Coventry University and
The University of Wisconsin Milwaukee Centre for By-products Utilization,
Second International Conference on Sustainable Construction Materials and Technologies
June 28 - June 30, 2010, Università Politecnica delle Marche, Ancona, Italy.
Main Proceedings ed. J Zachar, P Claisse, T R Naik, E Ganjian. ISBN 978-1-4507-1490-7
http://www.claisse.info/Proceedings.htm

Experimental Study on Corrosion Resistance of Strain Hardening Cement-based Composites

Koichi Kobayashi[1], Hoshito Kurachi[2], and Keitetsu Rokugo[1]

[1] *Department of Civil Engineering; Gifu University – Yanagido, Gifu City, Gifu Pref., Japan. E-mail: <ko2ba@gifu-u.ac.jp>, <rk@gifu-u.ac.jp>,*
[2] *Takenaka Civil Engineering & Construction.*

ABSTRACT

This paper aimed at clarifying the corrosion protection performance of SHCC (Strain Hardening Cement-based Composites) as a repair material. Chloride solution was sprayed on the specimens to accelerate chloride-induced corrosion of reinforcing steel. After being exposed to a deterioration environment, chloride penetration depth and corrosion state on the reinforcing steel were investigated. SHCC was proved to be superior in chloride proof performance to normal concrete and PCM. A patching by SHCC as far as beyond the reinforcement had an excellent chloride proof and corrosion preventing performance, while a surface coating by SHCC could not prevent corrosion of the steel in the substrate RC member. Since the fiber content did not affect chloride proof/corrosion preventing performance of SHCC, high workability and high corrosion preventing performance could both be achieved at the same time by decreasing the fiber content in SHCC.

INTRODUCTION

Ever since the first stretch of high-standard motorway was opened in 1963, more than 10,000km motorways have been opened and are being used in Japan. Road bridges including those on local roads of 15m or more span that have been used more than 50 years currently take up about 6% of all bridges but are expected to reach up to about 40% 20 years from now. With the trend that less budget is allocated to new construction projects, the maintenance of existing structures will be an important issue in future.

Japan has a very long shoreline and many RC structures are susceptible to chloride-induced deterioration. Moreover, deicing salt has been increasingly used in cold regions. Chloride-induced deterioration of reinforced concrete is known to cause a rapid decline in performance as compared to other deteriorating mechanisms. For the repair of concrete with chloride-corroded rebar, a patch repair method that uses polymer cement mortar (hereinafter PCM), or a surface coating method in which resin coat is applied on the surface of the structure have been commonly used. However, the structures repaired by either method often suffer from deterioration again, which is mostly caused by insufficient cohesion or incompatibility between the base material and repair material.

Strain hardening cement-based composites (SHCC), also referred to as engineered cement-based composites (ECC), is a material that shows a subsequent increase in tensile stress after the first cracking under uniaxial tensile stress [JSCE concrete committee (2008)]. Matrix composition of SHCC is similar to conventional mortar; it is therefore considered to be a very appropriate repair material, which is required to provide unity with the substrate or good crack bridging ability [Lim and Li 1997]. While SHCC suffers numerous cracks under a bending or tensile force, these cracks are minute and it is expected to exhibit high permeability resistance. Therefore SHCC can be effectively used as a patch repair material or surface coating material for the repair of concrete with corroded rebar [Sahmaran and Li 2007, Sahmaran et al. 2008, Sahmaran and Li 2008, Miyazato and Hiraishi 2005, Kamal et al. 2008].

This study investigates the steel corrosion prevention performance of SHCC as a repair material (patch repair and surface coating). Specimens consisting of base material concrete and SHCC with various different mixture ratios of fibers as repair material layered on top of the base material were prepared, and cracks were introduced. After subjecting the specimens to a degradation promotion environment in which chloride solution was sprayed on the specimens, the chloride penetration and the degree of corrosion of rebars inside the specimens were examined. Specimens with PCM as the repair material, and monolithic specimens consisting only of each of the repair materials were also prepared for comparison purposes.

EXPERIMENTAL PROCEDURE

Materials and Composition

Normal concrete (NC) was used as the base material, and SHCC and PCM were used as the repair materials. Table 1 shows the physical properties of fibers used in the experiment. Here, high strength polyethylene fiber (PE) was used. Japan's annual shipment of polyethylene is about 2.6 million tons. About 80,000 tons of polyethylene are used per year for construction purposes, and lifeline-related piping applications such as water pipelines and gas pipes account for about 70% of that use.

Table 2 shows mixture compositions of SHCC. Besides the typical volumetric fiber ratio of 1.5% for SHCC [Yamada et al. 2008], mixtures with smaller fiber ratios of 1.0% and 0.75% were used, aiming at improving workability of SHCC by reducing plastic viscosity and yield value of SHCC. The cement used was a high early strength Portland cement, and as the aggregate silica sand with a diameter range of from 100 to 200mm was used. The additives used were a high range water reducing agent and a viscosity agent.

Table 2 also shows the mixture composition of NC; the maximum coarse aggregate size was 15mm. PCM was a low-shrinkage type pre-mixed product of polyvinyl acetate-vinyl versatate (Va/VeoVA) designed for repair work. It should be noted that the corrosion inhibitor was not used in this study even for the specimens that simulate a patch repair. As for the reinforcement, D10 was used.

Specimens

Figure 1 shows the specimens used for the investigation on the corrosion protection performance. Monolithic specimens consist respectively of SHCC, PCM, and NC. They were prepared in the form of RC beams with a cross section of 50 x 100mm and a length of 1800mm, which were then pulled to produce cracks (see section 2.3) and cut into small specimens with a length of 150mm. Non-crack specimens were also prepared for the monolithic pieces of NC. One each specimen was prepared for each type.

Table 1. Mechanical and Geometrical Properties of PE Fiber

Diameter	Length	Density	Tensile strength	Young's modulus
0.0012mm	12mm	0.97 g/cm^3	2.6GPa	88GPa

Table 2. Mix Compositions

	W/C	Unit mass (kg/m^3)						
		W	C	S	G	Fiber	HRWRA	VMA ***
SHCC-1.5%	0.3	342.0	1264.0	395.0 *	-	14.6	37.90	0.90
SHCC-1.0%	0.3	343.7	1270.4	397.0 *	-	9.7	38.09	0.90
SHCC-0.75%	0.3	346.3	1280.1	400.0 *	-	7.3	38.38	0.91
NC	0.55	180	327	810	920	-	0.8175 **	-

*: Silica sand, **: WRA, *** Viscosity modifying admixture

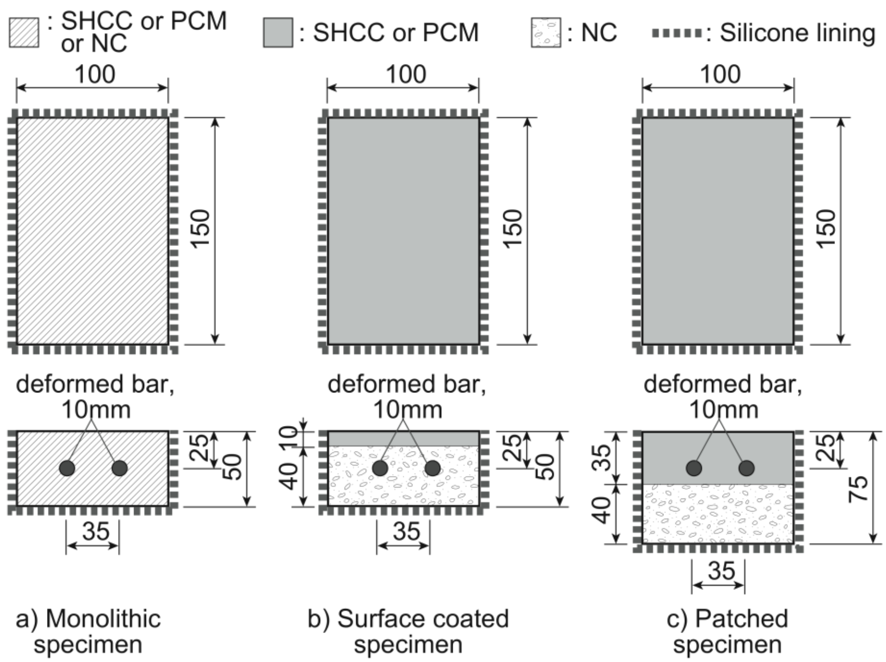

Fig. 1 Specimens

Surface coated specimens simulate a surface coating by SHCC. Initially, RC beams of NC with a cross section of 40 x 100mm and a length of 1800mm were prepared as the substrate part, and SHCC or PCM was overlaid with a 10mm thickness as a surface coating. The cover depth of reinforcing bars was 20mm, the bars being arranged in the substrate part. Patched specimens simulate a patch repair using SHCC to restore a cross section of RC member to the backside of the reinforcing bars. Similarly to the surface coated specimens, RC beam of NC were prepared with a cross section of 40 x 100mm and a length of 1800mm as a substrate part, and SHCC or PCM was overlaid with a 35mm thickness as a patching. While the cover depth was also 20mm, the reinforcing bars were arranged in the patching part.

On the surface of the substrate part of NC on which SHCC or PCM was to be overlaid, a setting retarder was used to delay the setting of cement on NC surface. On the next day of placing of NC, the surface mortar that has not hardened yet was washed away with water to expose the coarse aggregate, before applying SHCC or PCM thereon. This was to simulate the surface treatments that are usually required for the repair of RC structures, such as sandblasting, chipping, or water jet blasting. After the demolding on the third day, the specimens were supplied with water while curing at 20^{o}C for two weeks.

Table 3 shows the properties of each mixture. SHCC mixtures with lower fiber contents are expected to have better compactability as a patching material, as they have higher flowability. However, tensile strength and ultimate strain decreased with the decrease of the fiber content.

Table 3. Properties of SHCC

	Air (%)	Mortar flow (mm)		Slump (mm)	Compre -ssive strength (MPa)	Crack strength (MPa)	Tensile strength (MPa)	Ultimate strain (%)
		Before table drop	After table drop					
SHCC-1.5%	22	136	162		35.8	3.5	4.1	3.7
SHCC-1.0%	21	156	185		56.4	3.3	4.3	2.5
SHCC-0.75%	17	184	205		65.0	2.9	4.1	2.5
PCM					35.9			
NC	3.9			58	47.1			

Introduction of cracks

The beams with a length of 1800mm were pulled in a uniaxial direction for introducing cracks. The monolithic NC beams and the double-layer beams were loaded until the width of the residual cracks in NC reached after being unloaded about 0.4mm. The monolithic SHCC and PCM beams were loaded until the width of the cracks reached the same value as that of the cracks in the surface coating or the patching part of the double-layer beams at the time when the width of the residual cracks in the substrate part after being unloaded had reached about 0.4mm. Specimens were then cut out from the cracked beams with a length of 150mm.

Table 4 shows the precise residual crack width in both the substrate part and the repair part measured using a microscope with a magnification ratio of 175. The crack width shown here is that of the largest one of the cracks generated in each specimen. The crack widths were measured just above the two reinforcing bars, rebar (a) and rebar (b).

Table 4. Residual crack width in each specimen

	Monolithic	Surface coating		Patching	
	Crack width (mm)	Crack width (mm)		Crack width (mm)	
		Substrate	Repair	Substrate	Repair
SHCC-1.5%	0.02-0.04	0.38-0.41	0.02-0.06	0.32-0.51	0.02-0.12
SHCC-1.0%	0.03-0.04	0.39-0.40	0.02-0.05	0.39-0.40	0.03-0.06
SHCC-0.75%	0.05-0.11	0.37-0.40	0.03-0.06	0.40-0.40	0.01-0.04
PCM	0.25-0.69	0.40-0.41	0.52-0.65	0.36-0.62	0.36-0.43
NC	0.36-0.65				
NC-non crack	-				

Acceleration of deterioration

To let the chloride ion penetrate into the specimens only from the upper side, the other five sides were sealed with silicone (see Figure 1). Then a 3% chloride solution was sprayed on the specimens for 5 minutes every 6 hours to accelerate the deterioration.

Measurement of chloride penetration depth and steel corrosion

After 60 days of chloride spraying, the specimens were split parallel to the reinforcing bars to measure the chloride penetration depth. A solution of 0.1N silver nitrate was sprayed on the fresh split surfaces to determine the chloride-contaminated area.

After the measurement of the chloride penetration depth, the reinforcing bars were taken out form the specimens. The outline of the corroded parts on the reinforcing bar was traced on a plastic sheet to measure the corrosion area using a planimeter.

RESULTS AND DISCUSSIONS

Crack distribution

Figure 2 shows the crack distributions on the split surfaces of the specimens. A large crack runs transversely throughout the monolithic NC or PCM specimens and the PCM-overlaid specimens (Figure 2(c)). In contrast, five to ten fine cracks extend over the entire length of the SHCC monolithic specimens (Figure 2(a)).

In the SHCC-overlaid specimens, only one large crack was observed in the NC substrate part. At the same time, the SHCC layer had several fine cracks radiating from the point where the large crack in the NC substrate part reaches the interface between the substrate part and the overlaid part (Figure 2(b)). This characteristic crack distribution was observed in both the SHCC surface coated and patched specimens, and was contrasted with that of the SHCC monolithic specimens in which fine cracks were generated over the entire length of the specimens. The high density of the cracks in SHCC part in the vicinity of the NC crack can be attributed to a reduced stiffness in the cross section of the substrate containing the crack as compared to other parts.

The effect of the fiber content on the crack distributions was not observed in any type of the specimens that used SHCC.

Corrosion penetration depth

Figure 3 shows examples of the results of the chloride penetration test in which a silver nitrate solution was sprayed on the fresh split surfaces of the specimens. It is clear from this figure that the chloride has penetrated through the cracks. Figures 4, 5, and 6 show the chloride penetration depths that were determined based on the color change caused by the silver nitrate solution. The penetration depth was measured at the crack(s), and in the case with the HPHFCC specimens, the penetration depth shown here is the largest one of the penetration depths measured at plural cracks.

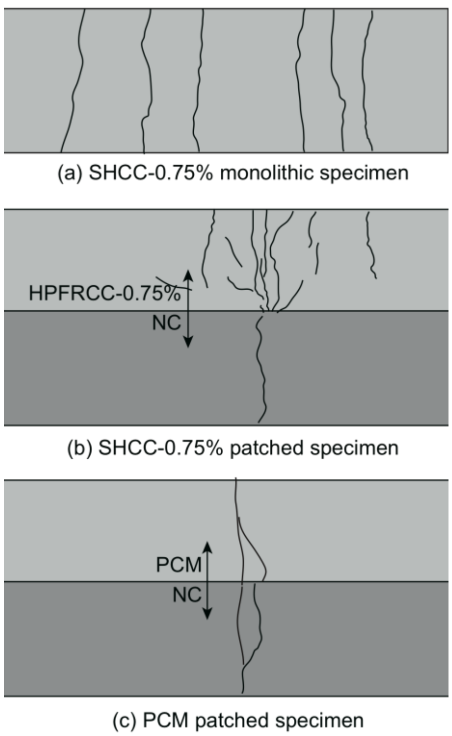

Fig. 2. Crack Distributions on the Split Surfaces of the Specimens

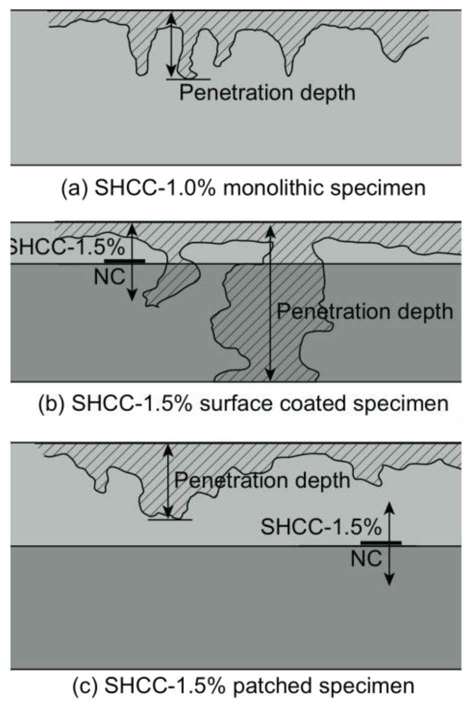

Fig. 3. Chloride Penetration on Split Surfaces of the Specimens

In PCM monolithic specimens and NC monolithic specimens with cracks, the chloride had reached the bottom surface of the specimens through the cracks (see Figure 4). In contrast, in SHCC monolithic specimens with the volumetric fiber content of 1.5% or 1.0%, the penetration depth of the chloride was as small as, or smaller than the thickness of the cover concrete, similarly to the NC specimens without cracks. This is considered to be because of the very small crack width as a result of the bridging by fibers and the small water-binder ratio [Sahmaran and Li 2007]. It seems to be reasonable that the larger penetration depth in the monolithic SHCC specimen with the fiber content of 0.75% is attributed to its larger width of the crack (see Table 4) [Aldea et al. 1999].

In all of the surface coated specimens including those with SHCC, the chloride had almost reached the bottom of the specimens (see Figure 5). Since the chloride can apparently penetrate about 20mm in SHCC within 60days as shown in Figure 4, the 10mm thickness of SHCC was insufficient to prevent the chloride from reaching the substrate. Once it reaches the substrate, it can penetrate into the substrate concrete very quickly through the wide cracks and the high water-cement ratio.

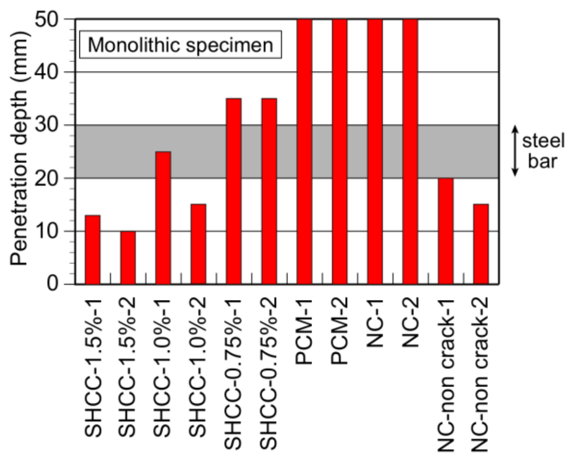

Fig. 4. Chloride Penetration Depth in Monolithic Specimens

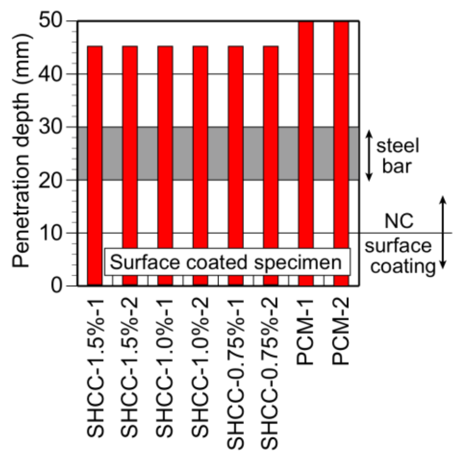

Fig. 5. Chloride Penetration Depth in Surface Coated Specimens

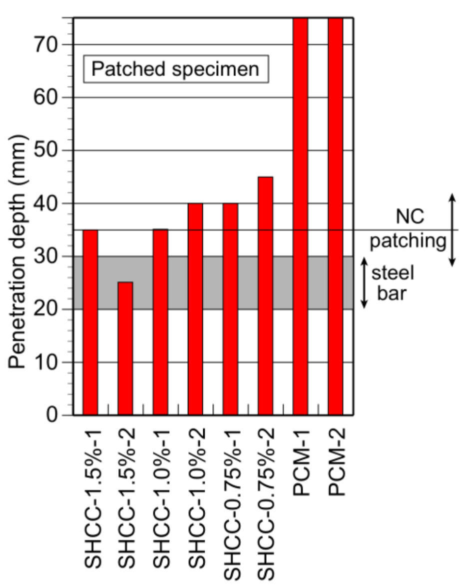

Fig. 6. Chloride Penetration Depth in Patched Specimens

While the chloride had reached the bottom surface of the specimen through the cracks in the PCM patched specimens, the chloride penetration depths were as small as 25-45mm in the SHCC patched specimens (see Figure 6). It should be emphasized here that these values were larger than those of the SHCC monolithic specimens (see Figure 4), even though the reinforcing steel was covered by the same mixtures of SHCC and the specimens had the same crack width regardless of the type. This may have been caused by the high density of fine cracks in the patching part neighboring the cracks in the substrate part. As Li points out, chloride permeability of HSCC depends on the number of the fine cracks in it [Sahmaran et al. 2007]. It seems reasonable to suppose that the chloride penetration processes through and from each crack affect each other when the cracks are arranged closely together. Moreover, the high strain at the high crack density area makes the matrix loose. In this study, such mutual interference interaction between cracks could not have affected the chloride penetration in the SHCC monolithic specimens because the crack spacing in these specimens was more than several cm.

Corrosion of reinforcing bar

Figures 7, 8 and 9 show the ratio of corrosion area on the reinforcing bars. Since two bars were arranged in each specimen, two results are shown for each specimen in the figure.

In the NC or PCM monolithic specimens with large cracks, the ratio of corrosion area on the reinforcing steel was relatively large (see Figure 7). This is attributable to the large chloride penetration depth in these specimens as shown in Figure 4. On the contrary, hardly any corrosion was found in the SHCC monolithic specimens including SHCC-0.75% in which the cracks were slightly wider and the penetration depth was larger than those in other SHCC monolithic specimens. The reason why the reinforcing bars did not corrode in SHCC-0.75% even though the chloride penetrated beyond the bars could be assumed as follows: SHCC has a very tight bond to the reinforcing bar, resulting in very fine cracks. Furthermore, the matrix with the low water-cement ratio plus the viscosity agent made the microstructures tight at the interfacial zone between the matrix and the steel due to the low bleeding, resulting in the low supply of oxygen and the water.

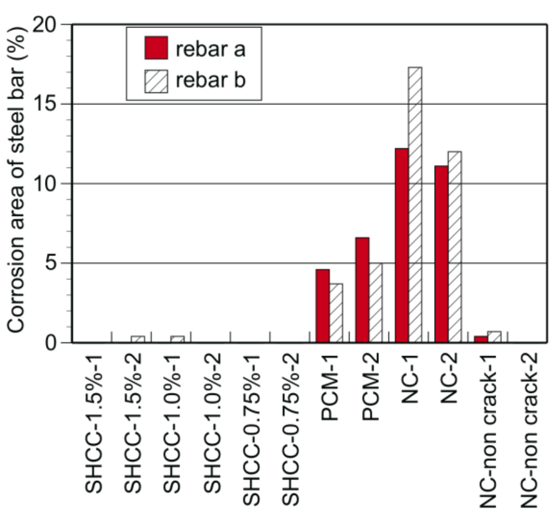

Fig. 7. Corrosion Area on the Two Steel Bars in Monolithic Specimens

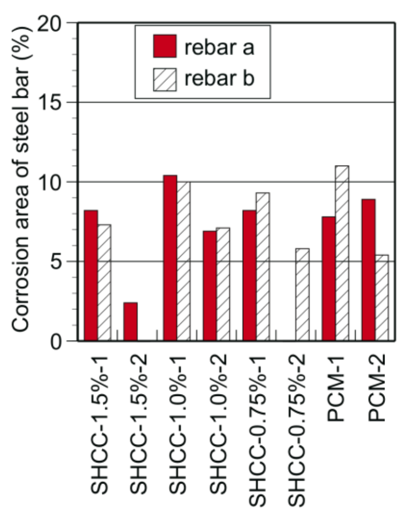

Fig. 8. Corrosion Area on the Two Steel Bars in Surface Coated Specimens

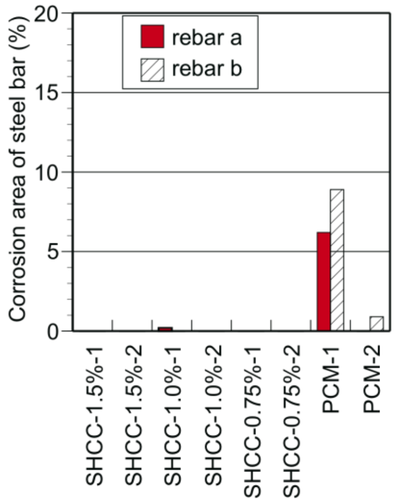

Fig. 9. Corrosion Area on the Two Steel Bars in Patched Specimens

As for the surface coated specimens, corrosion was observed in almost all the bars, regardless of the type of overlaid mixture (see Figure 8). This is attributable to the large chloride penetration depth. Moreover, it is supposed that the large crack opening in the substrate NC part led to formation of a debonding crack between the reinforcing bars and NC, allowing the chloride to penetrate deeper.

The PCM patched specimens failed to show sufficient corrosion prevention performance. As shown in Figure 9, the corrosion area ratios of the reinforcement in a PCM-patched specimen were as large as from 6 to 9 %, while these values were smaller than those of the monolithic NC specimens (see Figure 7). In contrast, the SHCC-patched specimen did prevent the steel corrosion, although it suffered from slightly deeper chloride penetration than the SHCC monolithic specimens as mentioned in the previous section (see Figures 4 and 6). Further, it is obvious from Figure 9 that the fiber content in SHCC did not affect the corrosion prevention performance, even if it was halved from 1.5% to 0.75%.

As demonstrated above, the corrosion protection performance of SHCC was hardly affected by the fiber content, while the mechanical performance was affected as shown in Table 3. This may be attributable to the difference in the strain of the specimen in each test. The average strain of all the specimens sprayed with chloride ranged from 0.2% to 0.3 %, while it was as large as or larger than 2% in the uni-axial tensile test. It should be emphasized here that the number and width of the cracks were hardly affected by the fiber content when the strain was within 0.3%. This resulted in the superior corrosion protection performance of all the SHCC mixtures when they were used as the patch repair material.

CONCLUSIONS

This paper aimed at clarifying the corrosion protection performance of SHCC as a repair material. For the purpose of improving workability, the volumetric fiber content in SHCC was decreased from its usual rate of 1.5% to as low as 0.75%.

Using these mixtures, the applicability of HPHRCC as a repair material for preventing steel corrosion was investigated. For this purpose, monolithic specimens made of SHCC, surface coated specimens that simulate surface coating with a 10mm thick SHCC layer overlaid on the substrate, and patched specimens that simulate patch repair with a 35mm thick SHCC layer overlaid so that the reinforcement was completely embedded, were prepared. Chloride solution was sprayed on these specimens to accelerate the chloride-induced corrosion of reinforcing steel. After being exposed to this degradation environment, the chloride penetration depth and the degree of corrosion on the reinforcing steel were investigated. The results obtained in this study can be summarized as follows:

- SHCC showed superior chloride proof performance as compared to NC and PCM.
- Surface coating with SHCC could not prevent corrosion of steel in the substrate RC member.
- Patch repair with SHCC as deep as beyond the backside of the reinforcement proved effective to suppress chloride penetration and to prevent reinforcement corrosion.
- The fiber content did not affect the corrosion preventing performance of SHCC as a patch repair material, and therefore high workability and high corrosion preventing performance could both be attained by decreasing the fiber content in SHCC.

REFERENCES

Aldea, C. M., Shah, S. P., and Karr, A. (1999). "Effect of Cracking on Water and Chloride Permeability of Concrete." *ASCE Journal of Materials in Civil Engineering*, 11(3), 181-187.

JSCE Concrete Committee (2008). "Recommendations for Design and Construction of High Performance Fiber Reinforced Cement Composites with Multiple Fine Cracks (HPFRCC)." Concrete Engineering Series No.82, <http://www.jsce.or.jp/committee/concrete/e/hpfrcc_JSCE.pdf>

Kamal, A., Kunieda, M., Ueda, N., and Nakamura, M. (2008). "Evaluation of crack opening performance of a repair material with strain hardening behavior." *Cement and Concrete Composites*, 30(10), 863-871.

Lim, Y. M. and Li, V. C. (1997). "Durable repair of aged infrastructures using trapping mechanism of engineered cementitious composites." *Cement and Concrete Composites*, 19(4), 373-385.

Miyazato, S., and Hiraishi, Y. (2005). "Transport properties and steel corrosion in ductile fiber reinforced cement composites." *Proceedings of ICF 11*, Torino, March.

Sahmaran, M., Li, M., and Li, V. C. (2007). "Transport properties of engineered cementitious composites under chloride exposure." *ACI Materials Journal*, 104(6), 604-611.

Sahmaran, M, Li, V. C., and Andrade, C. (2008), "Corrosion resistance performance of steel-reinforced engineered cementitious composite beams. *ACI Materials Journal*, 105(3), 243-250.

Sahmaran, M, and Li, V. C. (2008). "Durability of mechanically loaded engineered cementitious composites under highly alkaline environments." *Cement and Concrete Composites*, 30(2), 72-81.

Yamada, Y., Inaguma, T., Kobayashi, K., Fischer, G., and Rokugo, K. (2008). "Discussions of conditions for multiple cracking of HPFRCC based on Variability of strength properties." *Proceedings of 8th International Symposium on Utilization of High-Strength and High-Performance Concrete (8HSC-HPC)*. Tokyo, October, 1113-118.