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Landscaping of ASR-cracked retaining wall using HPFRCC shotcretes and observation over 5 years

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ABSTRACT: High performance fiber-reinforced cementitious composites (HPFRCCs) were shotcreted onto an ASR-cracked concrete gravity retaining wall on a trial basis primarily for its landscaping. The width of cracks in the HPFRCCs was mostly limited to not more than 0.1 mm even 5 years after application, proving the expected effect of HPFRCCs. Within the range of this application, the effects of placing steel reinforcement and sealing cracks in the substrate concrete were not appreciable. Acrylic coating on the HPFRCC layer had an appearance-improving effect only for a short period.

1 INTRODUCTION

High performance fiber-reinforced cementitious composite (HPFRCC) is a fiber-reinforced mortar characterized by strain-hardening behavior and multiple fine crack behavior under tensile forces, being expected to be useful for surface repair and patching of concrete structures (Kanda et al. 2006, Rokugo et al. 2009). Recommendations for design and construction of HPFRCC have been published by JSCE (2007) both in a book and on web.

While concrete structures having cracks due to alkali-silica reaction (ASR) include those that only require surface repair for landscaping, repair methods and materials for such surfaces have yet to be established.

In April 2003, HPFRCCs were shotcreted onto a concrete gravity retaining wall having ASR-induced cracks on a trial basis to improve the landscape. This was one of the earliest applications of HPFRCCs to actual structures. Observation was then carried out 1, 3, and 5 years after the application to check the state of cracking and other defective events.

This paper reports on the details of this trial application and the results of subsequent observation of the wall structure, while verifying the validity of the initially adopted techniques.

2 CRACKING AND REPAIR METHODS

2.1 *State of cracking of structure*

The structure under study is a concrete gravity retaining wall measuring 18 m in width and 5 m in height constructed in the mid-1970s. Since ASR-induced map cracking was recognized on this wall, crack injection and overlay were applied for repair in 1994. However, cracking reappeared on the surface by the time of a survey in 2002 carried out by the authors as shown in Figure 1.

Because of the past survey data and the map cracking of the wall, cores were drilled from the wall (80 cm from the bottom and 50 cm from the surface) to estimate the residual expansion of concrete by the JCI-DD2 method. Since the resulting residual expansion was 0.005 to 0.011%, it was judged that the future expansion of the retaining wall under study would be relatively small.

Figure 1. ASR-cracked concrete retaining wall.

Table 1. Repair materials and conditions of blocks.

Repair materials	Block No.	Reinforcement	Unbonded region at crack	Coating
Repair material A	1	Welded bar mesh	None	Acrylic coating compound was applied to all blocks from bottom to level of 2 m.
Fiber: PVA+ High strength PE	2	Expanded metal	None	
Volume fraction of fiber: 1.5%	3	None	None	
Matrix: Premixed polymer cement	4	None	Sealing	
Repair material B	5	Welded bar mesh	None	
Fiber: High strength PVA	6	Expanded metal	None	
Volume fraction of fiber: 2.1%	7	None	None	
Matrix: Premixed cement mortar	8	None	Sealing	
Repair material C				
Fiber: None	9	Welded bar mesh	None	
Matrix: Premixed cement mortar				

2.2 *Selection of repair methods*

In consideration of the small residual expansion due to ASR and the particularity of the structure of being a gravity retaining wall, it is unlikely that the safety of this structure would be significantly impaired in the future. It was therefore considered unnecessary the aesthetic appearance significantly deteriorated by cracking.

Though repair by crack injection and resin overlay was a possible option, this has already been applied earlier and failed to prevent re-deterioration as to apply such mechanical strengthening as earth anchors, but it was judged necessary to carry out surface repair primarily for landscaping to improve stated above (Fig. 1). It was thus considered necessary to overlay the surface with a repair material having excellent deformability across cracks. It was considered desirable to repair with cementitious materials from the standpoint of long-range aesthetic appearance. Surface overlays with HPFRCC shotcretes were therefore adopted on a trial basis.

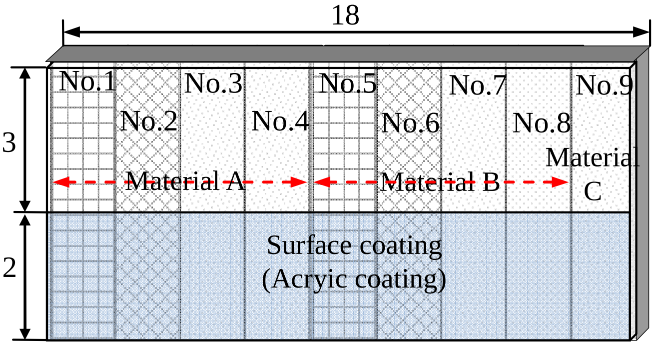


Figure 2. Blocks of different repair types on wall.

3 OUTLINE OF APPLICATION

3.1 *Repair types*

Figure 2 shows the blocks of different repair types on the retaining wall. Table 1 shows the repair materials and conditions of the blocks. The nine repair types were combinations of three shotcretes (A, B, and C) and two steel reinforcement types (welded bar mesh and expanded metal), with or without sealing of cracks, each type being applied to nine different blocks. Each block measured 1.8 m in width and 5 m in height. In blocks with crack sealing, a one-can polyurethane sealant was applied to cover 30 mm-wide areas on cracks to a thickness of 5 mm, to provide bondless areas between the HPFRCC and wall concrete, so as to facilitate the distribution of fine cracks in the HPFRCC over the cracked areas. Two days after the application of shotcretes onto the blocks, a one-can acrylic coating compound was applied to an area across all blocks from the bottom edge of the repair area to a level of 2 m. It was anticipated that the expected cracks in the HPFRCCs would not damage the acrylic overcoat because of their small crack widths, thereby making such cracks scarcely visible from outside.

3.2 *Shotcretes and steel reinforcements*

Shotcrete A was a HPFRCC shotcrete mortar comprising premixed polymer mortar, polyvinyl alcohol (PVA) fibers, and high strength PE (polyethylene) fibers with a total fiber content of 1.5% by volume. Shotcrete B was a HPFRCC shotcrete mortar comprising premixed mortar and high strength PVA fibers with a fiber content of 2.1% by volume. Shotcrete C was a normal cementitious shotcrete mortar for repair. The spray thickness was 50 to 70 mm.

The welded bar mesh was made of D6 bars (SD295) welded into a grid with 100 mm intervals. An expanded metal with a mesh size of 75 by 203 mm (spec: XS-82) was also used. These steel reinforcements, which were placed 10 mm off the wall surface to be embedded in the sprayed HPFRCCs, were expected to allow the cracks in the HPFRCCs to be finely distributed without localization.

(a) Before construction (b) Surface treatment

(c) Reinforcement (d) Unbonded region

(e) Spraying (f) After construction

Figure 3. Shotcreting after surface treatment with water jet.

Table 2. Compression and bending test results.

Materials	Compressive strength (f’c) (MPa)	Young's modulus (E) (GPa)	Bending strength (fb) (MPa)	f’c/fb
A	37.6	15.5	6.72	5.6
B	54.2	20.5	8.31	6.5
C	59.3	29.7	4.65	12.8

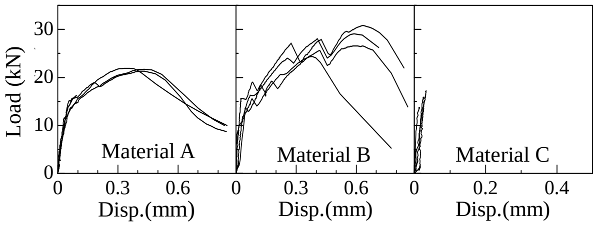


Figure 4. Load-displacement (deflection) curves of bending specimens.

3.3 *Application*

Figure 3 shows the state of shotcreting. Prior to shotcreting, the wall surface was chipped by a water jet to a depth of a few millimeters. The shotcretes were then sprayed to the surface after placing steel reinforcements and sealing the cracks (Blocks 4 and 8). HPFRCC shotcrete A was mixed using a geared mixer with a capacity of 320 liters and pumped with a snake pump for shotcreting. HPFRCC shotcrete B and shotcrete C were produced using a Hobart mixer with a capacity of 120 liters and pumped with a squeeze pump.

Figure 5. Appearances of wall before after water jet treatment.

4 TEST RESULTS OF SHOTCRETES

Since the tension test method for HPFRCCs had yet to be established by the time of this trial application, only compression and bending tests were conducted. Table 2 gives the compression and bending test results at an age of 1 month. Figure 4 shows the load-displacement (deflection) curves of bending specimens 10 by 10 by 400 mm in size measured during third-point flexural loading testing. The static moduli and flexural strengths of both HPFRCC shotcretes were lower and higher, respectively, than those of shotcrete C. Their compressive-to-flexural strength ratios (fc/fb) were smaller than that of shotcrete C. The compressive strength and static modulus of HPFRCC shotcrete B were both higher than those of HPFRCC shotcrete A. In the flexural load-displacement curves of HPFRCC shotcretes A and B measured during third-point loading, the load increased as the displacement increased after the crack onset, clearly showing the so-called deflection-hardening properties. The cracking loads of both HPFRCC shotcretes A and B in the bending testing were similar at around 13 kN, but both the maximum bending load and the displacement at the maximum bending load of HPFRCC shotcrete B were greater than those of HPFRCC shotcrete A.

5 CHANGES OF WALL SURFACE OVER TIME AFTER APPLICATION

5.1 *Observation of cracks and others*

5.1.1 *Method of crack observation and acrylic overcoat*

Wall surface observation has been carried out at regular intervals after application, including visual observation of cracks using a crack scale. The crack width has also been measured using a microscope since 2 years after application.

In the acrylic-coated area 2 m from the bottom edge, such defective events as blistering, delamination, and cracking began to increase in the coating membrane 2 years after application. Delamination and cracks in the coating membrane became so apparent as to mar the aesthetic appearance by 4 years after application. The uncoated area also became so dirty that cracks were difficult to define. For this reason, the area from the bottom edge up to a level 2.5 m above was cleaned with a water jet 4 years after application with the aim of improving the aesthetic appearance of the coated area and facilitate crack measurement. Figure 5 shows the appearances before and after treatment with a water jet.

5.1.2 *Crack mapping*

Cracks were marked with chalk in the range between 1 m above (uncoated) and 1 m below (coated) the level 2 m from the bottom edge. These marks were then photographed with a digital camera and made into a crack map by image analysis. Such a crack map was produced 1, 3, and 5 years after application. Figure 6 shows the appearances of the retaining wall surface and the crack maps.

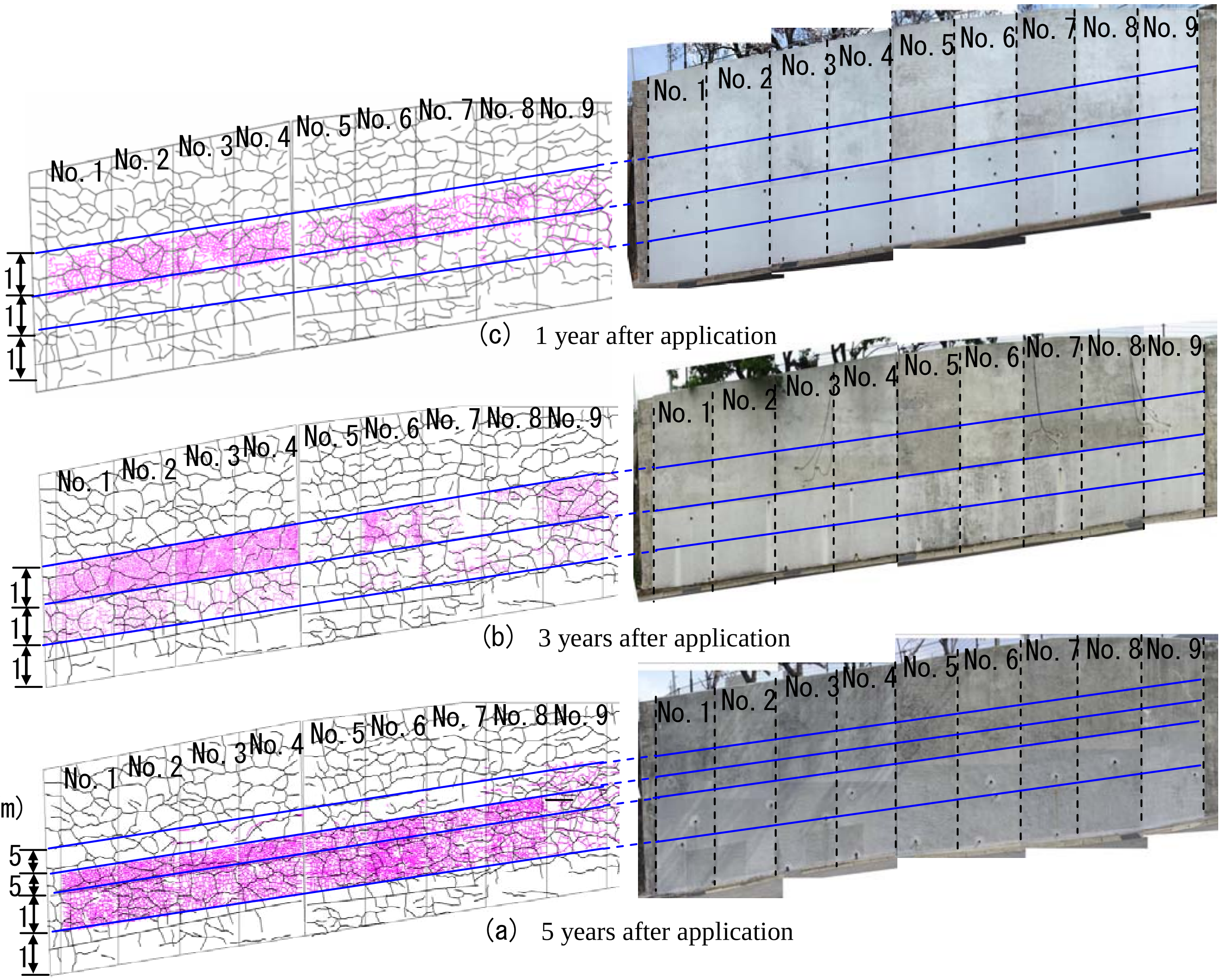
5.1.3 *Up to 1 year after application*

In Block 9 repaired with shotcrete C, fine cracks have been observed since 1 month after application. A continuous long crack in the vertical direction approximately 4.5 m in length was recognized 3 months after application. Map cracks occurred all over the block 10 months after application. In all blocks repaired with shotcretes A and B, fine cracks with a width of not more than 0.05 mm were found 10 months after application.

One year after application, fine mesh cracks were observed in all blocks repaired with all shotcretes. Greater numbers of cracks at smaller intervals were observed in shotcretes A and B than in shotcrete C. In regard to the acrylic-coated areas, cracks were scarcely found in shotcretes A and B, whereas cracks were observed in shotcrete C. This is presumably because wide cracks that the coating film cannot follow occurred in the area repaired with shotcrete C. Dirtiness on shotcretes A and B was slightly more obvious than on shotcrete C but not to an extent that is aesthetically problematic.

5.1.4 *3 years after application*

Three years after application, larger numbers of-cracks than 2 years before were found in the blocks repaired with HPFRCC shotcrete A (Blocks 1 to 4) and shotcrete C (Block 9). In the blocks repaired with HPFRCC shotcrete B (Blocks 5 to 8), however, the numbers of cracks were smaller than those 2 years earlier. This is presumably because in shotcrete B with a higher fiber content than shotcrete A, more fibers were exposed to the air, being more prone to surface contamination with dust and microbes in the atmosphere, which hid most cracks on the surface of shotcrete B. This can also be inferred from the color



(c) 1 year after application

(b) 3 years after application

(a) 5 years after application

Figure 6. Appearances of wall surface and crack maps.

of shotcrete B, which was darker than those of other shotcretes (Fig. 6 (b)).

Three years after application, cracks were also found in the coated areas of shotcretes A and B. The number of cracks was smaller in shotcrete B than in shotcrete A.

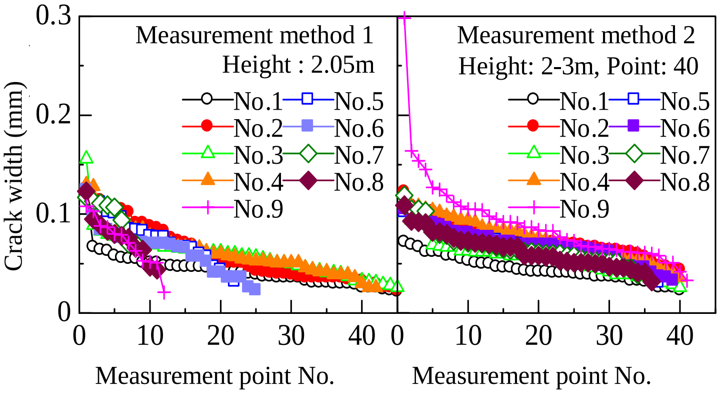
5.1.5 *5 years after application*

As stated above, the area from the bottom edge to a level 2.5 m above was cleaned with a water jet 4 years after application to improve the aesthetic appearance of the area coated with acrylic and facilitate crack measurement. Five years after application, numerous cracks were observed in shotcretes A and B in the area uncoated with acrylic and cleaned with a water jet (the area between 2 and 2.5 m from the bottom edge). On the other hand, most cracks were blocked up with microbes and dirt, making visual observation difficult, in the rest of the uncoated area, which was not cleaned with a water jet (the area between 2.5 and 3 m from the bottom edge). Cracks were readily observed on the surfaces of shotcrete C regardless of waterjetting. As described later, slightly wider cracks tended to occur at slightly larger intervals in the coated area than in the uncoated area of all blocks.

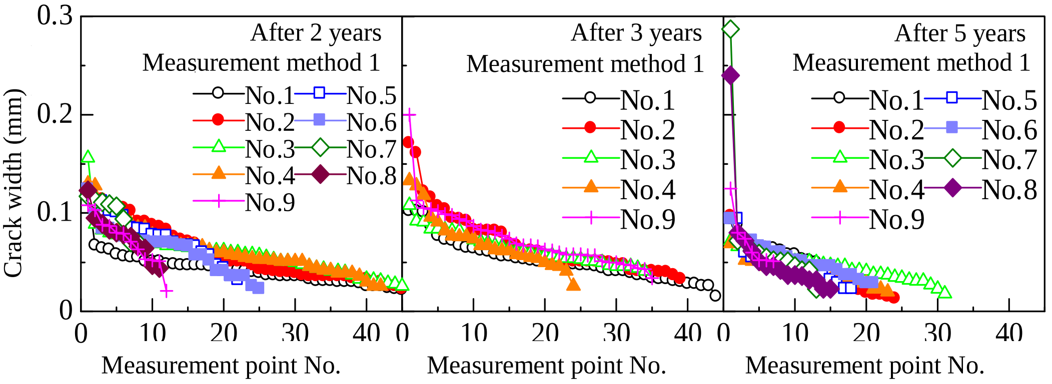
5.2 *RChanges in the crack width over time*

5.2.1 *Methods of measuring crack width*

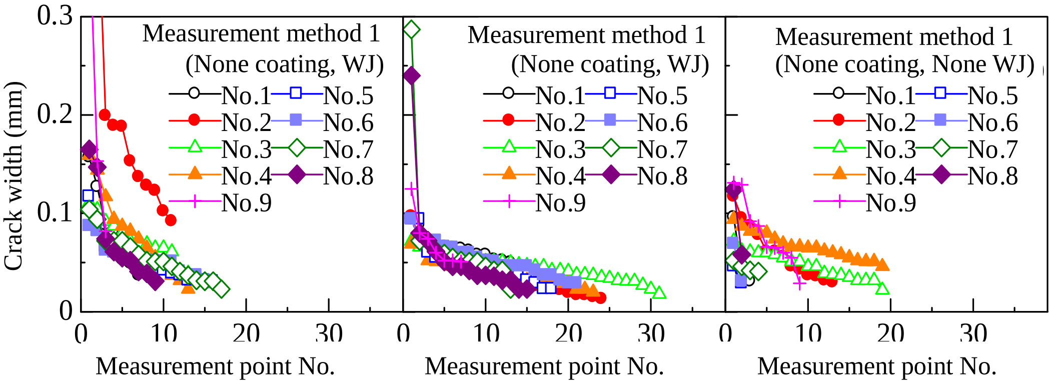
The crack widths on the surface were measured using a microscope, beginning 2 years after application



(a) Comparison between measurement methods.



(b) Changes in crack width over time.



(c) Acrylic overcoat and changes in cracks over time.

Figure 7. Results of crack width measurement.

by the following methods:

Method 1: Draw a horizontal line 900 mm from the left edge of each block at a specified level and measure the crack widths of all cracks across that line.

Method 2: Randomly select 40 cracks from the uncoated area 1.8 m in width of each block between the levels 2 m and 2.5 m from the bottom edge and measure their widths in situ.

Crack widths were measured 2, 3, and 5 years after application as follows:

1) 2 years after application: Method 1 at a level of 2.05 m and Method 2

2) 3 years after application: Method 1 at a level of 2.05 m

3) 5 years after application: Method 1 at levels 1.95, 2.05, and 2.55 m

Figure 4 shows the results of crack width measurement. The horizontal axis represents the number of cracks measured. The crack width measurements are arranged in descending order, with the widest crack being plotted at the left end.

5.2.2 *Comparison between measurement methods*

Figure 7(a) shows the results of crack width measurement 2 years after application by methods 1 and 2. The cracks in blocks repaired with HPFRCC shotcretes A and B (Blocks 1 to 8) were 0.1 to 0.15 mm in width at the largest, mostly being fine cracks with a width of less than 0.1 mm. In Block 9 repaired with shotcrete C, the crack width measurements were similar to those in HPFRCC-repaired blocks by Method 1, but the maximum crack width was around 0.3 mm by Method 2, with the width of more than 40% of the cracks being not less than 0.1 mm. The difference of the measurement method may have affected the crack width measurements of shotcrete C, which partially contained large cracks. While Method 2 can emphasize large crack widths, the selection of cracks is subject to the operator's arbitrary decision. It was therefore decided to adopt Method 1 for measurement 3 and 5 years after application. Note that shotcrete C included apparent "through cracks" showing traces of water leakage from the backside.

5.2.3 *Changes in crack width over time*

Figure 7(b) shows the changes in the crack width over time measured by Method 1 on a horizontal line 900 mm in length from the left edge of each block at a level of 2.05 m. Since it was difficult to measure the crack width in Blocks repaired with HPFRCC shotcrete B (Blocks 5 to 8) due to contamination, only crack widths in blocks repaired with shotcretes A and C (Blocks 1 to 4 and Block 9) were measured 3 years after application. Five years after application, however, the crack widths of all blocks were measured, as surface contamination was cleaned with a water jet a year earlier.

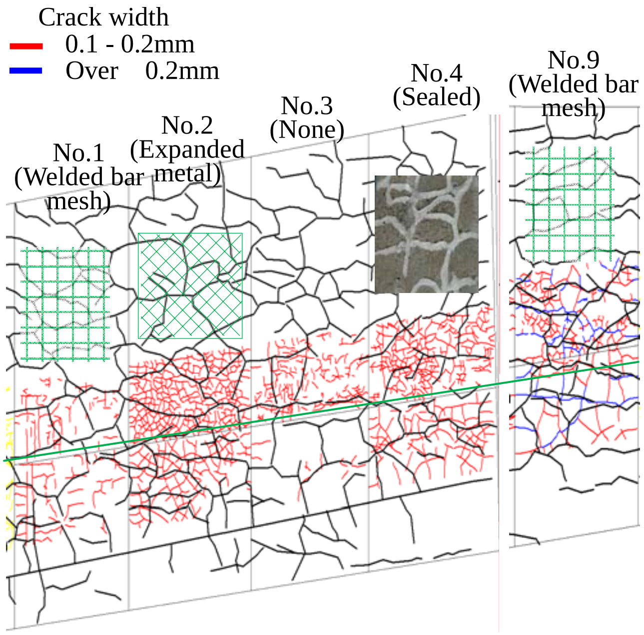


Figure 8. Effects of steel reinforcement and crack treatment.

No increase in the crack width over time was observed in all shotcretes, with most crack widths remaining around 0.02 to 0.1 mm. Figure 7(b) shows no large crack widths in shotcrete C, because no large local cracks were included in the measurement range.

5.2.4 *Acrylic overcoat and changes in cracks over time*

Figure 7(c) shows the results of crack width measurement in (a) coated areas cleaned with a water jet (along the line at a level of 1.95 m); (b) uncoated areas cleaned with a water jet (along the line at a level of 2.05 m); and (c) uncoated areas not cleaned with a water jet (along the line at a level of 2.55 m).

As stated above, the crack widths in coated areas tended to be greater than those in uncoated areas. In areas uncoated and not cleaned with a water jet, the widths of most cracks were less than 0.1 mm regardless of the shotcrete type. In regard to HPFRCC shotcretes A and B, this may be because the cracks were measured narrower because of being blocked up with microbes and dirt. In regard to shotcrete C, this may be because large cracks were outside of the measurement range by the adopted measurement method. The fact that crack width measurement in shotcrete C is affected by the measurement method is also recognized in the graphs for uncoated and uncleaned areas in Figure 6, in which few cracks are visually observable in shotcretes A and B, whereas many cracks are observed in shotcrete C. Thus cracks in shotcrete C should have been observed over a wider range.

5.3 *Effects of steel reinforcement and crack treatment*

Three years after repair, cracking was investigated in relation to steel reinforcement and crack treatment.

Figure 8 shows crack maps of HPFRCC shotcrete A and shotcrete C 3 years after application. Only large cracks judged as being 0.1 mm or wider by a crack scale are shown in the figure. As is seen from Blocks 1 and 9 having welded bar mesh, when repaired with shotcrete C, cracks with a width of 0.2 mm or more occur in the shotcrete directly above the underlying cracks in the retaining wall concrete, while smaller cracks 0.1 to 0.2 mm wide developed between these wider cracks. When repaired with HPFRCC shotcrete A, no cracks related to underlying cracks were found, but predominant cracks ran in the vertical and horizontal directions at intervals similar to those of the embedded welded bar mesh. When reinforced with expanded metal, cracks resembling the mesh shape developed. Though steel reinforcement was placed to finely distribute cracks in the HPFRCCs, its effect was not appreciable partly because of the small tensile deformation of the HPFRCC layer.

In Block 4 where the cracks in the retaining wall concrete were sealed beforehand with a sealant, the number of cracks with a width of 0.1 mm or more exceeded that in Block 3 having no steel reinforcement. This tendency was clearer in the area coated with acrylic. Though cracks in the retaining wall were sealed beforehand with the aim of finely distributing cracks in the HPFRCC, the effect of sealing turned out to be not clear partly because of the small tensile deformation of the HPFRCC layer similarly to steel reinforcement.

6 CONCLUSIONS

A surface of a concrete gravity retaining wall having cracks due to alkali-silica reaction was repaired by spraying fiber-reinforced cementitious composites forming multiple fine cracks (HPFRCCs) for landscaping and subjected to observation over five years. The following results were obtained:

1) Crack widths were mostly limited to not more than 0.1 mm in HPFRCC shotcretes A and B 5 years after application. The use of the HPFRCCs for surface repair thus had the expected effect of improving the aesthetic appearance of the landscape.

2) Because of the fine cracks of both shotcretes A and B, most cracks were blocked up with microbes and dirt, making visual observation difficult, by 3 and 5 years after the application of shotcretes A and B, respectively.

3) Steel reinforcement was placed in the HPFRCCs, and cracks in substrate concrete were sealed with a sealant to weaken the bond with the HPFRCC near the cracks, with the aim of finely distributing the cracks in the HPFRCCs, but no appreciable effects were obtained partly because of the small tensile deformation of the HPFRCC layer.

4) An acrylic overcoat on the HPFRCCs hid their fine cracks for approximately 2 years. However, the acrylic coating then deteriorated, with delamination and cracking increasing, and began to impair the aesthetic appearance by 4 years after application. Thus the acrylic overcoat on the HPFRCCs had an appearance-improving effect only for a short period.

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