

Crack width control of reinforced concrete one-way slabs utilizing expansive strain-hardening cement-based composites (SHCCs)

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ABSTRACT: In this paper, the method to replace part of the concrete at the tensile bottom of one-way slabs with expansive SHCC has been used to improve cracking behavior and durability of RC members. This paper explores the structural application of an expansive SHCC and the results of test on five simply supported slabs are described. The effect of expansive admixture and thickness of SHCC layer (20 and 40mm) on the ultimate flexural load, first crack load, crack width and spacing, and the load-deflection relationship of one-way slabs was investigated. The results indicate that the use of SHCC cover at the bottom of slabs has significantly increased the initial crack load, yield load, and ultimate load, while the use of expansive admixture in SHCC material had little effect on those of one-way slabs with a SHCC layer. Considerable reduction in crack width and spacing was observed for slabs with a SHCC layer and this tendency is remarkable for slabs with an expansive SHCC layer and thicker SHCC layer.

1 INTRODUCTION

1.1 Background

Plain concrete is weak in tension but an effective and strong material in compression. Reinforcement is an essential element in reinforced concrete (RC) structures overcoming the low tensile strength of concrete by carrying the tensile stress. Nevertheless, cracks in RC structures occur during concrete's hardening or due to environmental effects after concrete's solidifying. Cracking on the extreme of RC members is one of the main factors influencing the durability of RC members because surface cracks can permit chemical reaction to generate the oxidation of reinforcement surface. Therefore, crack control is essential to control the corrosion of reinforcement bars.

Strain-hardening cement-based composite (SHCC) is a new class of fiber-reinforced cement composite (FRCC) and composite material consisting of cement paste, silica sand, fly ash, and short random fibers. The SHCC exhibits a pseudo strain-hardening behavior accompanied by multiple cracking in uniaxial tension. The multiple cracking characteristics of SHCC enhance the impermeability and durability of this new material. However, such rich

mix material has already been known to shrink significantly at early ages, which is likely to be caused mainly by autogenous shrinkage. At the stage of SHCC's hardening, autogenous shrinkage leads to cracks which deteriorates the durability and cracking behavior of SHCC material.

1.2 Objective

This paper explores the structural application of an expansive SHCC to improve the crack-damage behavior of RC flexural member. The results of test on ten simply supported slabs are described. The effect of the type of SHCC (PE1.5 and PVA1.8) and thickness of SHCC layer (20 and 40mm) on the ultimate flexural load, first crack load, crack width and spacing, and the load-deflection relationship of one-way slabs was investigated.

2 EXPERIMENTAL PROGRAM

2.1 Specimen manufacture

This experimental program's two parameters are: the type of SHCC (with or without expansive admixture) and the layer thickness (20 and 40mm) of the

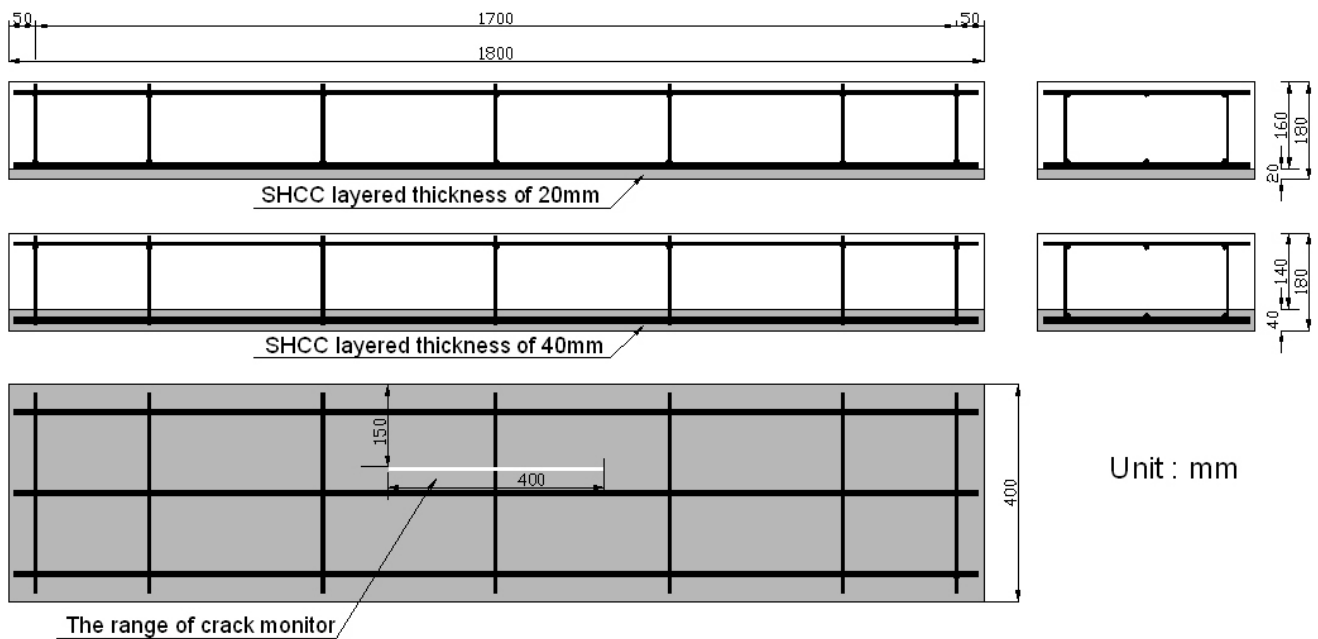


Figure 1. Section and reinforcement details of slabs.

SHCC. The main part of the experimental program uses eight RC slabs: a Control RC slab, four RC slabs with different layer thicknesses for two normal SHCCs, and three RC slabs with different layer thicknesses for an expansive SHCC. Each slab had an overall depth of 180 mm, width of 400 mm, and length of 1,800 mm. The slabs were composed of RC substrate and SHCC layers, except for the Control slab.

Cross-sectional dimensions and the reinforcement arrangement of the slabs are given in Figure 1, and an overview of the experimental specimens is given in Table 1.

The Control RC slab, i.e. RC-S, was designed with 30 MPa compressive strength concrete and 400 MPa yield strength steel. The longitudinal reinforcement in both tension and compression consisted of three deformed bars 16 mm in diameter, corresponding to a reinforcement ratio of 0.01, respectively. Shear reinforcement was arranged to insure the flexural failure of the RC slabs. The transverse reinforcement consisted of deformed bars 10 mm in diameter at 250 mm centers.

For the two RC slabs (NS-20 and NS-40), layers of high strength SHCC with PE fibers, 20 mm and 40 mm thick, respectively, were substituted for the concrete surrounding the main flexural reinforcement, as shown in Figure 1. The specified compressive strengths of SHCC specimens were 60 MPa. The dimensions and reinforcement configuration of the SHCC-layered slabs are the same as those of the Control slab, RC-S.

It is generally known that rich mixtures shrink significantly in the early stages due to autogenous

shrinkage. This autogenous shrinkage leads to cracks that may exacerbate the cracking behavior and decrease the structural performance of the SHCC material. In the present investigation, an expansive SHCC has been developed to reduce shrinkage cracks in high strength SHCC using a high volume of cement. For the two slab specimens (ES-20 and ES-40), a layer of expansive SHCC was placed on the bottom of each slab to investigate the effect of expansive SHCC on the initial crack strength and crack damage mitigation of SHCC-layered slabs. Each specimen had a different SHCC layer thickness (20 and 40 mm).

2.2 Materials

All the mix proportions use the dry weight of the ingredients. The plain concrete mixtures include 15 mm maximum-size coarse aggregate and fine sand aggregate, ordinary Portland cement, two kinds of high range water-reducing admixture, and water. The common materials used in the SHCC mixtures are ordinary Portland cement, silica sand with maximum grain sizes of 200 μm and specific gravity of 2.60 g/cm^3 , water, a high range water-reducing admixture, and a dry viscosity agent that enhances the workability of the mixed materials, avoids material segregation, and improves the fiber distribution during mixing. In addition, high-density polyethylene (PE) fibers and an expansive additive, which is ettringite and calcium hydrate combined formation type, and a specific gravity of 3.05 g/cm^3 , were used for the expansive SHCC. High strength SHCC specimens were reinforced with PE fibers.

PE fibers, with a diameter of 12 μm and length of 12 mm, were manufactured with a tensile strength of 2,600 MPa and an elastic modulus of 88 GPa.

The SHCC mixtures were prepared in an Omni mortar mixer because the relatively high mixing effort imparted by this type of mixer facilitates the dispersion of small diameter PE synthetic fibers. The dry ingredients, i.e., the cement, silica sand, dry viscosity agent, and synthetic fibers, were mixed first until a homogeneous mixture was reached (based on color and visual appearance). This step was followed by the addition of water and the high range water-reducing admixture, with a mixing time of three minutes.

Three dumbbell-shaped specimens were prepared from each mixture, as shown in Figure 2. The tested section length was 100 mm and the cross-section was 30 x 30 mm. All tensile specimens were demolded 24 hours after casting. After demolding, they were air-cured at 74°F at 65% relative humidity for four weeks.

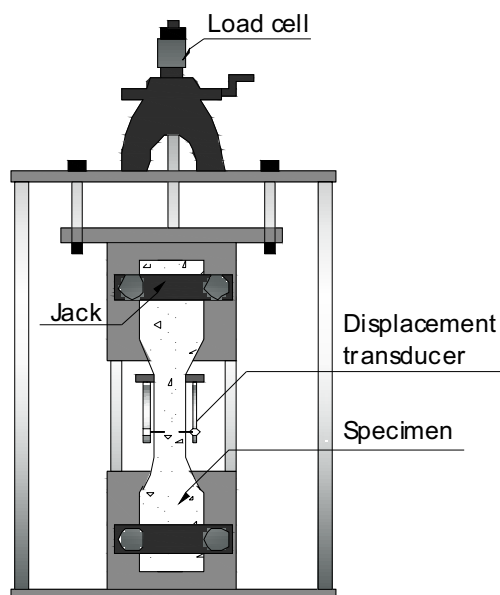


Figure 2. Set-up and specimen for the direct tension test.

2.3 Testing method

To evaluate the tensile performance of each SHCC specimen, direct tension tests were conducted according to Japan Society of Engineers recommendations (*cf.* chunking mechanism using clamp jigs) (Japan Society of Civil Engineers 2008). The direct tensile loading apparatus is shown in Figure 2. Two identical loading fixtures were used: one hinged chuck was connected to the loading bar from a hand-cranked loading jack placed on the steel frame; one fixed chuck was mounted on the bottom base of the steel frame. The upper fixture was pulled by the load along the two guide pins. Tensile loads were introduced to the tensile specimens along the central axis via the pulling action of the upper fixture. The applied tensile load was measured using a load cell with a capacity of 100 kN installed in the upper part of the loading device. Two linear variable differential transducers (LVDTs) were mounted on the two sides of the specimen for deformation measurement as well as test control. The displacement of the central 100 mm region of the dumbbell-shaped specimen was measured by means of two LVDTs, and the tensile strain was calculated by dividing this measured displacement by the reference length of 100 mm. LVDT holders were specially designed to allow easy adjustment of centering and offsetting for the LVDT transducers. The displacement rate was 0.25 mm/minute.

All slabs were tested as simply supported slabs under four-point loading with a net span of 1,700 mm and shear span of 750 mm. Bending tests were displacement-controlled by imposing an average displacement under the two loading points, as shown in Figure 3. The controlled displacement rate was 0.4 mm/minute. Slabs were tested in a testing system that uses a 500 kN capacity loading frame. During flexural testing, the deformations under the two loading points and rotations at both ends of the slabs were measured using two LVDTs. Crack formations were visually observed, and at specified and yield

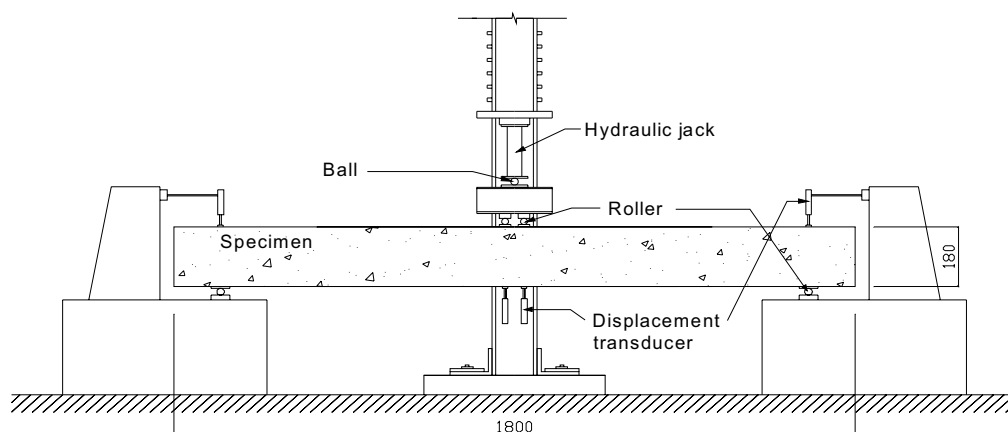


Figure 3. Set-up for the four-point bending test of RC one-way slabs.

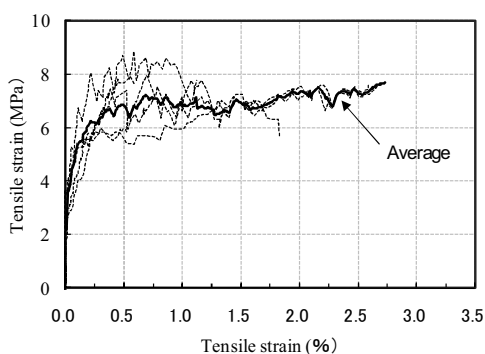
loads, the crack number and width were microscopically measured over a 400 mm central zone of the slab's tensile face. Deflections under the point loads and the rotation at both ends of slab were recorded during testing.

3 EXPERIMENTAL RESULTS

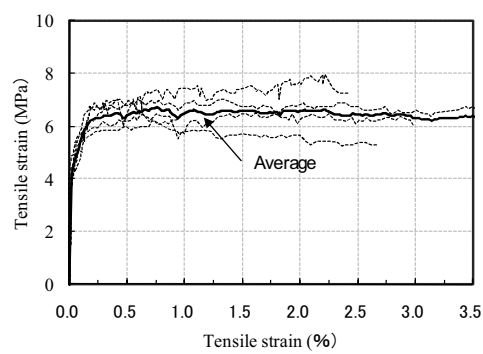
3.1 Mechanical properties of SHCC

Figure 4 provides the uniaxial tension test results from five dumbbell-shaped SHCC specimens. Most of the tensile specimens show a similar trend to each other. An elastic response is observed up to the first crack load of the SHCC. After the first crack, the tensile stress increases with an increase in the strain;

thus, multiple cracks develop up to the peak stress. A major crack is generally observed when the tensile stress reaches the peak stress. Beyond the peak stress, the tensile stress drops gradually due to some of the fibers pulling out from the matrix or breaking near the major crack. The high strength SHCC (SHCC-PE) with 1.5% PE fibers shows average first-crack and tensile strengths of 2.77 and 7.99 MPa, respectively. The average strain capacity is 1.43%. Figure 4b shows the tensile response of the expansive SHCC (Ex-SHCC-PE), which has an expansive additive replacement of 8% in terms of the volume of cement. This Ex-SHCC-PE material shows higher first-crack strength and less strain capacity than the SHCC-PE without the expansive admixture replacement. The expansive admixture with-

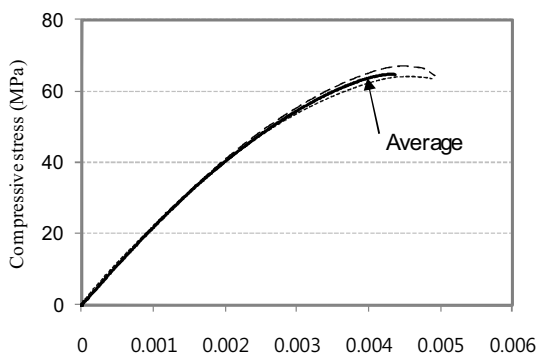


(a) SHCC-PE

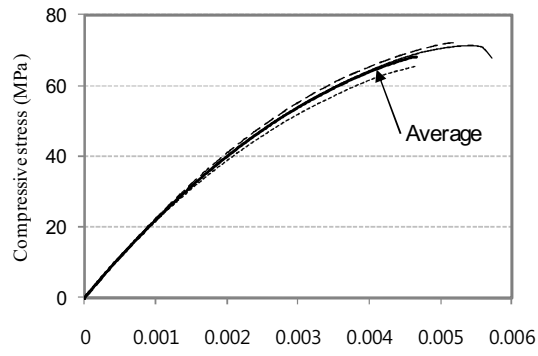


(b) Ex-SHCC-PE

Figure 4. Direct tensile behavior of SHCC materials.

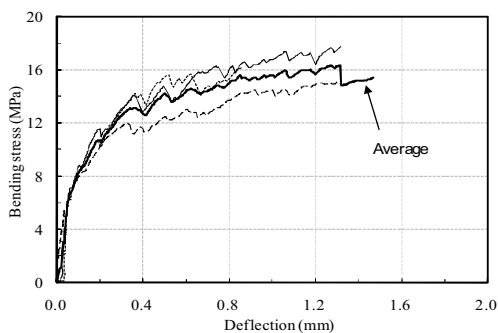


(a) SHCC-PE

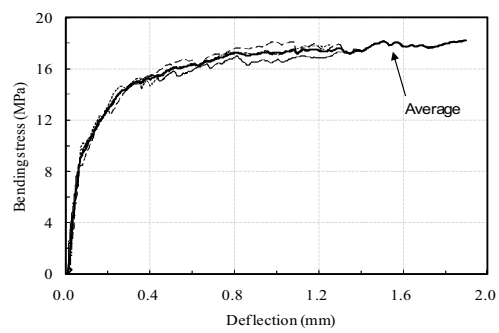


(b) Ex-SHCC-PE

Figure 5. Compressive responses of SHCC materials.



(a) SHCC-PE



(b) Ex-SHCC-PE

Figure 6. Flexural behavior of SHCC materials.

in 8% appears to have had little effect on the cracking pattern of the high strength SHCC. The compressive stress versus strain responses of the high strength SHCC specimens are shown in Figure 5. The peak strength and corresponding strain in the SHCC specimens are clearly greater than those in the concrete specimens. The expansive admixture additions result in an increase in compressive strain at peak strength, as shown in Figure 5.

The static modulus of elasticity of the SHCC specimens increases with an increase in compressive strength, like the conventional cement-based composites.

Figure 6 presents the flexural stress versus mid-span deflection curves of SHCC prisms. For conventional concrete, an abrupt drop occurs soon after the first crack load. The maximum load and flexural strength are at the first crack. However, SHCC materials show a ductile post-cracking behavior after the first crack load. The typical bending responses of the SHCC specimens are similar to their tensile responses. An elastic response is observed up to the first crack load. Then the bending stress increases with an increase in the mid-span deflection; thus multiple cracks develop at the bottom surface of the prism up to the modulus of rupture, where a major crack is observed. The ultimate flexural stress increases about 3.9 - 4.9 times in comparison with that of the conventional concrete. The flexural strength of the Ex-SHCC-PE material is 1.08 times larger than that of the SHCC-PE materials.

3.2 Flexural behavior of RC one-way slabs

The load versus mid-span deflection curves for the

RC substrate and SHCC layer composite slabs are shown in Figures 7a and b. For comparison, the load versus deflection curve of a conventional RC one-way slab is given in the two figures. Based on the bending test results, Table 1 shows a comparison of the flexural performance of the one-way slabs. From a comparison with a comparable conventional RC slab, the addition of the SHCC layer at the bottom of the RC slab increases both the initial crack load and the flexural stiffness after the crack load, as shown in Figure 8.

Investigating the complete flexural load versus deflection curves of the slab specimens, significant differences between conventional RC slabs and SHCC-layered slabs can be noted. It is clear that the initial crack load increases significantly by layering the SHCC materials at the bottom of one-way slabs. This phenomenon is noted also for SHCC-layered slabs with a smaller layer thickness. No significant difference is evident among the deformation capacities, defined as the mid-span deflection at the peak load of the slab specimens, of all the specimens. This finding is in contrast to previous test results for the plain concrete prism (Zhang et al. 2006, Leung et al. 2007, Shin et al. 2007, Yun & Rokugo, 2008) and consistent with the results for the ECC-layered RC beam observed by Maalej & Li (1995). The results presented in Table 1 indicate that SHCC-layered slabs exhibit a small increase in the ultimate load as compared to conventional RC slabs.

Based on these results, it may be concluded that the addition of a SHCC layer can improve the initial cracking and flexural strength of a RC one-way slab. Specifically, the addition of an expansive SHCC layer can result in a significant improvement for the

Table 1. Comparison on the flexural performance of RC one-way slab specimens.

Specimen	Initial crack		Yielding		Ultimate		Increase percentage*	
	Load	Deflection	Load	Deflection	Load	Deflection		
	kN	mm	kN	mm	kN	mm	%	
RC-S	15	0.20	86	4.11	90	14.13	0	
NS-20	30	0.46	101	4.66	105	10.75	100	
ES-20	32	0.48	101	3.90	102	4.56	113	
NS-40	22	0.36	109	4.46	116	13.40	47	
ES-40	27	0.49	102	6.82	102	7.61	80	

* The percentage of initial cracking strength increase compared to conventional RC slab.

Table 2. Cracking behaviors of RC one-way slab specimens.

Specimen	Load stage		50kN		75kN		Yielding				
	No. of cracks	Average crack width	No. of cracks	Average crack width	No. of cracks	Average crack width	No. of cracks	Average crack width	Maximum crack width		
										25kN	
										ea	mm
RC-S	5	0.013	9	0.021	10	0.072	10	0.183	1.36		
NS-20	4	0.011	8	0.021	18	0.024	49	0.028	0.33		
ES-20	0	0.000	1	0.015	11	0.017	54	0.022	0.16		
NS-40	7	0.016	11	0.020	19	0.024	35	0.028	0.12		
ES-40	0	0.000	4	0.018	10	0.027	15	0.028	0.18		

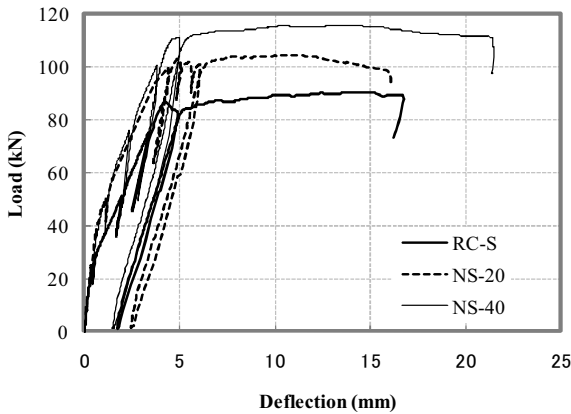
capacity of a pavement to resist initial cracking.

3.3 Cracking behavior of RC one-way slabs

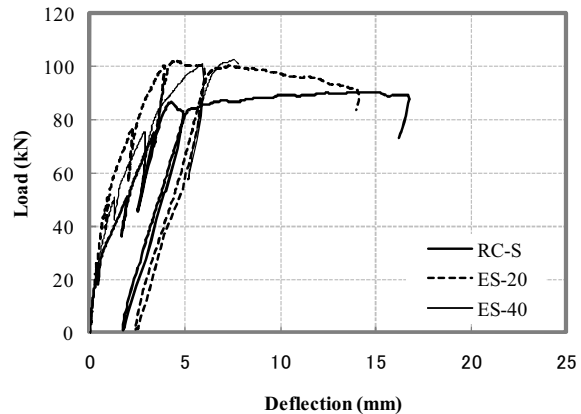
A photo microscope equipped with a 50x lens and a monitor/computer were used to monitor the development and width variation of cracks that developed over a 400 mm center length at the tensile face of the

bottom slab during loading.

Table 2 contains information on the cracking behavior of conventional and SHCC-layered one-way slabs, and gives data on the number of cracks and average width of cracks at predefined loading stages, i.e. 25, 50, 75 kN, and the yielding load. The effect of a layer of SHCC on crack mitigation is clear from Table 2. The SHCC-layered slabs show superior

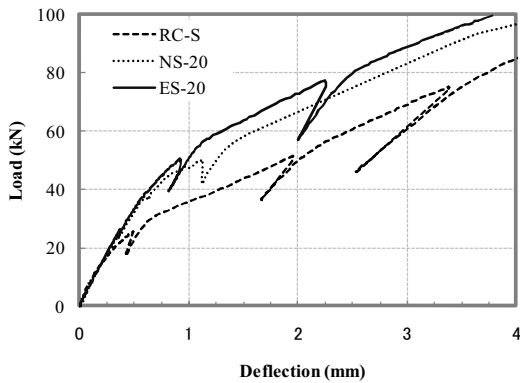


(a) RC slabs layered with SHCC-PE material

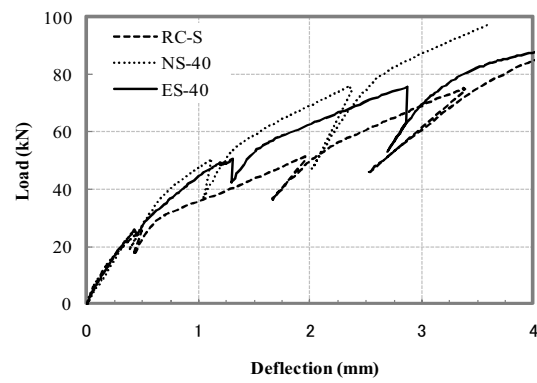


(b) RC slabs layered with Ex-SHCC-PE material

Figure 7. Responses of RC one-way slab specimens.

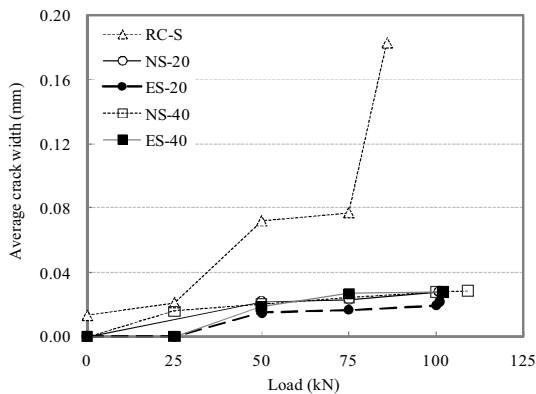


(a) RC slabs layered with layer thickness of 20mm

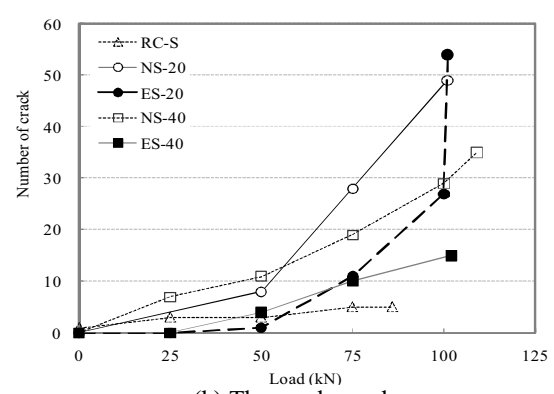


(b) RC slabs layered with layer thickness of 40mm

Figure 8. Initial behaviors of RC one-way slab specimens.



(a) The average crack width



(b) The crack number

Figure 9. Variation of average crack width of slab specimens as function of load.

cracking resistance, with finer and a higher number of cracks than the conventional RC slab.

Table 2 respectively provide information regarding the maximum widths of cracks at the yield load and the average widths and number of cracks for the ES series slabs at predetermined loading stages. The RC slabs with a layer of expansive SHCC show finer cracks than the NS series slabs. In particular, this phenomenon is noteworthy for the initial loading stage and the RC slab with a thin SHCC layer, as shown in Figure 9a and b. Figure 10 shows three series of pictures illustrating the crack width increase as a function of loading for the Control RC slab, NS-40 and ES-40 specimens.

The sheet scale in the upper part of Figure 10 is a reference for checking the position of the cracks. These series of pictures indicate a significant difference in the cracking behavior of the three specimens. From Figure 10, it can be concluded that the crack width in the SHCC layer maintains a low value because of the appearance of multiple fine cracks in the SHCC material. These multiple cracks accommodate further imposed deformation as soon as they form. An expansive admixture reduces the autogenous shrinkage and restraining stress in the high strength SHCC. From these results, it is shown that expansive SHCC is effective for reducing the initial crack tendency, reducing the restrained tensile

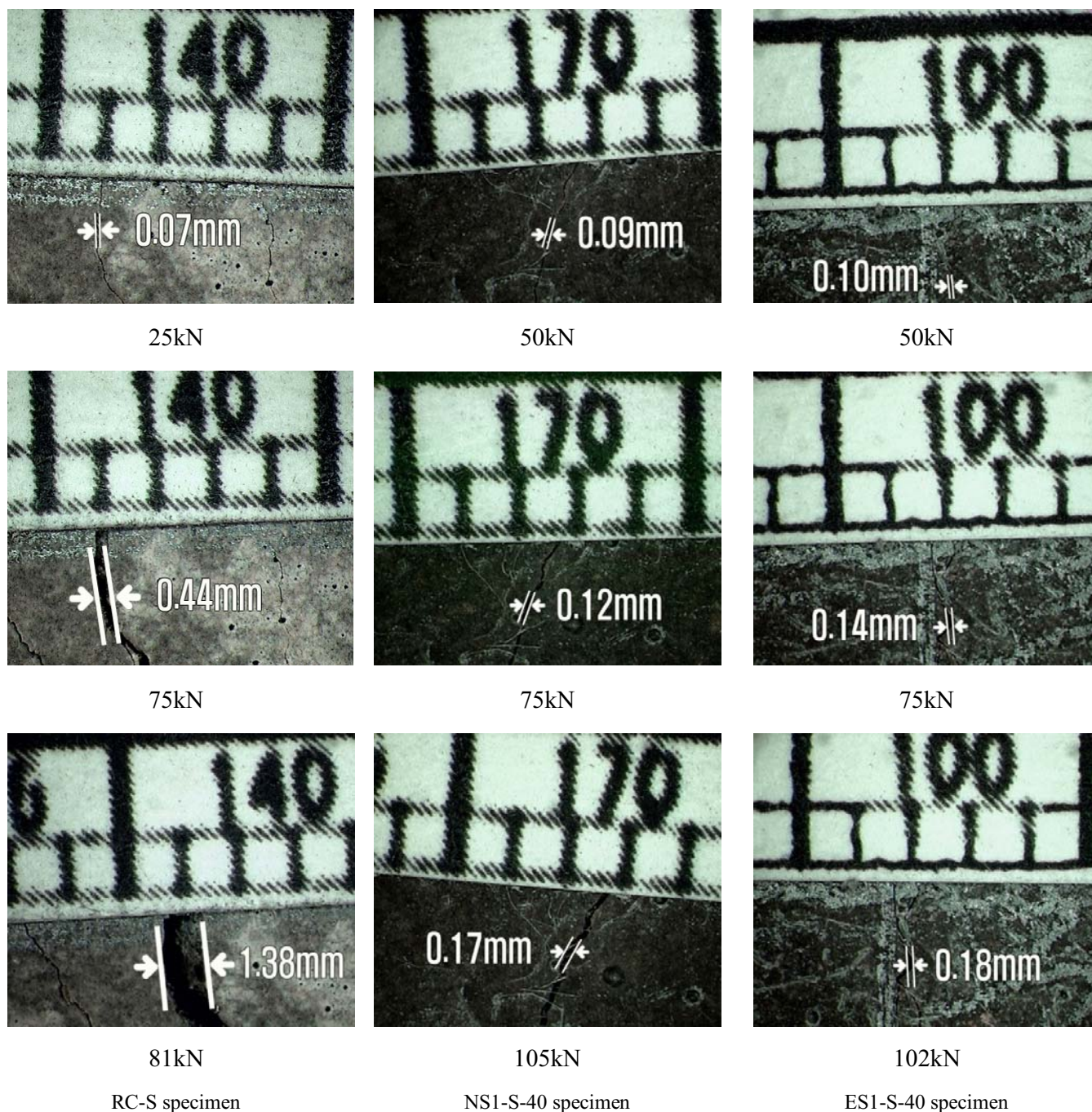


Figure 10. Variation of crack width of RC and SHCC-layered slabs as function of load.

stress, and increasing the initial crack strength.

4 CONCLUSION

This study investigates the flexural performance and cracking behavior of RC one-way slabs layered with different types and thicknesses of SHCC. For this purpose, eight one-way SHCC-layered RC slabs, including a Control RC slab, were designed and tested. To examine the effect of a layer of SHCC on the tensile face and the flexural and cracking behavior of one-way RC slabs, different types and layer thicknesses of SHCC were applied to the tensile region of RC slabs.

The replacement of 8% expansive admixture in volume of cement increases the first tensile crack and the compressive and flexural strengths of high strength SHCC material compared to a high strength SHCC material without an expansive admixture, whereas the tensile strength and strain capacity decrease. The addition of an expansive admixture appears to have little effect on the cracking pattern of high strength SHCC under direct tensile and flexural loading.

From the bending tests of SHCC-layered RC slabs, it is found that the application of a layer of SHCC at the bottom of one-way RC slabs increases flexural strength and stiffness. The improvement of the flexural performance increases according to the layer thickness and tensile performance of the SHCC applied. Specifically, RC slabs with a layer of expansive SHCC show higher initial crack strength and flexural stiffness after initial cracking compared to the Control high strength SHCC-layered slabs. The high ductility and multiple cracking capacity of SHCC are responsible for such a performance improvement. But the flexural performance improvement of SHCC-layered RC members is less dramatic than the strengthening effect of SHCC applied to plain concrete members, as reported by previous researchers.

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