Performance of Strain hardening cementitious composite as strengthening and protective overlay in flexural members

Sardar Umer Sial¹ and M. Iqbal Khan^{2,*}

¹Graduate Student, Department of Civil Engineering, King Saud University, Riyadh, Saudi Arabia

²Professor, Department of Civil Engineering, King Saud University, Riyadh, Saudi Arabia

Abstract. Strain-hardening cementitious composites (SHCC) are advanced type of cement-based composite materials having superior crack control and tensile properties. Owing to such characteristics, SHCC can be used for strengthening and crack-width control of structural members. This paper presents a study on the flexural response of reinforced concrete (RC) beams with different overlays of SHCC. The work consists of RC-SHCC overlay beams, in which SHCC overlays of different thicknesses (15% and 30% of beam height, plus cover) and reinforcement ratios (0% and 0.4%) were cast at the bottom of the RC beams. The performance of the RC-SHCC overlay beams was compared with control RC beams having concrete overlays of similar parameters. A series of eight laboratory-scale control and composite beam specimens were tested under four-point bending test. From the experimental results, it was observed that RC-SHCC overlay beams showed improved flexural capacity and crack control as compared to that of control beams. The beams with unreinforced SHCC overlays showed significant improvement at service stage, while beams with reinforced SHCC overlays showed significant improvement at peak stage. The SHCC overlay beams without reinforcement have showed improved ductility as compared to control beams with concrete overlays. Additionally, the SHCC overlays performed as a protective layer for controlling the crack widths in the composite beams.

1 Introduction

Strengthening of existing structural members is an inevitable process in today's construction sector. The cost for strengthening activities of under-designed and deteriorated structures becomes hefty. Flexural elements are one example for strengthening applications. One of the most common techniques of beam strengthening is to increase the section depth by overlaying a cement-based material layer at the bottom region. The aim of overlaying is not only to increase the flexural strength, but also to prevent further deterioration of the structural health of the beam. The selection of the overlay material is critical in achieving an improved structural response of the beam. Utilization of a composite material with improved tensile strength, fracture toughness and crack control can be an efficient alternative of concrete for overlaying strengthening techniques. In recent years, new composite materials have been developed called strain hardening cementitious composites (SHCC) with unique strength, ductility and crack control properties under tension [1]. SHCC is designed using micro-mechanical principles based on fiber, matrix and their interfacial interaction [2-4]. Localized failure in SHCC can be avoided through improved fiber bridging response at the crack, resulting in the multiple cracking behavior under tension. With a moderate fiber volume fraction of 2.0%, SHCC can exhibit an ultimate strain capacity exceeding 3% with characterized strain hardening response [2, 5]. Also, some studies are done on the durability of SHCC with respect to crack-width control [6, 7].

The utilization of SHCC overlays for the strengthening of flexural members can be an effective repair solution. Not only because of its load carrying capacity, but because of SHCC material's better crack width control, it is expected to improve the durability of the strengthened beam by controlling the crack widths in the tensile region [8-9]. In one study [10], flexure performance of reinforced concrete (RC) beams strengthened with ultra-high performance UHP-SHCC and mortar overlays (thick. 25% of section height) was evaluated. It was found that the use of UHP-SHCC overlay with a light reinforcement (0.6%) in RC beam has resulted in enhanced load capacity and reduced ductility when compared to these of beams strengthened with mortar. Similarly, flexural responses of UHP-SHCC and ordinary reinforced concrete overlays were also assessed in beam strengthening application and it was revealed that UHP-SHCC has significantly improved the load capacity of the strengthened beam [11]. From the available literature, it is realized that strengthening potential of SHCC overlay is not yet fully explored. Particularly, the effect of SHCC overlay thickness and overlay steel ratio on the flexural and cracking performance of strengthened beams needs an insight investigation. Therefore, the efficient technique of SHCC overlay beams to achieve an optimized performance was investigated and is presented as the main aim of the paper.

* Corresponding author: miqbal@ksu.edu.sa

2 Materials and methods

2.1 Material properties

The materials and mixture proportions of SHCC mix used for overlaying the beams are listed in Table 1. A mix design with water to binder (w/b) ratio of 0.26 was used for SHCC mix. The binder material consists of Type-1 Ordinary Portland cement (OPC) and Class-F fly ash (FA). The specific gravities of OPC and FA were 3.14 and 2.3 g/cm³, respectively. The Blaine fineness of OPC and FA were 373 and 450 m²/kg, respectively. The median grain sizes of OPC and FA were 14 µm and 10 µm, respectively. Sieved fine dune (silica) sand of median grain size of about 200 µm (passing sieve # 50) was used as a fine aggregate in SHCC mix to maintain adequate stiffness and volume stability. An optimized amount of modified polycarboxylic ether-based superplasticizer of specific gravity of 1.1 and dry extract of 36% was used in SHCC mix to ensure proper workability and uniform fiber dispersion. Polyvinyl alcoholic (PVA) fibers (2% by volume) were used in SHCC mix. The physio-mechanical properties of PVA fibers are given in Table 2. The materials and mixture proportions of concrete mix used in the substrate and overlay of the beams are presented in Table 3. Concrete with water-to-cement ratio of 0.5 was designed for a target 28-day cylinder compressive strength of 35 MPa. OPC, fine sand (2.63 g/cm³), crushed sand (2.68 g/cm³) and 10 mm coarse aggregate (2.65 g/cm³) were used in the concrete mix. An optimized amount of superplasticizer was used in the concrete mix to achieve a target slump of 180±20 mm.

Table 1: Mixture proportions of SHCC.

W/B	Unit weight (kg/m ³)				
	Cement	Fly ash	Dune Sand	Water	PVA Fiber*
0.26	555	666	466	315	2

* Fiber volume fraction

Table 2: Properties of Polyvinyl alcoholic (PVA) fibers.

Length (mm)	Diameter (µm)	Specific gravity (g/cm ³)	Tensile Strength (MPa)	Young's Modulus (GPa)	Elongation (%)
12	40	1.3	1600	42	7

Table 3: Mixture proportions of concrete.

W/C	Unit weight (kg/m ³)				
	Cement	Coarse Aggregate	Fine Sand	Crushed sand	Water
0.5	350	1070	488	262	175

2.2 Test setup

Standardized test setup specified in ASTM C39 was used for concrete cylinders (100 x 200 mm²) for determination of the 28-day compressive strength. For the tensile strength of SHCC, dumbbell-shape samples (24/40×40×240 mm³) were tested in a uniaxial tension test using a 30kN Instron's 3367 testing machine at a controlled test speed of 0.0025mm/sec, as shown in Figure 1(a). An extensometer was attached at the middle of the sample to measure the strain in a gauge length of 80 mm. The flexural strength of the SHCC was determined by testing prisms (75×75×300 mm³) in a three-point flexural test at a displacement rate of 0.2 mm/min as shown in Figure 1(b). A set of LVDTs was placed at the midpoint to measure the mid-span deflection of the prism.

(a) Tension Test

(b) Flexural Test

Fig. 1: Tensile and flexural test setup for SHCC samples.

2.3 Beam details

In this experimental work, laboratory-scale reinforced concrete (RC) beams overlaid with different SHCC thicknesses were cast for flexural testing. Schematic diagram of a beam specimen having a span of 1800 mm and cross section of 150mm wide and 230/260mm deep is shown in Figure 2. This size of the specimens is adequate for pure flexure behavior, fulfilling the condition of shear span to depth ratio ≥ 2 . Same reinforcement was provided in all specimens, i.e., two-φ16 mm steel re-bars at the bottom and two-φ8 mm steel re-bars at the top ending with a standard 90° hook. The stirrups (φ8 mm) were provided at a spacing of 100 mm in the shear spans to avoid the shear failure. Also, U-shaped shear connectors were provided at the interface of concrete and SHCC overlay to avoid interfacial failure. The variable in these specimens was the thickness of SHCC overlay and the overlay steel ratio. The cross-sections of the specimens are shown in Figure 3, where (a) sections are RC beams strengthened with concrete and SHCC overlays of thickness 60 mm (cover + 15% of beam depth) and 90 mm (cover + 30% of beam depth), respectively. Sections (b) are similar to the previous sections except for the additional steel rebars (2-φ8mm) were added to the overlay. Appropriate labels were assigned to beam specimens, where RC stands for reinforced concrete, C stands for control, SHCC stands for strain-hardening cementitious composite, O stands for overlay, R stands for overlay reinforcement and the

number stands for the thickness of overlay. The SHCC overlays started from the cover of the beams and the overlay thickness included 30mm of cover as it can be removed for the strengthening of existing beams. All the beam specimens were cast starting from the reverse side of the formwork. In the casting process, concrete was firstly placed in the inverted steel cage to the required level in the formwork. After initial setting of concrete, concrete surface was roughened with a wire brush to achieve a proper bond between substrate and overlay. Fresh SHCC overlay was secondly laid over the existed concrete substrate. The hardened RC-SHCC overlay beams were cured for 28 days under the wet conditions. Different stages of casting process of RC-SHCC overlay beam are presented in Figure 4.

Fig. 2: Rebar details of beam specimens (units: mm).

Fig. 3: Sectional view of RC-SHCC overlay beam specimens (units: mm).

2.4 Testing procedure of beams

The four-point flexural test was performed on the beam specimens at 28-days as shown in Figure 5. Servo controlled hydraulic testing machine AMSELOR having a capacity of 3000kN was used for the test. The bending span between the loading points was 550 mm. A monotonic transverse load was applied until final failure of the beam specimens. The arrangement of strain gauges and linear variable differential transducers (LVDT) can be seen in Figure 5. One LVDT was placed vertically to measure deflection at mid-span. Similarly, LVDTs were placed horizontally above and below the beam at the mid-span for the measurement of the curvature. Strain gauges were fixed on the top face of the beam to measure compressive strain at the mid-span. Strain gauges were also fixed on steel re-bars to measure steel strain at the mid-span. Moreover, to monitor strain variation along the section depth, two strain gauges were attached to the side face of the section. The crack propagation in loading span was monitored during the test using digital cameras.

Fig. 4: Casting process of beam specimens.

Fig. 5: Test setup of specimens.

3 Test results and discussions

3.1 Material characterization

For steel, main bottom rebars ($\phi 16$ mm) were tested in tension to determine its mechanical properties. The mean value of tensile yield strength, ultimate strength, Young's modulus and yield strain of $\phi 16$ steel rebar were found to be 550 MPa, 650 MPa, 200 GPa, and 0.00275, respectively. For concrete, averaged 28-day cylinder compressive strength and modulus of elasticity were determined to be 41 MPa and 33 GPa, respectively. The concrete samples exhibited brittle behavior. For the SHCC, dumbbell-shape samples were tested at 28 days age under uniaxial tension whose stress-strain response is given in Figure 6. The average ultimate tensile strength and the tensile strain of the SHCC at 28-days were 4.35 MPa and 2%, respectively. The SHCC prisms under flexural test exhibited stress-deflection curves at 28 days as shown in Figure 7. The average flexural strength and

ultimate mid-span deflection of the SHCC at 28 days were 20.46 MPa and 2 mm, respectively. The multiple cracking behavior with low crack widths (<0.1 mm) was observed in both types of the test specimens. The tension sample exhibited a fine cracking pattern dispersed throughout the length of the sample. The flexure sample exhibited a fine cracking pattern branched out under the loading point, as depicted in Figure 7.

3.2 Load-deflection relationship

The load-deflection curves of the beam specimens are presented in Figure 8. The load and deflection values are directly used to plot the graphical relationship. The load-deflection curve of the 'RC-O-C-60' having 60 mm of the concrete overlay can be seen in Figure 8(a). The beam exhibited the usual flexural response of a tension-controlled beam, i.e., yielding of the steel rebars before the concrete crushing in compression. The curve consisted of elastic and inelastic parts. The elastic part has two regions: uncracked elastic region before cracking started and cracked elastic region before steel yielding as indicated by the change in the slope in the curve. When the bottom steel yielded, the curve entered the inelastic zone and followed a mild upward slope until the peak load. At this point, the concrete crushing started, and after sustaining some more deformation as shown by the falling slope, the beam dropped the load.

Fig. 6: Tensile stress-strain curves of tested SHCC samples.

The trend of load-deflection curve of 'RC-O-SHCC-60' is similar to that of 'RC-O-C-60'. The variation in elastic and inelastic region are also noticeable. After the beam reaches its peak load, crack localization occurred in SHCC overlay, and the curve followed a downward slope. The beam gradually sustained some inelastic deformation before complete failure. The beams 'RC-O-C-90' and 'RC-O-SHCC-90' exhibited similar load-deflection responses as shown in Figure 8(b). With introduction of reinforced overlay, as in case of 'RC-O-C-R-60', the beam demonstrated the similar response as the previous overlay beams up to peak load. However, after peak load, the beam showed a softening curve, which ended with a rapid drop of load. For 'RC-O-SHCC-R-60' beam, a similar load-deflection response is observed with different

lengths of the elastic and inelastic regions as shown in Figure 8(c). A rapid load drop from peak point can be noticed for this specimen. Similar responses were observed for beams 'RC-O-C-R-90' and 'RC-O-SHCC-R-90' as shown in Figure 8(d). It can be seen that the elastic stiffness of all SHCC overlay beams is greater than that of their corresponding control concrete overlay beams.

Fig. 7: Flexural stress-deflection curves of tested SHCC samples.

In Table 4, the load and corresponding deflection values at the cracking, yielding, peak and ultimate stages of the specimens are presented. In addition, the percentage differences in the values of SHCC overlay beams with that of their corresponding control concrete overlay beams are also presented in brackets. The load carrying capacities of the SHCC overlay beams are greater than those of their corresponding control concrete overlay beams, especially at cracking and yielding stages. At the cracking stage, the loads of 'RC-O-SHCC-60', 'RC-O-SHCC-90', 'RC-O-SHCC-R-60' and 'RC-O-SHCC-R-90' are 63%, 83%, 46% and 44% greater than those of their corresponding control concrete overlay beams, respectively. Similarly, at the yielding stage, the loads of 'RC-O-SHCC-60', 'RC-O-SHCC-90', 'RC-O-SHCC-R-60' and 'RC-O-SHCC-R-90' are 14%, 24%, 8% and 14% greater than those of their corresponding control concrete overlay beams, respectively. It was noted that the beams with reinforced overlays performed better than the beams with unreinforced overlays in terms of the peak load carrying capacity. At the peak stage, the loads of 'RC-O-SHCC-60', 'RC-O-SHCC-90', 'RC-O-SHCC-R-60' and 'RC-O-SHCC-R-90' are 3%, 1%, 10% and 18% greater than those of their corresponding control concrete overlay beams, respectively.

As far as the deflection is concerned, the reduction in deflection can be noted with the increase in the overlay thickness and reinforcement. At the cracking stage, the deflections of 'RC-O-SHCC-60', 'RC-O-SHCC-90', 'RC-O-SHCC-R-60' and 'RC-O-SHCC-R-90' are 41%, 53%, 33% and 56% greater than those of their corresponding control beams, respectively. At the yielding stage, the deflections of 'RC-O-SHCC-90', 'RC-O-SHCC-R-60' and 'RC-O-SHCC-R-90' are 3%, 2%,

and 4% greater than those of their corresponding control beams, respectively; whereas for 'RC-O-SHCC-60', it was 17% lesser. Similarly, at the peak stage, the deflections of 'RC-O-SHCC-60', 'RC-O-SHCC-90' and 'RC-O-SHCC-R-60' are 41%, 24% and 36% lesser than those of their corresponding control beams, respectively; whereas for 'RC-O-SHCC-R-90', it was 14% greater.

Fig. 8: Load and mid-span deflection curves of beam specimens.

Although the deflections of overlay beams decreased significantly at the peak stage, their deflections at ultimate point are near to that of control beams. At the ultimate stage, the deflections of 'RC-O-SHCC-60' and 'RC-O-SHCC-R-60' are 10% and 23% lesser than those of their corresponding control beams, respectively; whereas for 'RC-O-SHCC-90' and 'RC-O-SHCC-R-90', it was 14% and 26% greater respectively.

From these results, it can be concluded that the SHCC layered beams showed significant improvement (30-50%) in load carrying capacity at cracking and yielding stages. The peak load carrying capacity of the beams with the unreinforced SHCC overlays (RC-O-SHCC-60, RC-O-SHCC-90) is not significantly greater ($\approx 2\%$) than that of their control beams with the unreinforced concrete overlays (RC-O-C-60, RC-O-C-90). However, in case of the reinforced SHCC overlay beams (RC-O-SHCC-R-60, RC-O-SHCC-R-90); a noticeable improvement in the range of 10% to 15% can be achieved as compared to that of their control beams with the reinforced concrete overlays (RC-O-C-R-60, RC-O-C-R-90). It can also be seen that the deflections of the overlay beams are decreasing with increase in overlay thickness and reinforcement. Since the deflection is concerned with the ductility of the beams, a detailed discussion is presented in the next section.

3.3 Ductility analysis

Ductility of a beam is the capacity to deform while sustaining a significant percentage of the peak load in the inelastic region. As explained previously, the SHCC overlay beams have enhanced load capacity as compared to the concrete overlay beams. However, the ductility of the overlay beams needs to be analyzed in detail to gauge the overall flexural performance of beams. This analysis can be performed by calculating Member Ductility Index (μ_{mem}). This index is calculated by the ratio of ultimate deflection (δ_u) to yielding deflection (δ_y), which considers the inelastic region from yielding to final failure point of the overlay beam specimens.

In Table 5 and Figure 9, the ductility indices of the overlay beam specimens are presented. It can be observed that the ductility indices of the SHCC overlay beams are decreasing with increase in overlay thickness and reinforcement. This effect on ductility is mainly due to the addition of the tension carrying area (SHCC) in the beams, which resists tension along with steel. It can be noted here that the unreinforced SHCC overlay beams showed promising ductility values. The ductility indices of 'RC-O-SHCC-60', 'RC-O-SHCC-90' and 'RC-O-SHCC-R-90' are 8%, 11% and 21% greater than that of the respective control concrete overlay beams, respectively; whereas for 'RC-O-SHCC-R-60', it was 24% lesser than that of the control beams. The difference between the ductilities of SHCC and concrete overlay beams is not that significant ($\approx 20\%$) and it can be said that the ductility of the SHCC overlay beams is almost similar to that of the concrete overlay beams. An important observation is that with introduction of rebars in the overlays, the ductility of specimens reduced by almost 50% as compared to specimens with unreinforced overlays. Although, beams with reinforced SHCC overlays (of 60 mm and 90 mm) have higher peak load capacities than unreinforced SHCC overlay beams, their ductility is lesser which raises serious concerns regarding warning before final failure. The overlay beams without reinforcement have showed improved ductility along with enhanced load capacity in service stage.

Table 4: Load and deflection values of beam specimens at different stages.

Beam	Cracking ^a		Yielding ^b		Peak ^c		Ultimate ^d	
	Load kN	Deflection mm	Load kN	Deflection mm	Load kN	Deflection mm	Load kN	Deflection Mm
RC-O-C-60	15.23	0.49	94.78	10.31	117.72	37.45	94.18	43.62
RC-O-SHCC-60	24.87 (63%)	0.69 (41%)	108.32 (14%)	8.58 (-17%)	121.06 (3%)	22.28 (-41%)	96.84 (3%)	39.09 (-10%)
RC-O-C-90	15.51	0.53	87.46	7.85	127.50	28.79	102.00	38.73
RC-O-SHCC-90	28.37 (83%)	0.81 (53%)	108.47 (24%)	8.07 (3%)	128.25 (1%)	22.01 (-24%)	102.60 (1%)	44.23 (14%)
RC-O-C-R-60	15.43	0.47	126.69	9.00	146.06	19.70	116.80	26.35
RC-O-SHCC-R-60	22.50 (46%)	0.63 (33%)	136.46 (8%)	9.16 (2%)	161.05 (10%)	12.67 (-36%)	128.80 (10%)	20.33 (-23%)
RC-O-C-R-90	15.93	0.41	137.13	9.32	152.80	13.94	121.54	19.83
RC-O-SHCC-R-90	22.94 (44%)	0.63 (56%)	156.54 (14%)	9.73 (4%)	179.17 (17%)	15.86 (14%)	143.33 (18%)	25.00 (26%)

Where ^a is the first cracking stage, ^b is the tensile rebar yielding stage, ^c is the peak moment stage and ^d is the ultimate stage.

3.4 Cracking behavior

The cracking patterns of tested beam specimens are presented in Figure 10. For concrete overlay beam specimens, a usual ductile failure was observed, i.e., extensive bottom steel yielding followed by top concrete crushing. With start of loading, the cracks started to occur along the length of the beam and propagated upwards. After the steel yielding, the width of the cracks started to increase significantly. At the peak load, crushing of the top of concrete in the mid-span occurred and failure happened. Near the failure, horizontal cracks occurred in the mid-span of the beams below the main bottom rebars, showing the spalling off the cover.

Table 5: Ductility indices of beam specimens.

Beam	Deflections δ		Ductility $\mu_{mem} = \delta_u / \delta_y$
	Yield δ_y (mm)	Ultimate δ_u (mm)	
RC-O-C-60	10.3	43.6	4.23
RC-O-SHCC-60	8.6	39.1	4.56 (8%)
RC-O-C-90	7.9	38.7	4.93
RC-O-SHCC-90	8.1	44.2	5.48 (11%)
RC-O-C-R-60	9.0	26.4	2.93
RC-O-SHCC-R-60	9.2	20.3	2.22 (-24%)
RC-O-C-R-90	9.3	19.8	2.13
RC-O-SHCC-R-90	9.7	25.0	2.57 (21%)

For SHCC overlay beam specimens, cracks started to develop with the start of loading. The cracking initiated in the concrete substrate followed by very fine cracks in the SHCC overlay. After the yield point, the cracking kept on occurring in the SHCC overlay, but the concrete substrate cracks started to widen and propagate upwards. At the peak load, the SHCC overlay exhausted and the localization of cracks occurred. With further loading, the top concrete crushed completely and the beam failed. The cracking in the SHCC overlays was identified in two different patterns [12]. The first SHCC cracking pattern

consisted of multiple cracks developed randomly throughout the layer as shown in Figure 11(a). These cracks occurred due to bending of the beam, which induced uniform tensile stresses in the overlay. The second SHCC cracking pattern consisted of multiple cracks diffusing from the concrete substrate crack as shown in Figure 11(b). With an increase in the concrete crack width, strain concentration caused the SHCC cracks to diffuse into this particular location, which can be seen as diffused multiple cracking pattern.

Table 6 shows the maximum crack width developed in the concrete substrate at service, yielding and peak load stages for each specimen, in addition to its differences with those of the control specimen as percentages between brackets. It can be observed that the concrete cracks in control beams were much wider as compared to SHCC overlay beams. At the service stage, the SHCC overlay restricted the maximum concrete crack widths in the beams by 20% to 60% of that of the concrete overlays, except for RC-O-SHCC-R-90, which was similar to the control beam. Similarly, the maximum concrete crack widths were also decreased by 20% to 50% in the SHCC overlay beams at the yielding and peak stages. The average crack width in the SHCC overlay was measured to be less than 0.1 mm at the service stage. ACI committee report 224R-01 [13] specifies a maximum permissible concrete crack width of 0.41 mm for interior exposure at the service stage. The SHCC overlay beams had crack widths under the permissible limits of ACI. Hence, it can be said that the beam strengthened using SHCC overlay has the potential to limit the crack widths.

In Table 7, the properties of cracks developed in the beams are presented. The average crack spacing of concrete in SHCC overlay beams are lesser than that of control beams. Moreover, the total number of concrete cracks in SHCC overlay beams is greater than that of control beams, except for RC-O-SHCC-R-60. The effectiveness of using reinforced SHCC overlay in beams can be seen by an increased number of SHCC cracks and decreased average crack spacing as compared to that of beams with unreinforced SHCC overlays. It is clear that a large number of the cracks developed in the SHCC layer

as compared to the concrete substrate in all the SHCC overlay beams. Also, the number of cracks in the SHCC overlay increased with an increase in overlay thickness and reinforcement. Therefore, it can be concluded that the SHCC overlays can improve the cracking performance of the strengthened beams as compared to concrete overlays.

Fig. 9: Comparison of ductility indices of beam specimens.

Fig. 10: Cracking patterns of tested overlay beams.

(a) Normal Cracking (b) Diffused Cracking

Fig. 11: Magnified cracking patterns of 'RC-O-SHCC-R-90' beam.

Table 6: Maximum concrete crack width at different loading stages.

Beam	Maximum crack width developed in the concrete substrate (mm)		
	At service load	At yielding load	At peak load
RC-O-C-60	0.61	1.4	4.1
RC-O-SHCC-60	0.21 (-66%)	1 (-29%)	2.4 (-41%)
RC-O-C-90	0.59	1.8	5.9
RC-O-SHCC-90	0.24 (-59%)	1 (-44%)	3 (-49%)
RC-O-C-R-60	0.3	0.78	2.22
RC-O-SHCC-R-60	0.23 (-23%)	0.44 (-44%)	1.63 (-27%)
RC-O-C-R-90	0.31	1.12	3.18
RC-O-SHCC-R-90	0.31 (0%)	0.56 (-50%)	1.46 (-54%)

Table 7: Crack properties of the beam specimens.

Beam	Cracks developed in the beam @ Peak					
	Concrete			SHCC		
	Avg. Crack Spacing (mm)	Max. Crack Spacing (mm)	Number of cracks (#)	Avg. Crack Spacing (mm)	Max. Crack Spacing (mm)	Number of cracks (#)
RC-O-C-60	122	170	14	-	-	-
RC-O-SHCC-60	55	144	24	18	80	75
RC-O-C-90	103	133	15	-	-	-
RC-O-SHCC-90	60	112	19	15	50	95
RC-O-C-R-60	66	140	25	-	-	-
RC-O-SHCC-R-60	63	138	20	15	78	100
RC-O-C-R-90	78	120	21	-	-	-
RC-O-SHCC-R-90	51	166	26	11	88	170

4 Conclusions

The effect of SHCC overlay thickness and reinforcement on the flexural and cracking performance of the RC-

SHCC overlay beams was investigated. The conclusions from this study are summarized as follows:

1. The RC-SHCC overlay beams showed enhanced load capacity as compared to concrete overlay beams. SHCC overlay beams showed an increase in load capacity of 40-60% at first cracking and 10-20% at yielding stages as compared to control beams. The ultimate load carrying capacity of the beams with the unreinforced SHCC overlays is not significantly greater ($\approx 2\%$) than that of the control beams. However, in case of the reinforced SHCC overlay beams, a noticeable improvement in the range of 10-20% was achieved.
2. The ductility of the SHCC overlay beams decreased with increase in overlay thickness and reinforcement. The SHCC overlay beams exhibited matchable ductility as compared to the control beams. The overlay beams without reinforcement have showed improved ductility as compared to control beams with concrete overlays. With introduction of rebars in the overlays, the ductility of specimens reduced by almost 50% as compared to specimens with unreinforced overlays.
3. The RC-SHCC overlay beams exhibited multiple fine cracks with the crack-width control in the beams. Additionally, the crack widths were restricted in both the concrete substrate and the SHCC layer. These findings indicate the action of SHCC overlay as a protective layer for controlling the crack widths and indirectly, improving the structural health of the composite beams.

References

- [1]. K. Rokugo, H. Yokota, N. Sakata, T. Kanda, *Concrete Journal*, **45**, 3-9 (2007).
- [2]. V.C. Li, S. Wang, C. Wu, *ACI Mater. J.*, **98**, 483-492 (2001).
- [3]. V.C. Li, D.K. Mishra, C. Wu, *Mater. Struct.*, **28**, 586-595 (1995).
- [4]. G. Fischer, V.C. Li, *Proc. Poland BMC* **7**, 29-36 (2003).
- [5]. V. C. Li, *Journal of Advanc. Concrete Tech.*, **1**, 215-230 (2003).
- [6]. M. Li, V.C. Li, *ACI Mater. J.*, **108**, 333-340 (2011).
- [7]. M. Sahmaran, M. Li, V.C. Li, *ACI Mater. J.*, **104**, 604-611 (2007).
- [8]. M. Maalej, V.C. Li, *ACI Struct. J.*, **92**, 167-176 (1995).
- [9]. K. Rokogu and T. Kanda, *Strain Hardening Cement Composites: Structural Design and Performance, State of the Art Report of the RILEM Technical Committee 208-HFC*, **SC3**, (2013).
- [10]. M. Hussein, M. Kunieda and H. Nakamura, *Cement & Concrete Composites*, **34**, 1061-1066 (2012).
- [11]. A. Kamal, M. Kunieda, N. Ueda and H. Nakamura, *コンクリート工学年次論文集*, **30**, 1483-1488 (2008).
- [12]. Z. Yongxing, Ph.D. Thesis, Department of Civil Engineering, Nagoya University, Japan, (2012).
- [13]. ACI Committee 224, *Control of cracking of concrete structures*, (2001).