Follow-Up Review of Early SHCC Applications in Japan

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Abstract. This paper discussed some early applications of SHCC to structures in which the authors were involved, describing their outlines and evaluations to date, while presenting various technical ideas related to SHCC. SHCC has been shotcreted for surface repair of concrete hydraulic structures, since around 2005. Premixed SHCC products have since then been progressively enhanced, with the application methods being improved. It has been continuously adopted, with no defects or significant deterioration over time having been reported. In the construction of emergency bays in Hida Tunnel around 2007, multilayer shotcrete lining was adopted, and SHCC was shotcreted as the protective layer for the lining. The follow-up review of the lining conducted in 2015 confirmed that the multilayer shotcrete lining including the thin layer of SHCC provides the desired performance. SHCC has been applied to the bases of new-type noise barriers as protective mortar along Tokaido Shinkansen since 2013. No problems have arisen regarding the renewed new-type noise barriers and the protective mortar (SHCC) for the bases.

Keywords: SHCC · HPFRCC · ECC · Tough mortar · Application · Follow-up

1 Introduction

A considerable period is required until a new material turns out to be good. Follow-up reports on the results of new material applications are not fully available, though they are strongly desired.

Strain-hardening cementitious composites (SHCC), which demonstrate strain-hardening and multiple fine-cracking behavior under tension, emerged in the 1990s as an attractive new cement-based material developed by substantially enhancing the performance of normal concrete and conventional steel fiber-reinforced concrete. Research on SHCC was early on conducted by Li, V.C. [1] and Kanda, T., et al. [2]. Note that SHCC are referred to in Japan as HPFRCC, ECC, tough mortar, etc. The term SHCC is used in this report as a generic term.

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In the 2000s, production and performance assessment technologies related to this material progressed with the organization of committees in Japan Concrete Institute (JCI) and Japan Society of Civil Engineers (JSCE), with trial application to structures being initiated. In 2003, the authors, together with Kanda, T., et al., carried out trial shotcreting of SHCC (ECC and tough mortar) for restoring the appearance of a gravity-type retaining wall with ASR cracks on the premises of a facility managed by Gifu Prefecture.

In 2007, JSCE published the Recommendations for Design and Construction of High Performance Fiber Reinforced Cement Composites with Multiple Fine Cracks (HPFRCC) (Draft) [3], facilitating their application to structures. The authors were involved in the application of SHCC to repair of agricultural hydraulic structures, construction of emergency bays in Hida Tunnel, large-scale renovation to Tokaido Shinkansen, repair of bridge girder ends, and so forth [4].

This paper reports on the outline of SHCC applications and their follow-up review, while describing technical ideas related to SHCC.

2 Trial Application of SHCC for Restoring the Appearance of ASR-Cracked Concrete Retaining Wall (2003 and 2008) [5]

2.1 Outline of Retaining Wall and Initial SHCC Shotcreting (April 2003) [6]

This gravity-type retaining wall (approximately 18 m in width and 4 to 5 m in height) constructed around 1970 suffered cracking due to ASR. In April 2003, surface repair was conducted by shotcreting SHCC and repair mortar to a thickness of 50 to 70 mm for the purpose of restoring. Figure 1 shows the block layout of the wall.

Block Nos. 1 to 4 were shotcreted with tough mortar, a type of SHCC, with compressive strength (f_c) of 37.6 MPa. The tough mortar contained polyvinyl alcohol (PVA) fibers 12 mm in length and high strength polyethylene (PE) fibers 12 mm in length (1.5 vol % in total). Block Nos. 5 to 8 were shotcreted with ECC containing 12-mm long high-performance PVA fibers (2.1 vol %) with f_c of 54.2 MPa. Block No. 9 was shotcreted with normal repair mortar with f_c of 59.3 MPa. The bottom area to a height of 2 m was additionally coated with acrylic. Prior to shotcreting, the wall surface was polished by waterjetting. Welded wire mesh (D 6, SD 295 at 100 mm pitch) was set on Block Nos. 1, 5, and 9. Expanded metal (75 by 203 mm, XS-82) was set on Block Nos. 2 and 6, both at around 10 mm from the wall surface.

2.2 Thin Layer Shotcreting of SHCC (October 2008)

In April 2008, the range from the bottom of the wall to a height of 2.5 m including the acrylic coating was polished by waterjetting, as stain on the acrylic became noticeable. In October 2008, shotcreting of SHCC (tough mortar) on the polished area was demonstrated to participants of an international convention held at this time nearby. The shotcreting thickness was approximately 20 mm from the bottom of the wall to a height of 1 m and 10 mm in the range of 1 to 2 m in height (Fig. 2).

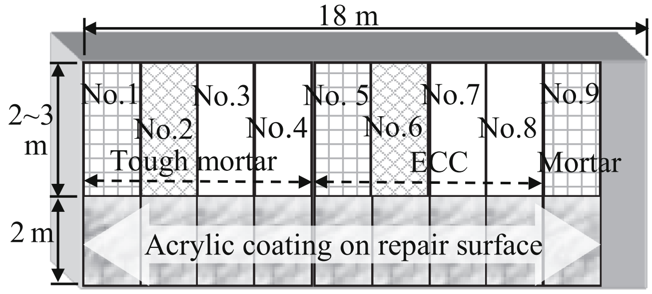

Fig. 1. Block layout of the wall.

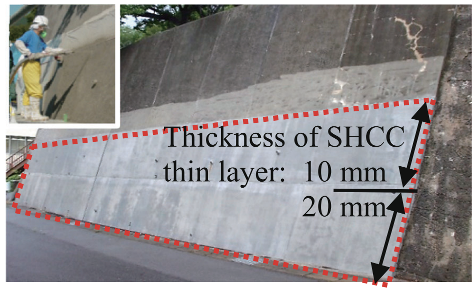

Fig. 2. Thin layer shotcreting of SHCC.

2.3 Follow-Up Survey (September 2020)

Figures 3 and 4 show normal and thermal images, respectively, taken with a drone-mounted camera in September 2020, which is 17 years after the initial application. These were made by synthesizing 23 images each into orthomosaic images of the wall frontal.

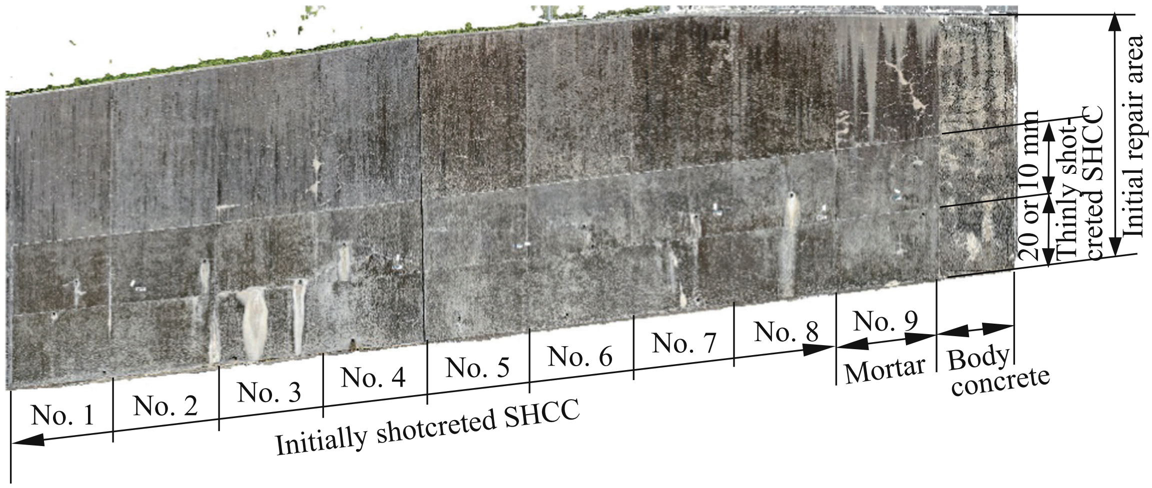

Fig. 3. Image of the retaining wall.

Stain due to efflorescence, etc., was less evident on Block Nos. 1, 2, 5, and 6 where reinforcement was laid out in the SHCC layer in the initial application (Fig. 3). In Block No. 9 (thin-layer SHCC on normal repair mortar), a wide range of delamination was recognized by hammering test and thermal imaging analysis (Fig. 4) under the thin-layer SHCC (10 to 20 mm in thickness), which was shotcreted five years after the initial application. Delamination was also found mainly near the boundaries between Block Nos. 5 to 9. On the other hand, no delamination was found in the initially shotcreted SHCC (the area above the level 2 m from the bottom, 50 to 70 mm in thickness) by hammering test and thermal image analysis.

2.4 Technical Discussion

SHCC was found superior to repair mortar in suppressing crack widening and inhibiting stain due to efflorescence. It was proven appropriate to select the thickness of 50 to

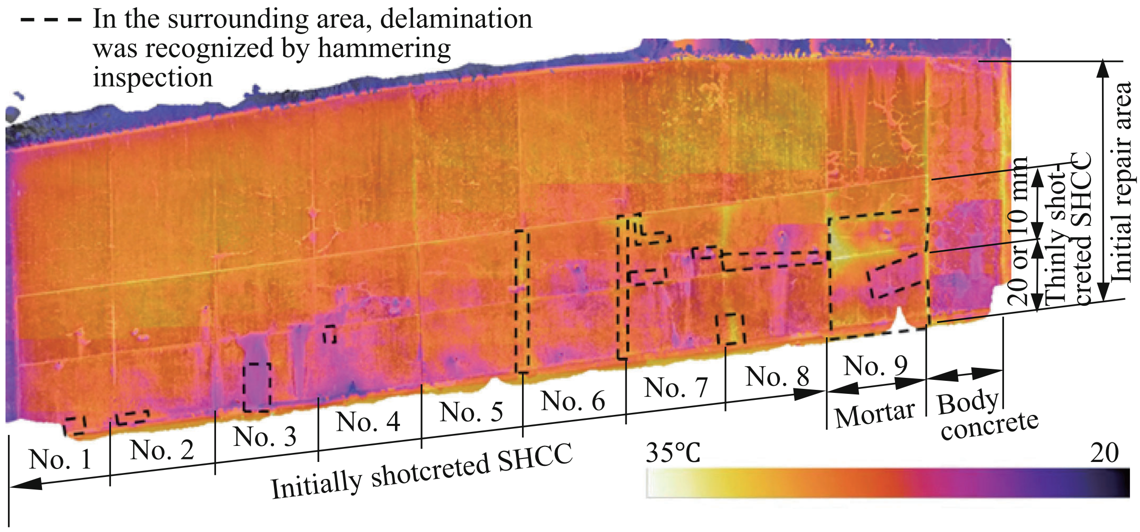

Fig. 4. Thermal image of the retaining wall.

70 mm, instead of 10 to 20 mm, in the initial shotcreting of SHCC onto this size of retaining wall, causing little delamination. The placement of reinforcement (welded wire mesh or expanded metal) was proven more effective, than without, in suppressing the crack width and inhibiting stain due to efflorescence. The restoring effect of acrylic coating over the lower half area after the initial application lasted only around two years.

3 Application of SHCC to Concrete Hydraulic Structures as a Surface Repair Material (2005–)

3.1 Repair of Concrete Hydraulic Structures

Construction of agricultural hydraulic facilities including waterways began in the 1950s in Japan. Some of them have been suffering from functional degradation with age, leading to the launch of a new subsidy system for repair in 2003. Hydraulic structures made of concrete are generally repaired by surface coating and patching, utilizing the existing concrete body, unless it is structurally deteriorated. The performances required for such repair materials include resistance to abrasion, resistance to frost attack, steel corrosion protection, and adhesion to the structural body. SHCC has therefore been used as a promising repair material.

3.2 Premixed SHCC Products

Premixed SHCC ready for mixing on site is generally used in wet shotcreting for surface repair of hydraulic structures. It incorporates 1.7 vol % PVA fibers to provide ultimate tensile strain (s_t) of around 1.0% and f_c of around 40 MPa. During the early stage of application for 10 years since 2005, only the mortar fraction was premixed while the short fibers were added during mixing in a mixer. However, premixed products with short fibers have become available since 2015. While a high-speed mixer rotating at more than 60 revolutions/min was initially used to ensure fiber dispersion, since 2015 the premixed products with short fibers can be mixed using a general-purpose low-speed mixer. In the production of the premixed products with short fibers at factories, in addition to adjustment of flowability and viscosity using water reducers and viscosity enhancing agents, there have also been changes in the aggregate size (from 0.5 mm or less to 1.0 mm or less), and changes in the fiber length (from 12 mm to 8 mm). Even after these changes, the maximum tensile strain remains at around 1.0%.

3.3 Repair Methods

Application of SHCC begins with removal of the deteriorated surface to a depth of approximately 1 mm by water jetting, and then follows patching or surface coating with SHCC by troweling (small areas) or shotcreting (Fig. 5). A squeeze pump is used for shotcreting, with the pumping distance being around 50 m at the maximum. After shotcreting with SHCC, the surface is sprayed with an acrylic emulsion at a spread of approximately 150 g/m^2 before troweling. The emulsion improves the trowel slidability, enhancing the efficiency of finishing work, while increasing the initial curing effect due to the formation of the emulsion coating on the finished surface. A method is also adopted for waterway tunnels by which fiber grid reinforcement is placed, onto which SHCC is shotcreted to form a 15 mm coating, to enhance the load-bearing capacity of the existing lining and prevent spalling (Fig. 6).

(a) Waterjetting (b) Coating with SHCC (c) Spraying with emulsion (d) Troweling

Fig. 5. Application of SHCC to agricultural waterway.

(a) Fiber grid reinforcement (b) Coating with SHCC (c) Completed

Fig. 6. Application of SHCC to waterway tunnel.

3.4 SHCC Applications to Concrete Hydraulic Structures and Follow-Up Review

Application of SHCC for repair of concrete hydraulic structures totaled more than 400 structures including open waterways, intakes, dams, and waterway tunnels made of concrete, with the area of application being more than 280,000 m^2. No report has been received regarding defects or significant age deterioration of SHCC for 16 years since its initial application. Rather, its crack-suppressing performance and resistance to frost damage are highly rated, with its application being continuously in demand.

4 Application of SHCC to Emergency Bays in Hida Tunnel as a Protective Layer for Multilayer Lining (2007)

4.1 Hida Tunnel

Hida Tunnel, which opened in July 2008, is a long tunnel spanning 10.7 km on the Tokai-Hokuriku Expressway, being located to the south of Shirakawago, a World Heritage site. It consists of the main tunnel and escape tunnel (pilot tunnel) with a cross-sectional area of 130 m^2 and 16 m^2, respectively. Excavation of the escape tunnel began in October 1996 prior to the main tunnel.

4.2 Multilayer Shotcrete Lining Adopted for the Emergency Bays [7]

After being completed in January 2007, the main tunnel was widened at 33 points to construct emergency bays. Multilayer shotcrete lining (Fig. 7) was adopted for the walls of 16 of the 33 emergency bays instead of conventional cast-in-place concrete lining, for the first time among domestic expressway tunnels.

Fiber-reinforced shotcrete with f_c of 36 MPa incorporating 0.75 vol % or 1.0 vol % polypropylene (PP) fibers 32 mm in length was used as the primary support layer to a thickness of around 150 mm after excavation to ensure stability of the excavation site and the surrounding ground.

Steel fiber-reinforced shotcrete with f_c of 36 MPa incorporating 0.75 vol % or 1.0 vol % steel fibers 30 mm in length was then applied as the secondary layer in two phases to a thickness of around 250 mm in total, to increase the structural performance.

As the tertiary layer, SHCC with f_c of 40 MPa incorporating 2.0 vol % PVA fibers 12 mm in length was applied to prevent spalling of the secondary layer, prevent corrosion of steel fibers, enhance water tightness, and improve the appearance (smooth the surface irregularities of the secondary layer). The SHCC was shotcreted with a thickness of 10 to 20 mm and then smoothed by surface rolling (Fig. 8).

4.3 Follow-Up Review of Multilayer Shotcrete Lining

Follow-up review of the multilayer shotcrete lining was conducted in 2015 based on the results of visual inspection and strength tests [8]. This section introduces the content of this review. Note that SHCC are characterized by their capability to form many fine cracks under tensile forces.

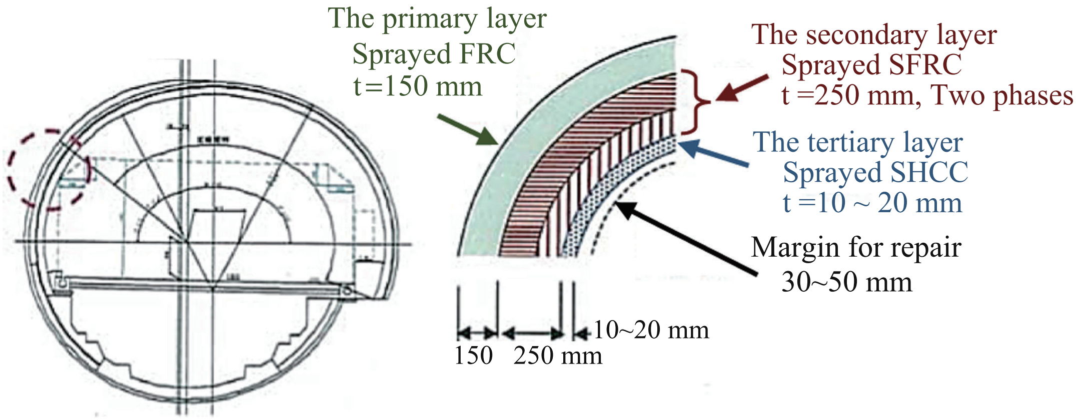

Fig. 7. Multilayer shotcrete lining.

Fig. 8. Completed shotcrete lining [7].

Fig. 9. Typical efflorescence [8].

Figure 9 shows a photograph of typical efflorescence at emergency bay No. 16 where efflorescence and cracks are extensively found. In this bay, the lengths of efflorescence and cracks totaled 20,450 mm and 17,045 mm, respectively. Despite their long extension, no water leakage was found, and the crack width was small, ranging from 0.2 to 0.5 mm, with no sign of progressive growth. Three core samples in total were drilled from emergency bays Nos. 12, 16, and 32 to be subject to compression tests, with the results of all cores exceeding 50 MPa with no delamination at the layer boundaries. Accordingly, the multi-layer shotcrete lining revealed no structural problem about 10 years after application, though with efflorescence and cracks [8].

Since it was confirmed by the follow-up review that the multi-layer shotcrete lining is providing the desired performance, SHCC forming the tertiary layer is also considered to provide the performance initially anticipated.

5 Application of SHCC to Viaducts of Tokaido Shinkansen as Protective Mortar for the Bases of Noise Barriers (2013–)

5.1 Large-Scale Renovation of Tokaido Shinkansen

Tokaido Shinkansen, a bullet train connecting Tokyo, Nagoya, and Shin-Osaka, has been in service since 1964. Along its overall length of 515 km, a large-scale renovation project has been under way since 2013 at steel bridges (total extension of 22 km), concrete bridges (148 km), and tunnels (69 km). Among the concrete bridges under renovation, those totaling 98.2 km are viaducts [9].

5.2 Application of SHCC to the Bases of New-Type Noise Barriers

Tokaido Shinkansen initially had no noise barriers, but they were progressively constructed thereafter, where required, mostly in residential areas. The loads due to the addition of such barriers were therefore not expected in the initial design of the viaducts. In the large-scale renovation project, noise barriers have therefore been replaced with a new type to minimize the effect of wind loads generated by the noise barriers on the cantilever parts of viaducts. In the new-type barriers, anchor bolts that pierce through the cantilever concrete together with the top and bottom steel plates (jackets) strengthen the cantilever members by making them composite structures [10]. As part of the large-scale renovation project of Tokaido Shinkansen, SHCC with f_c of 40 MPa, containing 2.0 vol % PVA fibers 12 mm in length, has been basically used since 2013 to the bases of the new-type noise barriers for the purpose of suppressing crack width, preventing steel corrosion, and securing inspection passages (Fig. 10). To date, the usage of SHCC on this line has exceeded 10,000 m^3.

(a) Before and after renovation of viaducts with new-type noise barriers

(b) Casting of SHCC to the bases

Fig. 10. Casting of SHCC to the bases of new-type noise barriers on viaducts.

5.3 Technical Discussion and Follow-Up Review

Prior to selecting the protective material for the bases of the new-type noise barriers, trial application was conducted using SHCC, high-early-strength concrete, PP fiber-reinforced concrete, ultraquick-setting non-shrink concrete, etc. These tests led to the selection of SHCC, which is less prone to cracking. The steel bases for the new-type noise barriers were coated with an epoxy primer to ensure unification with SHCC. It was therefore important to place SHCC within the setting time of the primer.

Replacement with the new-type noise barriers and SHCC placement in the bases are mostly carried out in a short time from midnight to early morning when the trains are out of operation. Experiments have confirmed that vibration equivalent to train running does not adversely affect the bond strength development between steel and SHCC [11]. This substantially relaxed the time limits of SHCC placement.

Ten years having passed since the start of replacement with the new-type noise barriers and placement of SHCC in their bases, no problems have arisen regarding the new-type barriers, the jackets of steel plates of the cantilever segments, or protective mortar (SHCC) for the bases.

6 Conclusions

This paper discussed some early applications of SHCC to structures in which the authors were involved, describing their outlines and evaluations to date, while presenting various technical ideas related to SHCC.

SHCC was shotcreted onto an ASR-cracked concrete retaining wall for restoring on a trial basis to a thickness of 50 to 70 mm in 2003. Five years later, a thin layer (10 to 20 mm) of SHCC was shotcreted on this wall. In an inspection conducted in 2020, delamination was discovered over a wide range of the thin layer of SHCC shotcreted on reference mortar. It was therefore judged appropriate that SHCC was initially shotcreted to a thickness of 50 to 70 mm, with reinforcement being laid out.

SHCC has been shotcreted for surface repair of concrete hydraulic structures including waterways, etc., since around 2005. Premixed SHCC products have since then been progressively enhanced, with the application methods being improved. It has been continuously adopted, with no defects or significant deterioration over time having been reported.

In the construction of emergency bays in Hida Tunnel around 2007, multilayer shotcrete lining was adopted, and SHCC was shotcreted as the protective layer for the lining. The follow-up review of the lining conducted in 2015 confirmed that the multilayer shotcrete lining including the thin layer of SHCC provides the desired performance.

SHCC has been applied to the bases of the new-type noise barriers as protective mortar along Tokaido Shinkansen since 2013. No problems have arisen regarding the renewed new-type noise barriers, the jackets of steel plates of the cantilever segments, and the protective mortar (SHCC) for the bases.

When cracks occur in concrete, the smaller their width, the more desirable in terms of both durability and aesthetic appearance. In the application cases stated above, SHCC is used as a concrete less prone to cracking and with smaller crack width. Meanwhile, despite abundant studies and various suggestions to make the most of its high tensile resistance and fracture toughness (energy-absorbing capacity), there are still few application examples to take advantage of these features, raising hopes for the future.

For a concrete-based material including fiber-reinforced concrete, deterioration is known to be accelerated under the combined effects of cracking, water, and member deformation/pressure. It is therefore important to take sufficient measures for waterproofing and drainage, suppress deformation by combining with structures with high stiffness, and ensure the bond between concreting lifts and at boundaries with other materials. With these points in mind, it is desired that SHCC will be extensively used, making bold and careful steps forward.

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