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DURABILITY OF HES-ECC REPAIR UNDER MECHANICAL AND ENVIRONMENTAL LOADING CONDITIONS

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Abstract

The lack of durability in concrete repairs induces premature repair deterioration and endless "repair of repairs". This paper suggests High Early Strength Engineered Cementitious Composites (HES-ECC) as a material solution to repair failures under both mechanical and environmental loading conditions. HES-ECC is a new class of HPFRCC, which has been micromechanically designed for concrete structure repair applications with high early strength, high ductility and toughness indicated by multiple micro-cracking behavior under unaxial tension. Experimental study shows that when subject to monotonic flexural loading, the HES-ECC layered repair system showed 100% increased load carrying capacity, and 10 times the deformation capacity of HES-Concrete layered repair system. When under the same level of fatigue flexural loading, HES-ECC layered repair system exhibited significantly longer service life. In addition, the high ductility of HES-ECC could relieve shrinkage induced stresses in the HES-ECC repair layer and at the HES-ECC/concrete interface, thereby suppressing large surface cracks and interface delamination. The concept of translating ECC repair material ductility to the whole repair system durability can be widely applied to many concrete structures repair applications for developing cost-effective and durable concrete repairs.

1. INTRODUCTION

The purpose of this research is to overcome the lack of durability in concrete repair, through innovations of cement based repair materials with ultra ductility in tension. It has been reported [1] that about 50% of repairs fail in the field. Concrete repairs are often perceived to lack both early age performance and long-term durability. While knowledge of the causes of failure and the recognition of the need for material compatibility has been increasing in recent years, a robust and cost-effective solution appears lacking. In this research, focus is placed on the source of the problem: a lack of tensile ductility in current repair mortars so that surface cracks, spalling and delamination are common failure phenomena.

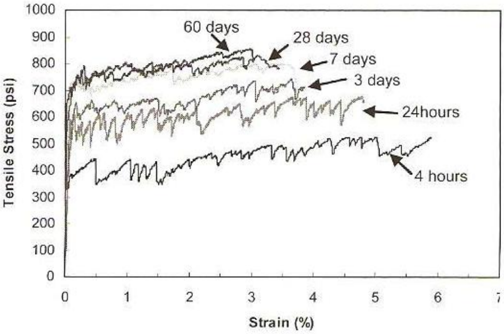

Figure 1: Tensile stress-strain curve of HES-ECC

The approach of this research is to utilize High Early Strength Engineered Cementitious Composites (HES-ECC) as a repair material to improve durability of repaired concrete structures. HES-ECC has been developed under the guidance of micromechanical models for concrete structures repair applications. HES-ECC can achieve high early age compressive strength of around 20 MPa at 4 h, 35 MPa at 6 h, 40 MPa at 24 h, and high late age compressive strength of around 50 MPa at 7 d, 55 MPa psi at 28 d, and 57 MPa at 60 d. It also has high tensile strain capacity of more than 3% and toughness indicated by multiple micro-cracking behavior under uniaxial tensile loading. Its tensile stress-strain curves at different ages are shown in Fig. 1.

2. HES-ECC REPAIR UNDER MECHANICAL LOADING

Mechanical loading can cause repair cracking and interface delamination between the repair layer and the concrete substrate. When cracks exist in the concrete substrate, mechanical loading such as traffic loading will induce the maximum bending stress in the repair layer near to the cracks. This is because there is no load transfer through the existing cracks. Interface delamination can also happen around existing cracks due to the lack of the deformation compatibility between the two layers. Therefore, the whole delaminated section in the repair layer is subject to the maximum bending stress. Cracking happens in the repair layer when the maximum stress exceeds the repair material's tensile strength. This phenomina is normally refered to "reflective cracking". The detailed discussion on stress distribution and failure mechanism in a repair system under mechanical loading can be found in Zhang and Li (2002) [2]. In this research, experimental study was made on the performance of a layered repair system under monotonic and fatigue flexural loading. The repair cracking, interface delamination, load carrying capacity and deformation carrying capacity of the repair system was investigated. Influence of concrete substrate surface preparation on the repair system's overall performance was also evaluated and reported here.

2.1 Experimental Program

A layered repair system was investigated for resistance to spalling and delamination under mechanical loading, such as that induced by wheel loading. This system contains a layer of repair material cast on a substrate layer of old concrete with initial crack and little extent of interfacial delamination. The layered system was initially used by Lim and Li (1997) [3] and Kamada and Li (2000) [4] to simulate the reflective cracking in overlaid pavement. As shown in Fig. 2, a vertical crack in the old concrete substrate was initially introduced to simulate already existed cracking in concrete structure. A horizontal interfacial crack between the repair layer and the substrate layer was also produced before testing to simulate an initial debonding zone above the crack location in the old concrete. The specimen was subjected to four-point bending load with load-deflection curve monitored during testing. The deflection of the specimen at the center was measured by two linear variable differential transducers (LVDTs), which were mounted on both sides at the center of the layered beam.

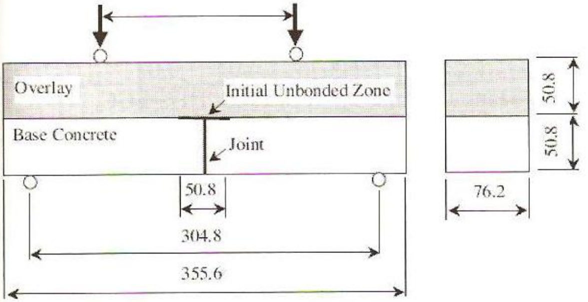

Figure 2: Dimensions of layered repair system under mechanical loading in mm

Both the monotonic and cyclic loading tests were conducted on a 250kN load capacity, MTS-810 testing machine equipped for closed-loop testing. The monotonic flexural test was carried out with deformation controlled by the displacement of the actuator. The displacement was increased at a constant rate of 0.1mm/min similar to ASTM C1018 "Standard Test Method for Flexural Toughness and First-Crack Strength of Fiber-Reinforced Concrete". The fatigue flexural test was conducted with load controlled using a sinusoidal waveform with a frequency of 2 Hz. It started with a ramp to the maximum load Pmax at a rate of 0.1 kN/s followed by a sine waveform fatigue loading. The maximum load (Pmax) is 0.9, 0.8 and 0.7 of the average load-carrying capacity of the layered repair system, which was obtained from the monotonic flexural test results. The ratio R between the minimum and maximum load levels was constant at $R = P_{min}/P_{max} = 0.1$. 3 specimens will be tested for each category.

Two different repair materials, HES-ECC and HES-Concrete, were investigated in this study. HES-Concrete was employed as control. The mixing proportion and properties of the repair materials are listed in Table 1 and Table 2.

Concrete beams with dimensions of 355.6 mm × 76.2 mm × 50.8 mm were first cast, and demolded after 24 hours. After demolding, the beams were cured in water at 22-26°C for 28 days. Then each beam was cut using a diamond saw into four concrete blocks with size of 177.8 mm ×76.2 cm × 50.8 cm. The blocks were then stored in the laboratory condition for another week and then smooth plastic tape was used to form vertical cracking and interfacial debonding before the repair layer was cast. The vertical cracking was in the middle of the concrete substrate, and the interfacial debonding length was 50.8 cm. Each repair layer, made of either HES-ECC or HES-concrete, was cast on the top of two concrete blocks which formed the concrete substrate. The layered specimens were then demolded at 6 hours, air cured, and tested at the age of 28 days.

The cotact surface was roughened in the fresh state using a chisel to remove slurry cement from external surfaces of coarse aggregates. Before placing the repair layers, the substrate surfaces were recleaned with a brush and high-pressure air to ensure a clean bonding surface, and then they were dampened to achieve better bonding with the repair layers. After that, 50.8-cm-thick repair layers made of each of the two repair materials were cast on the top of the concrete substrates.

Table 1: Repair materials composition

Material	C [(a)]	W	S	CA	SP	AC	V_f
HES-Concrete	1.0	0.4	1.3	1.3	0.005	0.04	--
HES-SFRC	1.0	0.4	1.3	1.3	0.005	0.04	0.01 [(c)]
HES-ECC (Mix 7)	1.0	0.33	1.0	0.064 [(b)]	0.0075	0.04	0.02 [(d)]

[(a)] Portland type III cement, [(b)] Polystyrene beads as coarse aggregates for HES-ECC, [(c)] Steel hooked fiber, [(d)] PVA fiber

Table 2: Repair materials mechanical properties

Material	ε_u %	f_c' (MPa) [(a)]	E (GPa) [(a)]	Tensile Behavior
HES-Concrete	0.01	49.9±1.6 (7d) 54.2±2.4 (28d)	26.2±1.4 (7d) 27.8±1.5 (28d)	brittle
HES-SFRC	0.01	51.4±2.4 (7d) 56.9±2.0 (28d)	25.7±2.0 (7d) 27.9±1.3 (28d)	quasi-brittle
HES-ECC	2.5~5	47.5± 1.9 (7d) 55.6±2.2 (28d)	20.6±0.7 (7d) 23.2±1.0 (28d)	ductile

[(a)] Mean ± standard deviation

2.2 Experimental Results

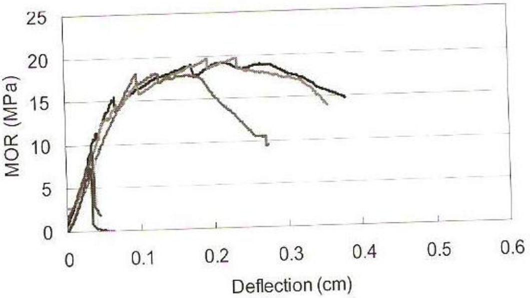

Figure 3: Flexural behavior of HES-ECC and HES-Concrete layered repair system under monotonic loading

The flexural behavior of HES-ECC repair system compared with HES-Concrete repair system under monotonic loading is shown in Fig. 3. The modulus of rupture (MOR) of the specimens were determined by

$$MOR = \frac{M}{bh^2/6}$$

where M is the bending moment at the center of the specimen, b is the width of the repair layer, and h is the thickness of the repair layer. It can be seen that HES-ECC layered repair system exhibited very ductile failure mode. This was in contrast with the sudden brittle failure mode of the HES-Concrete layered repair system. The flexural load carrying capacity of the HES-ECC repair system was significantly higher than HES-Concrete repair system. The MOR of the HES-ECC repair system was more than 100% higher than the HES-Concrete repair system. Furthermore, the deformation capacity of HES-ECC repaired system, represented by the specimen's center deflection at peak load, was 5 to 10 times higher than that of HES-Concrete repaired system. The greatly increased MOR and deformation capacity were contributed by the strain hardening behavior and high ductility of HES-ECC, which is in contrast with the tension softening behavior and brittle nature of HES-Concrete.

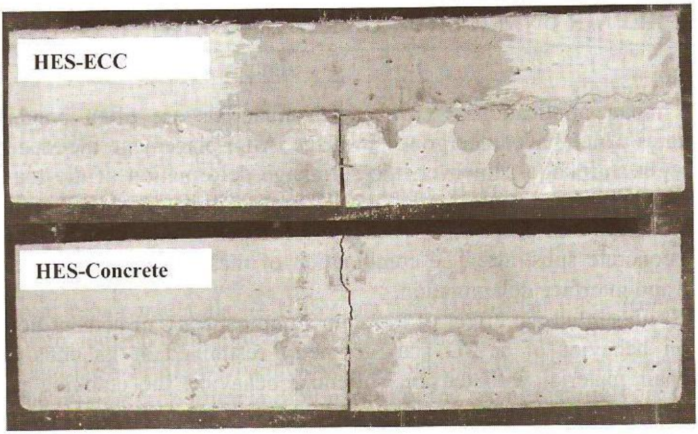

Figure 4: Cracking and interface delamination of different layered repair systems

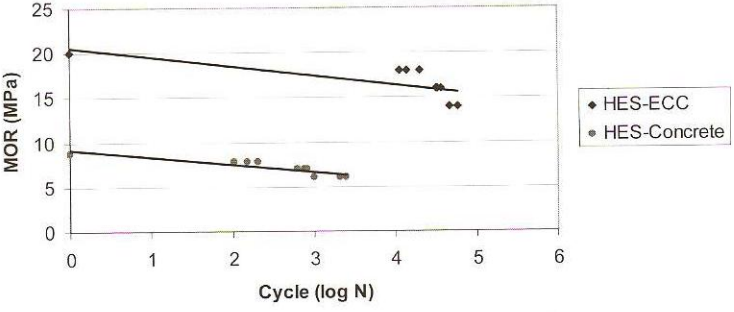

Figure 5: Fatigue life of different layered repair systems

The cracking pattern of the different layered repair systems can be seen in Fig. 4. The HES-Concrete / Concrete layered repair system had a sudden failure with one single crack formed in the repair layer. In contrast, the HES-ECC / Concrete layered repair system exhibited multiple micro-cracking behavior, with very tight crack width below 50µm. The significant difference of between the HES-ECC and HES-Concrete layered repair systems came from the kink-crack trapping mechanism: In the case of HES-Concrete repair, the initial interfacial crack always kinked into the repair layer and formed spalling. However for HES-ECC, the initial interfacial crack firstly kinked into the repair layer, and then trapped inside the HES-ECC because of the high toughness of the material. As the flexural load increased, the interfacial crack grew a little, and the kink-crack mechanism repeated till the final failure when the HES-ECC layer had its flexural strength exhausted. This kink-crack mechanism of HES-ECC repair helped to suppress repair spalling.

The fatigue flexural performance of different layered repair systems is shown in Fig. 5 in terms of MOR versus fatigue life (S-N). It is obvious that when the traffic loading is at the same level, the fatigue life of HES-ECC repair system is significantly longer than that of the HES-Concrete repair system.

3. HES-ECC REPAIR UNDER ENVIRONTAL LOADING

3.1 Background

In concrete repair applications, "new" repair materials are often bonded with "old" concrete substrates which have undergone shrinkage. After placement, the repair material will immediately begin shrinkage. However, the shrinkage deformation of the repair material is restrained by the concrete substrate, so that tensile stress will be developed in the repair layer, and both tensile stress and shear stress will be developed along the interface between the repair and the concrete substrate. The combination of these stresses is the reason to cause repair cracking and interface delamination.

Li (2004) [5] illustrated the effect of inelastic strain capacity of cementitious material on the deformation behavior of a 2-D slab geometry restrained at its ends. For brittle or quasi-brittle repair material with tension softening behavior, the cracking potential under restrained shrinkage is defined as:

$$p = (\varepsilon_{sh} - (\varepsilon_e + \varepsilon_{cp}))$$

where ε_{sh} is material shrinkage strain, ε_e is material elastic tensile strain capacity, and ε_{cp} is material tensile creep strain. If $p \geq 0$, one single crack forms in the repair material, with crack width proportional to the cracking potential p and increasing with the brittleness of the material.

In the case of a repair layer, the boundary conditions are different from what described above, because restraints are applied at the base of the slab rather than at its ends. This type of restraints will lead to a number of distributed cracks along the repair layer. In the case of plain concrete, these traction-free cracks will again open with crack widths proportional to p, resulting in relaxation of most of the tensile stress built up, and little or no shear stress at the layer/substrate interface. As a result, delamination at the interface is expected to be small.

For common tension-softening Fiber Reinforced Concrete (FRC) materials, shrinkage induced stresses are expected to induce surface cracking similar to normal concrete. However, since the cracks are bridged by fibers, the crack widths may be expected to be smaller, so that some tensile stress can still be maintained in the layer. As a result, the interface shear stress is not relieved, so that delamination may be more prominent compared with normal concrete.

In order to suppress both surface cracking of the repair layer and interface delamination, the repair material will need to exhibit "plastic straining" in order to relieve the tensile stress built up by restrained shrinkage. Once plastic straining occurs, the interfacial shear stress will also be relaxed, and interface delamination may be minimized. Plasticity in the form of microcrack damage has been demonstrated in HES-ECC, as this material exhibit an ultimate strength higher than the first cracking strength, accompanied by a large strain capacity ε_i at ultimate strength. For HES-ECC, the cracking potential [5] is modified as

$$p = (\varepsilon_{sh} - (\varepsilon_e + \varepsilon_i + \varepsilon_{cp})$$

The cracking potential p for concrete, SFRC, and ECC can be estimated, as shown in Table 3. The p-values for the three materials confirm that concrete and SFRC are subjected to tensile fracturing when undergoing restrained drying shrinkage, while ECC will experience microcrack damage in the inelastic straining range.

Table 3: Concrete, SFRC and ECC cracking potential estimation

Properties	Concrete	SFRC	ECC
ε_{sh} (%)	0.07	0.053	0.177
ε_e (%)	0.01	0.01	0.015
ε_i (%)	0	0	2.5 ~ 5
ε_{cp} (%)	0.02 ~ 0.06	0.02 ~ 0.06	0.07
$p = \varepsilon_{sh} - (\varepsilon_e + \varepsilon_i + \varepsilon_{cp})$ (%)	0 ~ 0.04	(-0.017) ~ 0.023	(-4.908) ~ (-2.408)

3.2 Experimental Program

Three different repair materials — HES-Concrete, HES-Steel Fiber Reinforced Concrete (HES-SFRC) with tension softening stress-strain curve and HES-ECC were investigated. HES-Concrete and HES-SFRC were employed as controls since they have been used in repair applications. The mixing proportion and properties of the repair materials are listed in Table 1 and Table 2.

Layered repair systems were experimentally investigated with each of the three repair materials – HES-Concrete, HES-SFRC and HES-ECC. Concrete substrates were cast initially with dimensions of 1560mm×100mm×100mm, as shown in Fig. 6. The concrete substrates were moisture cured until age of 28 days, and then left to dry in ambient condition for an additional 60 days before the repair layers were placed. The additional 60 days were for the purpose of allowing any potential shrinkage in the substrates to occur before bonding the repairs. The contact surfaces of the substrates were prepared the same way as the layered specimen under mechanical loading described in section 2.2.

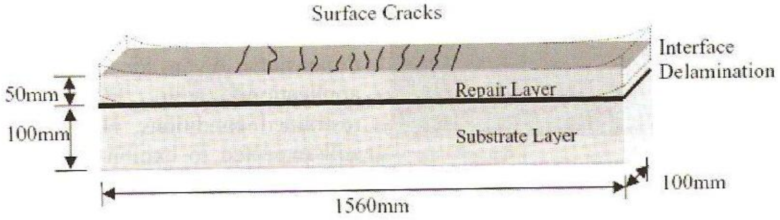

Figure 6: Layered repair system configuration and potential failure modes

After a clean bonding surface with appropriate moisture level was achieved, a 50-mm-thick repair layer made of each of the three repair materials was cast on the top of the concrete substrate. The repair layers were moisture cured for 24 hours and then demolded. After demolding, the layered specimens were moved into a room with ambient conditions of 20-30℃, and 25-55% RH.

3.3 Experimental Results

The surface cracking pattern of HES-Concrete, HES-SFRC and HES-ECC repairs are shown in Fig. 7. Table 4 summarizes crack number and crack width of the three repaired systems respectively at the age of 60 days. Three specimens were tested for each repair material. It can be seen that when HES-Concrete was used as the repair material, 3-4 cracks localized at age of 60 days. The maximum crack width of the three specimens was 520μm.

When HES-SFRC was used as the repair material, 1-4 localized cracks formed, and the maximum crack width of the three specimens was 130μm. The smaller crack width of HES-SFRC repair can be contributed by the steel fiber's bridging effect. It should be noted that because of a positive shrinkage cracking potential, the restrained shrinkage induced crack width for HES-Concrete or HES-SFRC repair is a structural property, which is dependent on structural dimensions.

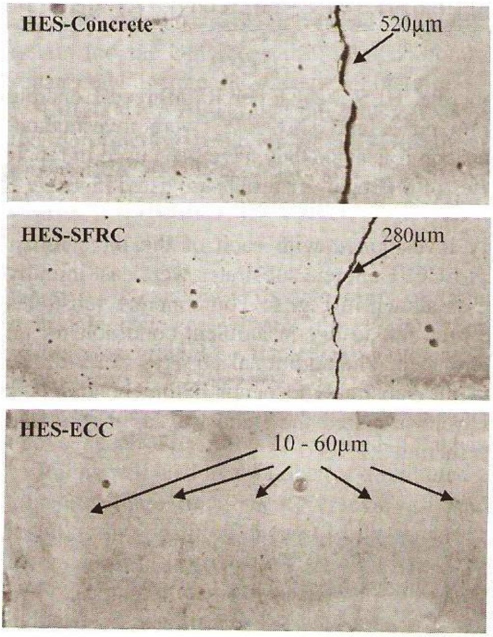

Figure 7: Repair surface cracking

In contrast, when HES-ECC was used as the repair material, 83-113 micro-cracks were formed with the maximum crack width of 60μm, which was much smaller than that of HES-Concrete or HES-SFRC repair. The average crack width of HES-ECC repair was around 30μm. No localized fracture was observed. Since shrinkage strain of HES-ECC was less than 0.3 % (Table 3), it was much below HES-ECC's tensile strain capacity of 2.5-5 %. Therefore, the restrained shrinkage cracking of HES-ECC was occurring in its strain-hardening stage, during which the material formed multiple microcracks with steady crack width. This indicates that the restrained shrinkage crack width of HES-ECC repair is a material property, which is independent of structural dimensions. Even for larger scale repair applications with different types of restrained conditions, HES-ECC repair is still expected to exhibit tight crack width below 60μm.

Table 4: Interface delamination and surface cracking of different layered repair systems

Repair Material	Specimen Number	Cracking	
		Number	Width (μm)
HES-Concrete	(1)	3	169 ; 370 ; 520
	(2)	4	190 ; 340 ; 360 ; 490
	(3)	4	70 ; 380 ;420 ; 450
HES-SFRC	(1)	2	110 ; 120
	(2)	4	50 ; 90 ; 120 ; 130
	(3)	1	280
HES-ECC	(1)	83	10 - 50
	(2)	109	10 - 60
	(3)	113	10- 50

At the age of 60 days, both the HES-ECC and the HES-Concrete repaired systems exhibited relatively low delamination heights at the specimen ends, which were 80μm for the former and 90μm for the latter at the maximum. The maximum delamination length was 80mm for the HES-ECC repair and 170mm for the HES-Concrete repair at the maximum. The HES-SFRC repaired system had much larger delamination height than the HES-ECC or HES-Concrete repaired system at the age of 60 days, which is 290μm. Its delamination length was also larger, around 340mm. Fig. 8 shows the interface delamination profiles of the three layer repair systems at different ages, which are vertical displacement/delamination of the repair layers at different locations along the repair/substrate interface. These profiles are approximately symmetric about the mid-point of the specimen, as would be expected.

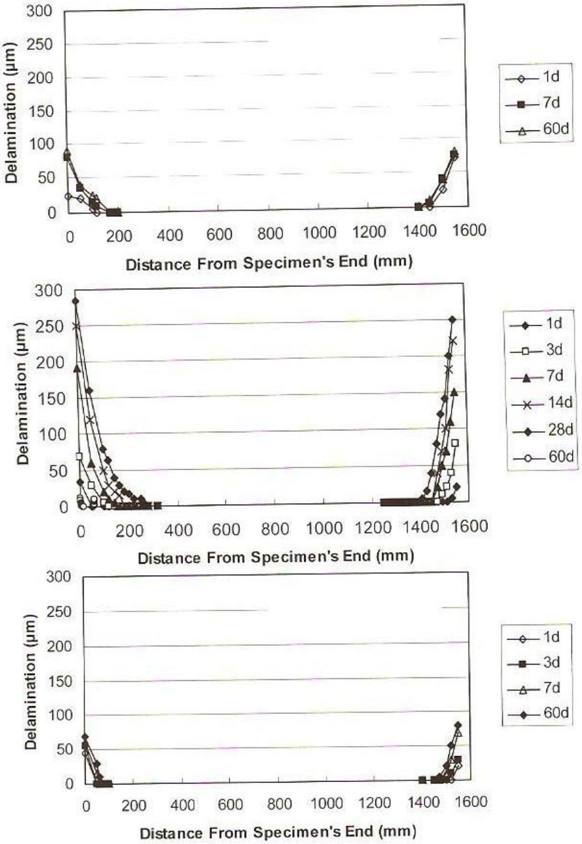

Figure 8: Interface delamination profile of HES-Concrete, HES-ECC and HES-SFRC repaired systems

4. CONCLUSIONS

This study evaluated performance of HES-ECC layered repair system under both mechanical and environmental loading conditions. When subject to monotonic loading, the

HES-ECC layered repair system exhibited 100% increased load carrying capacity, and 10 times the deformation capacity of HES-Concrete layered repair system. Instead of forming one single crack in the HES-Concrete repair layer, the initial interfacial crack would kink into the HES-ECC repair layer, and then trapped there. Upon additional loading, delamination resumes at the interface. The unique kink-trap-cracking behavior repeated itself with increasing flexural loading till the flexural strength of HES-ECC was exhausted. In this way, repair spalling was successfully suppressed by using HES-ECC.

When under the same level of fatigue loading, HES-ECC layered repair system showed significantly longer service life than HES-Concrete layered repair system. The interface properties did not exhibited effect on the cycles experienced before failure. Like the monotonic flexural test, the deformation capacity of the HES-ECC layered repair system was much larger than the HES-Concrete layered repair system. And the maximum deflection before failure was bigger when the interface is smooth. There was no evident difference on the specimen's cracking pattern under the monotonic and the fatigue loading conditions.

When subject to restrained drying shrinkage, the high ductility of the HES-ECC repair layer could accommodate the shrinkage deformation by forming multiple micro-cracks with tight crack width. By this means, tensile and shear stresses at the interface was released, so that both repair cracking and interface delamination could be suppressed. For the traditional HES-Concrete repair, several localized cracks normally formed in the repair layer with large crack width. For the HES-SFRC repair, still several localized cracks formed, but the cracks were bridged by steel fibers. Since the cracks could not open freely to accommodate the repair layer's shrinkage deformation, the interface delamination was much larger than HES-Concrete and HES-ECC repairs.

The above experimental results suggest that HES-ECC can be a very durable repair material with prolonged service life, no matter under environmental loading or mechanical loading. The common failure modes such as large surface cracking, spalling and interface delamination can be successfully suppressed by the uniquely large tensile strain capacity of HES-ECC material.

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