tested with 3 and 5 specimens respectively.

4. TEST RESULTS

4.1 Load-deflection curves

Tests were conducted in order to evaluate the bending properties of the test beams. The measured load-deflection results are shown in Figure 4. The modulus of elasticity of the test beams, as deduced from the slope of the load-deflection curves, is about the same. As compared to the NTB-CON70 beam, the NTB-EXPE70 beam showed similar overall strength. However, it has a much higher deflection limit, demonstrating greatly improved ductility.

The HTB-EXPE70 test beam was 1.47 times stronger than the HTB-CON70 beam. The limit deflection was 2.84 times that of HTB-CON70. For the HTB-CON70, the yield strain of the reinforcing bars exceeds the ultimate strain of the concrete material. As the limiting load was applied to the beam, a sudden crack fracture occurred in the concrete before the reinforcing bar yielded. As a result, the high tensile properties of the reinforcing bars could not been fully utilized. On the other hand, with the HTB-EXPE70, the higher ductility of SHCC combined with the crack dispersion properties have a strain relieving effect and thus the high tensile properties of the reinforcing bars have been fully demonstrated. While the load capacity capacity of the HTB-CON70 beam has been improved by 1.26 times over the NTB-CON70 beam, the HTB-EXPE70 beam has been improved by 1.88 times over the HTB-CON70. These results indicate that the higher tensile properties of expansive SHCC, as compared to concrete, has improved the load bearing and deflection capacities of the beam.

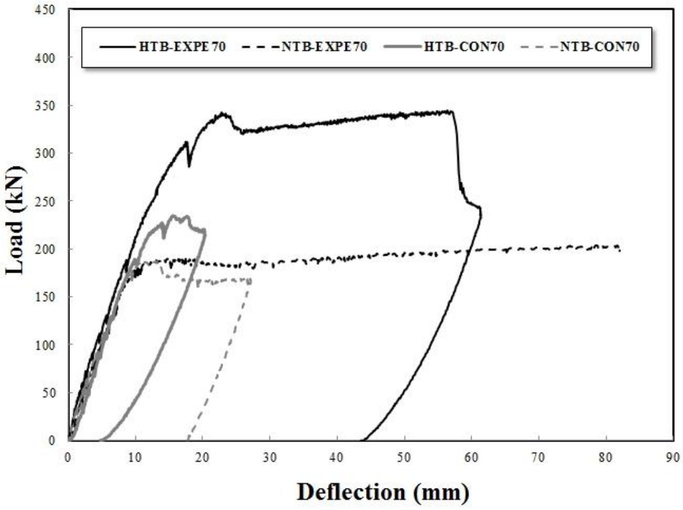
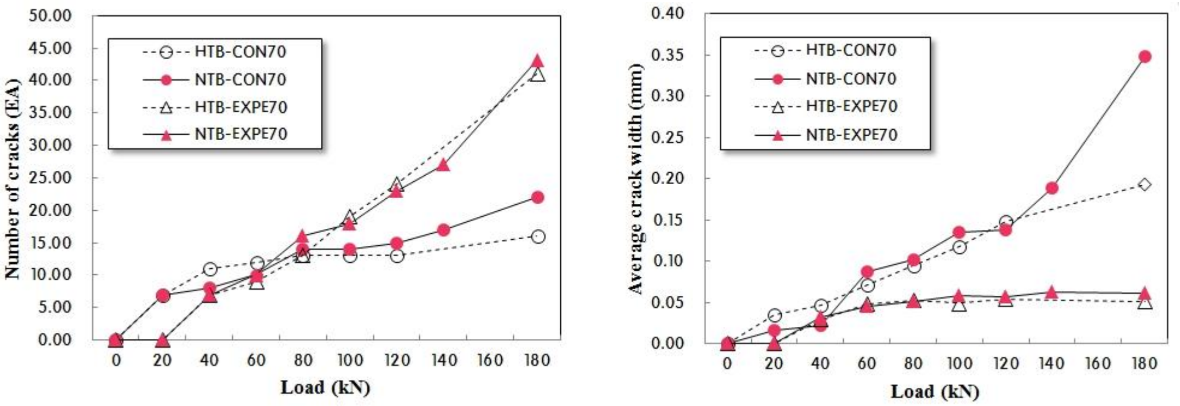


Figure 4. Load - deflection relationship

Figure 5. Failure behavior of beams

4.2 Evaluation of crack Behavior

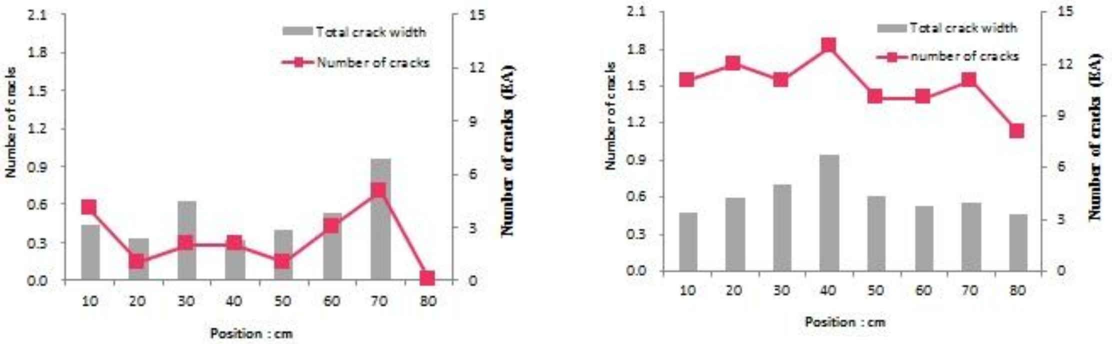
The number and width of cracks on the tension side were measured and recorded by inspecting the center region of the concrete beams spanning 800mme with a microscope. Figures 6(a) & (b) show the average number and width of the cracks that developed under various loads. As can be seen on Figure 6(a), the number of cracks in the HTB-CON70 beam has stopped increasing as the load increased over 40KN. The cracks in the NTB-CON70 beam also stopped increasing in number with loads over 60 KN. However, with the HTB-EXPE70 and NTB-EXPE70 beams, the number of cracks tends to increase with heavier loads due to the bridge action of the fibers and the consequent crack dispersion effect.



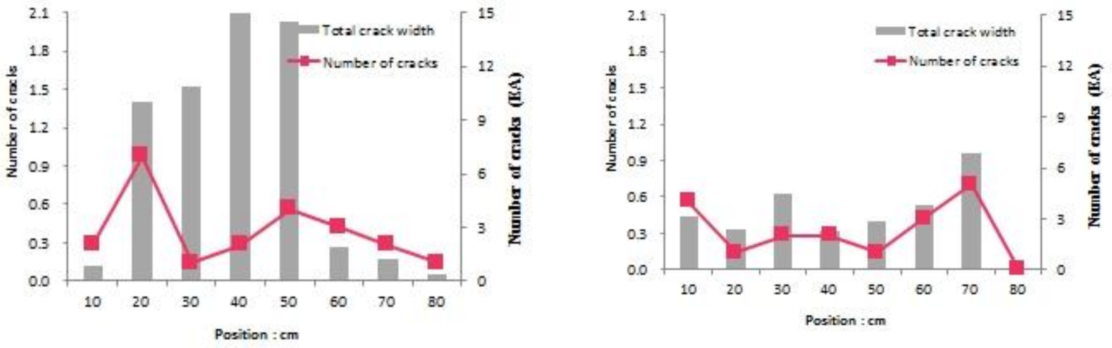
(a) Number of cracks (b) Average crack width

Figure 6. Load - deflection curve

As shown in Figure 6(b), for the HTB-CON70 and NTB-CON70 beams, the average width of the cracks tends to increase gradually as the load increase. The NTB-CON70 beam, contrary to the HTB-CON70 beam, displayed abrupt increases in crack width for loads over 120 KN. It has been postulated that the normal strength reinforcing steel bars in the NTB-CON70 beam, having half the yield strength of the steel bars used in HTB-CON70 beam, reached their yield points earlier as the steel bars used for both beams were identical in size.

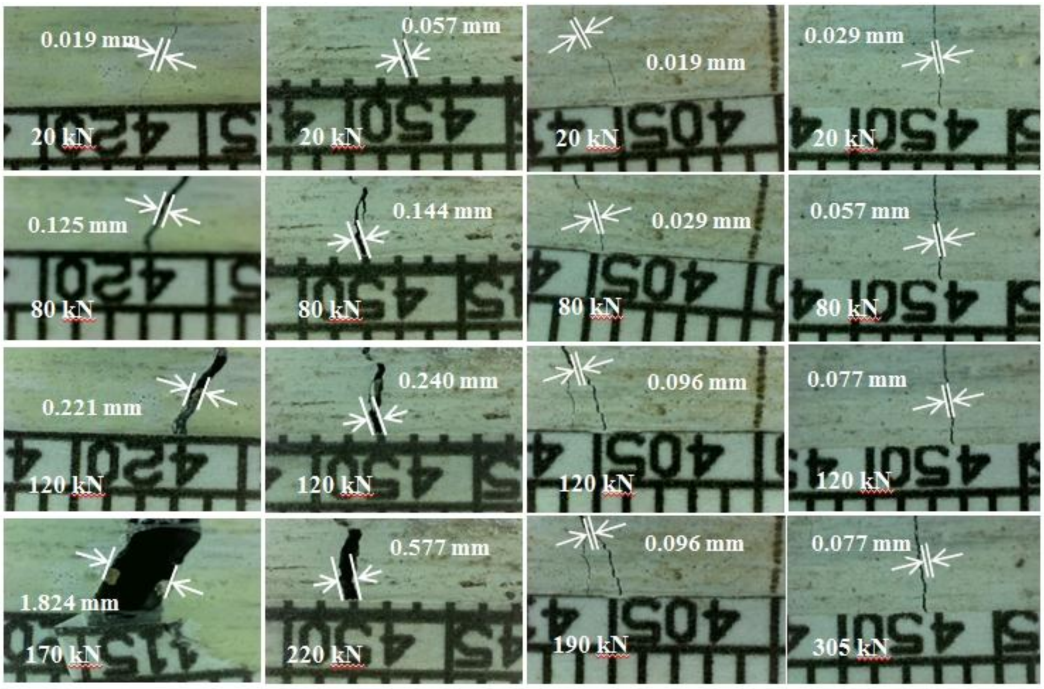


(a) HTB-CON 70 (b) HTB-EXPE 70



(c) NTB-CON 70 (d) NTB-EXPE 70

Figure 7. Crack distribution of beams at yielding load



(a) NTB-CON70 (b) HTB-CON70 (c) NTB-EXPE70 (d) hTB-EXPE70

Figure 8. First crack propergation

For the HTB-EXPE70 and NTB-EXPE70 beams, average crack width remained more or less the same when the load had been increased over 60 KN. Thus, the type of concrete has little effect on the number of cracks, but the resulting width increase can lead to a variety of issues such as the corrosion of the reinforcing steel bars and neutralization of the concrete as the structure becomes exposed to weather. The SHCC beam has shown that the crack width remained about the same while the number of fine cracks increased with the increased load, thus being more resistant to weather.

Figure 7 shows the number of cracks and the total width of cracks at various positions. As shown in Figures 7(a), (b), (c) & (d), the total width of the cracks are about the same for both common concrete and SHCC beams, However, the SHCC beam shows a greater number of cracks, which may be interpreted as SHCC having superior crack dispersion properties.

5. CONCLUSIONS

An experiment was conducted to evaluate the crack mitigation properties of the SHCC beam. By assessing the load-deflection curves and comparing the crack widths and numbers, the following conclusions were obtained.

1) When the same reinforcing steel bars were used, the expansive SHCC beam displayed greater bending strength over the concrete beam due to the improved tensile characteristics of the SHCC. Thus, when using high strength steel, SHCC will be more effective than concrete in that it can better utilize the higher yield strain characteristics of the high strength steel.
2) For the concrete beam, crack widths increased continuously with load increases while the number of cracks remained about the same. However, for the SHCC beam, crack widths remained about the same while the crack numbers increased with the load. These results show that the expansive SHCC has excellent crack dispersion properties compared to concrete.
3) Near the yield point, the concrete beam showed crack concentrations and the average crack width increased. On the other hand, the SHCC beam developed numerous fine cracks. Hence, by incorporating expansive SHCC in structural elements, structural durability may be improved due to the crack dispersion effect.

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