Cement and Concrete Research 39 (2009) 382–390

Contents lists available at ScienceDirect

Cement and Concrete Research

journal homepage: http://ees.elsevier.com/CEMCON/default.asp

Autogenous healing of engineered cementitious composites under wet–dry cycles

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ARTICLE INFO

Article history:
Received 1 December 2007
Accepted 21 January 2009

Keywords:
Self-healing
Mechanical properties
Transport properties
Tensile properties
Permeability
Cracks

ABSTRACT

Self-healing of Engineered Cementitious Composites (ECC) subjected to two different cyclic wetting and drying regimes was investigated in this paper. To quantify self-healing, resonant frequency measurements were conducted throughout wetting–drying cycles followed by uniaxial tensile testing of self-healing ECC specimens. Through self-healing, crack-damaged ECC recovered 76% to 100% of its initial resonant frequency value and attained a distinct rebound in stiffness. Even for specimens deliberately pre-damaged with microcracks by loading up to 3% tensile strain, the tensile strain capacity after self-healing recovered close to 100% that of virgin specimens without any preloading. Also, the effects of temperature during wetting–drying cycles led to an increase in the ultimate strength but a slight decrease in the tensile strain capacity of rehealed pre-damaged specimens. This paper describes the experimental investigations and presents the data that confirm reasonably robust autogenous healing of ECC in commonly encountered environments for many types of infrastructure.

1. Introduction

Cracks can occur during any stage of the life of a concrete structure. They can be due to the concrete material itself as in the case of restrained shrinkage, or due to external factors such as excessive loading, harsh environmental exposure, poor construction procedures, or design error. Cracks have many negative effects on the mechanical performance and durability of concrete structures. The development of concretes that can automatically regain this loss of performance is highly desirable. Along this line, self-healing of cracked concrete, commonly known as autogenous healing, is an often studied phenomenon [1–12]. Experimental investigation and practical experience have demonstrated that cracks in cementitious materials have the ability to seal themselves, e.g. water flowing through cracked concrete slows over time. In extreme cases, these cracks can be sealed completely.

The complicated chemical/physical processes of self-healing of cracks in concrete have been previously investigated [2–5]. The effects of various parameters on self-healing, including crack width, water pressure, pH of healing water, temperature, water hardness, water chloride concentration, and concrete composition, have been discussed in previous works. The following mechanisms of autogenous healing in concrete have been cited: further hydration of the unreacted cement [2,5], expansion of the concrete in the crack flanks (swelling of C–S–H), crystallization (calcium carbonate), closing of cracks by solid matter (impurities) in the water and closing of cracks by loose concrete particles resulting from crack spalling [4]. Among these, most researchers have indicated that crystallization of calcium carbonate within the crack is the main mechanism for self-healing of mature concrete [2–6].

Typically, a modified version of Poiseuille's Formula is used to describe water flow in concrete cracks [5]. This model, derived from parallel plate flow theory of an incompressible fluid, along with experimental results, shows that crack width is the dominating factor ineffectively engaging the above mentioned five mechanisms of self-healing. Therefore, much of previous works have implied the need of crack width control to attain effective self-healing in cementitious materials. Unfortunately, crack width in concrete structures depending on steel reinforcements has not attained adequate reliability for robust self-healing to take place.

Engineered Cementitious Composite (ECC) is a unique type of high performance fiber reinforced cementitious composite. ECC features high tensile ductility (tensile strain capacity) with moderate fiber content, typically 2% by volume. Of special interest is the capability of ECC materials to deform to high tensile strains under load, commonly over 3%, while maintaining a tight crack width of about 60 μm up to failure [13], as shown in Fig. 1. ECC with self-controlled crack width as low as 20 μm have been developed [14]. This steady state crack width can be seen as an inherent material property of ECC, similar to compressive strength or elastic modulus. With this characteristic, ECC material is expected to have good potential to engage self-healing in a variety of environmental conditions, even when the composite is tensioned to several percent strain. The establishment of self-healing in ECC looks to improve the long-term ductility and durability of ECC after cracking, and to establish a much more durable civil engineering material.

The tight crack width in ECC is a result of its ability to experience flat crack propagation — with much of the crack flank maintaining constant (steady state) crack width as the crack length increases indefinitely [15]. Unlike normal concrete or fiber reinforced concrete, this feature of ECC allows self-control of crack width independent of steel reinforcing ratio

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doi:10.1016/j.cemconres.2009.01.013

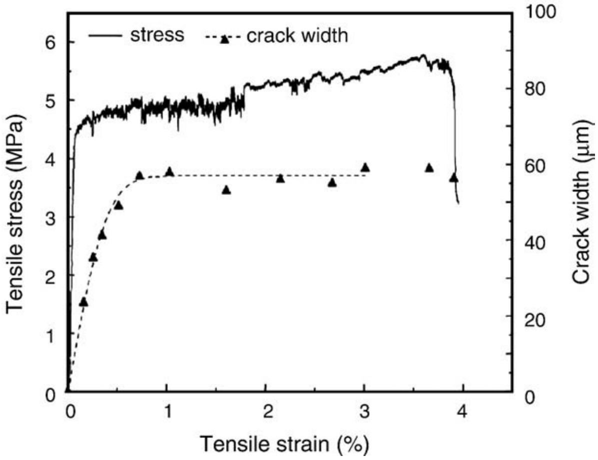

Fig. 1. Typical tensile stress–strain–crack width curve of ECC [13].

and structural dimensions. Given this characteristic, the small crack width in specimens for laboratory investigation is identical to that in full-scale structures. When combined with the tensile strain-hardening response in ECC, desired small crack width can be easily imposed on ECC specimens for examining rehealing of crack damage, without the need for feedback control as in the case of controlling cracks in tension-softening normal concrete or fiber reinforced concrete.

While knowledge of the process of self-healing in concrete is available, specifics with regard to self-healing in ECC are limited, especially in the case of exposure to various environmental conditions. These conditions can vary greatly and include: the drying action of wind and sun; rain-water containing dissolved sulfurous compounds from industrial pollutants(i.e. acid rain); bridge-deck run-off or road spray contaminated with chlorides from deicing salts; freezing and thawing action; sulfate attack and carbonation. The present investigation focuses on the self-healing of pre-damaged mature (six months of age) ECC materials under cyclic wetting and drying. Wetting and drying was used as an accelerated test method to simulate outdoor environmental conditions in which ECC structures are subjected to the drying action of wind and sun and wetting by rain runoff or snowmelt. Specimen damage is imposing by tension loading to fixed amount of tensile strains. As specimens self-heal under exposed cyclic wetting and drying environments, monitored resonant frequency change indicates the extent and rate of self-healing. In addition to reporting these data, the recovery of mechanical and transport properties of ECC after self-healing, are also presented.

2. Experimental program

2.1. Self-healing examination methods

In this investigation, resonant frequency measurements, uniaxial tensile tests and water permeability tests were used to quantify self-healing behavior in terms of mechanical and transport properties recovery. These test methods are briefly summarized below.

2.1.1. Resonant frequency measurements

The material resonant frequency measurement based on ASTM C215 (Standard Test Method for Fundamental Transverse, Longitudinal, and Torsional Resonant Frequency of Concrete Specimens) appears to be a particularly promising and relatively simple technique to monitor the extent and rate of autogenous healing. This test method (ASTM C215), which relies on changes in resonant frequency, has proven a good gauge of material degradation due to freeze thaw damage and is specifically referenced within ASTM C666 for freeze thaw evaluation. In the present work, however, rather than quantifying damage, this technique (using

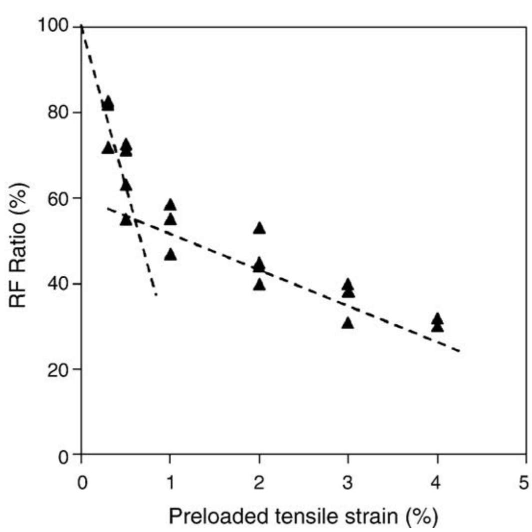

Fig. 2. Resonant frequency as a function of ECC material damage (i.e. tensile strain deformation beyond elastic stage) [16].

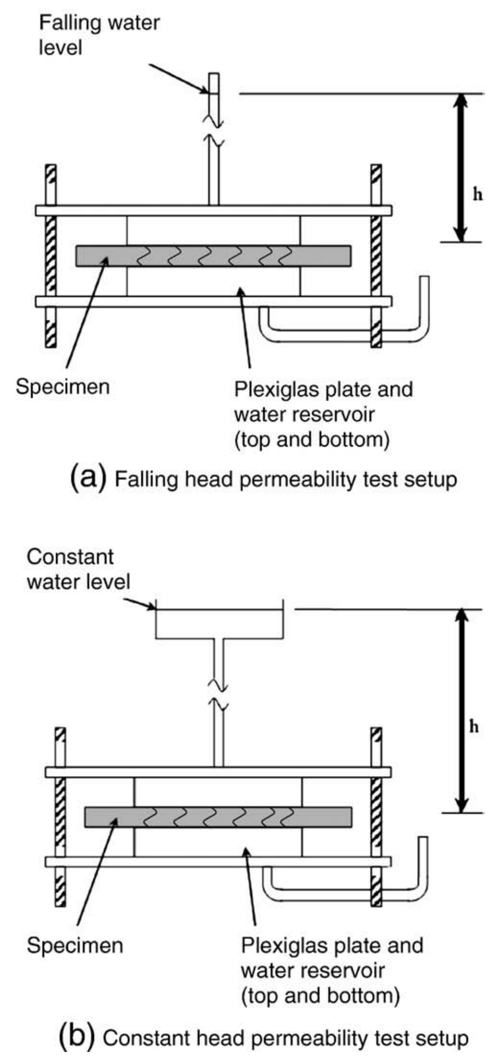

Fig. 3. Permeability test setups.

Table 1
Mix proportions of ECC.

Materials	Cement	Aggregate	Fly ash	Water	HRWR	Fiber
Unit weight (kg/m^3)	578	462	694	319	17	26

the transverse frequency mode) is adapted as an approximate measure of the extent and rate of self-healing in cracked material, when healing is seen as a reduction in material damage. ECC specimens measuring 230 mm by 76 mm by 13 mm were prepared for this study.

Preliminary research [16] indicates that a bi-linear relationship exists between the resonant frequency and ECC multiple cracking damage (i.e. tensile strain deformation) for pre-loaded ECC specimens (Fig. 2). The bilinear nature is likely a result of the increase in the number of cracks as well as increase in crack width at small strain values (below about 1%), while further tensile straining is accommodated mainly by increasing the number of microcracks with averaged crack width remaining more or less constant. This results in a sharper drop in resonant frequency at smaller strain values, and a slower decay at strain values higher than about 1%. In Fig. 2, the “RF Ratio” is the resonant frequency at any given preloaded strain, normalized by that at zero strain, i.e., the resonant frequency measured with the virgin ECC without preloading. Therefore, the change of resonant frequency can be used as a rapid means to quantify the degree of damage (accompanying tensile straining beyond the first crack) to which an ECC specimen has been subjected and the degree of recovery in pre-damaged ECC specimens after exposed to various environments for self-healing.

2.1.2. Uniaxial tensile test

Uniaxial tensile test was used to assess the quality of self-healing, the magnitude of recovered mechanical properties were measured under uniaxial tensile loading. Specifically, the tensile strength, strain capacity and stiffness were recorded after the damaged specimens were exposed to various environments for self-healing. A servo-hydraulic testing system was used in displacement control mode to conduct the tensile test. The loading rate used was 0.0025 mm/s to simulate a quasi-static loading condition. Aluminum plates were glued both sides at the ends of coupon ECC specimens (230 mm × 76 mm × 13 mm) to facilitate gripping. Two external linear variable displacement transducers were attached to the specimen to measure the specimen deformation. More details of this test can be found in [13].

This same set-up was used to apply the preloading for this self-healing study. Tensile strain values up to 3% were applied to simulate various levels of damage in ECC. Multiple microcracks were induced in these pre-damaged specimens. However, even at the high strain level, the crack widths remain at below about 60 μm.

2.1.3. Water permeability test

To conduct permeability test, a falling head test was used for specimens with a low permeability, while a constant head test was used for specimens (such as those with large crack width) with a permeability too high to practically use the falling head test. The falling head and constant head permeability test setups have been adapted from Wang et al. [17] and Cernica [18]. These two setups are shown schematically in Fig. 3(a) and (b), respectively.

The coefficient of permeability k of specimens in the falling head test and in the constant head test can be determined using Eqs. (1) and (2), respectively.

$$k = \frac{a \cdot L}{A \cdot t_f}\left(\frac{h_0}{h_f}\right) \tag{1}$$

$$k = \frac{V \cdot L}{A \cdot h_0 \cdot t_f} \tag{2}$$

where a is the cross sectional area of the standpipe, L is the specimen thickness in the direction of flow, A is the cross sectional area subject to flow, t_f is the test duration, h_0 is the initial hydraulic head, h_f is the final hydraulic head, and V is the volume of liquid passed through the specimen during the test.

This permeability test technique was adopted to examine the self-healing of pre-damaged ECC after exposing to wet–dry cycles. In this manner, autogenous healing leading to recovery of resistance to water transport via permeation was investigated.

2.2. Environmental conditioning

The experimental program consisted of two cyclic wetting and drying regimes. One cyclic regime (CR1) subjected ECC specimens to submersion in water at 20 °C for 24 h and drying in laboratory air at 21 ± 1 °C for 24 h, during which no temperature effects are considered. This regime is used to simulate cyclic outdoor environments such as rainy days and unclouded days. The second cyclic regime (CR2) consisted of submersion in water at 20 °C for 24 h, oven drying at 55 °C for 22 h, and cooling in laboratory air at 21 ± 1 °C for 2 h. This was used to simulate cyclic outdoor environments alternating between rainy days and days with sunshine and high temperatures.

2.3. ECC specimen preparation

The mix proportions of ECC material used in this investigation are given in Table 1. The ECC material utilized for these studies has a tensile strain capacity of about 3% and an average steady state crack width of 60 μm. To prepare the ECC, Type I ordinary portland cement, sand with 110 μm average grain size, Class F normal fly ash supplied by Boral Materials Technologies, 12 mm Kuralon-II REC-15 polyvinlyalcohol fibers supplied by Kuraray Company, and a polycarboxylate-based high range

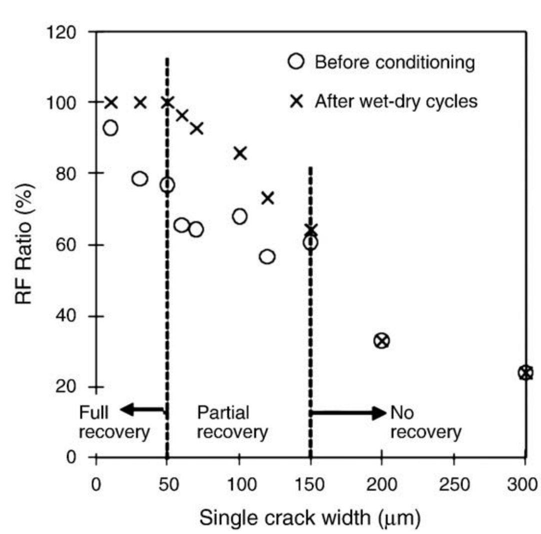

Fig. 4. Resonant frequency (RF) ratio as a function of crack width.

Table 2
Crack characteristics of pre-loaded ECC.

Tensile strain (%)	Number of cracks	Maximum crack widths (μm)
3	39	90
2	27	60
1	15	60
0.5	7	70
0.3	5	50

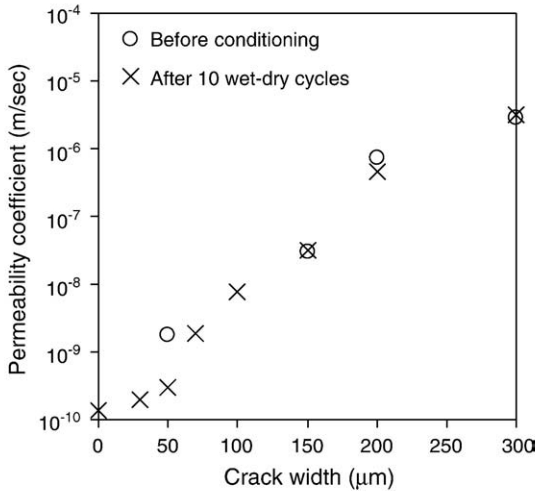

Fig. 5. Permeability coefficient as a function of crack width before and after conditioning.

water reducer (ADVA® Cast 530) from W.R. Grace & Co. were used. A series of coupon specimens was cast from a single batch prepared using a forced-based Hobart mixer. The fresh ECC was then covered with plastic sheets and demolded after 24 h. The specimens were left to air cure under laboratory conditions of humidity and temperature for 6 months. The compressive strength of ECC was about 60 MPa at the age of 28 days.

The specimens were first preloaded to different predetermined uniaxial tensile strain levels from 0.3% to 3%, at the age of 6 months. On unloading, a small amount of crack closure of about 15% was observed. To account for this, all crack width measurements were conducted in the unloaded state. Table 2 shows the average number of cracks within two pre-loaded specimen series and their corresponding crack widths over a gauge length of 100 mm. The maximum, rather than the average crack width, is reported here to highlight the extremely tight crack widths inherent in ECC as compared to concrete. While self-healing in structures will take place in the loaded state, this unloading is expected to have only a small impact on ECC self-healing capabilities. After unloading, these specimens were subsequently exposed to ten wet–dry cycles (CR1 or CR2).

2.4. Single-crack specimens

To examine the effect of crack width on self-healing, a separate series of mortar coupon specimens measuring 230 mm by 76 mm by 13 mm reinforced with a small amount (0.5 vol.%) of polyvinyl alcohol (PVA) fiber were prepared. For these specimens, except for the fiber content, the other constitutes were the same as given in Table 1. These specimens

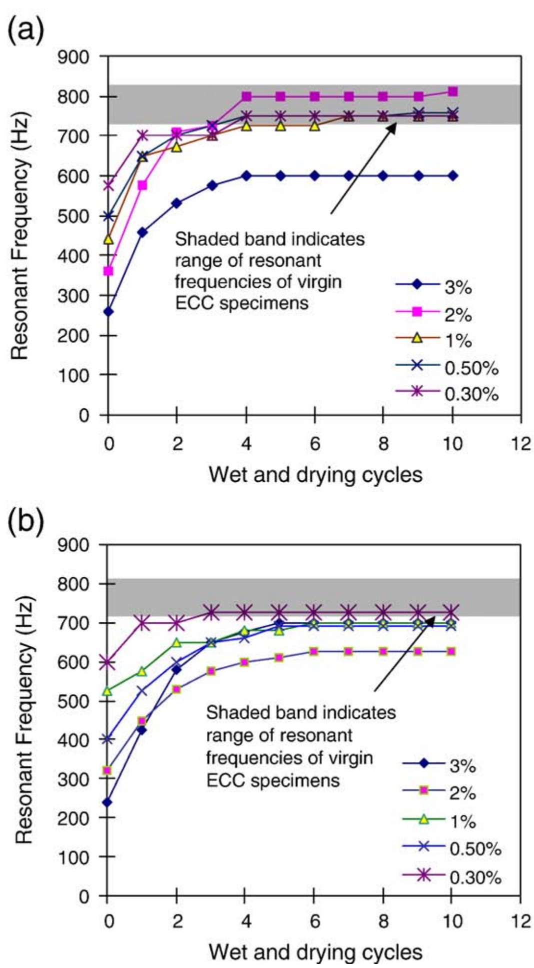

Fig. 6. Self-healing rate of ECC under cyclic wetting and drying. (a) Resonant frequency recovery under CR1 (water/air cycle). (b) Resonant frequency recovery under CR2 (water/hot air cycle).

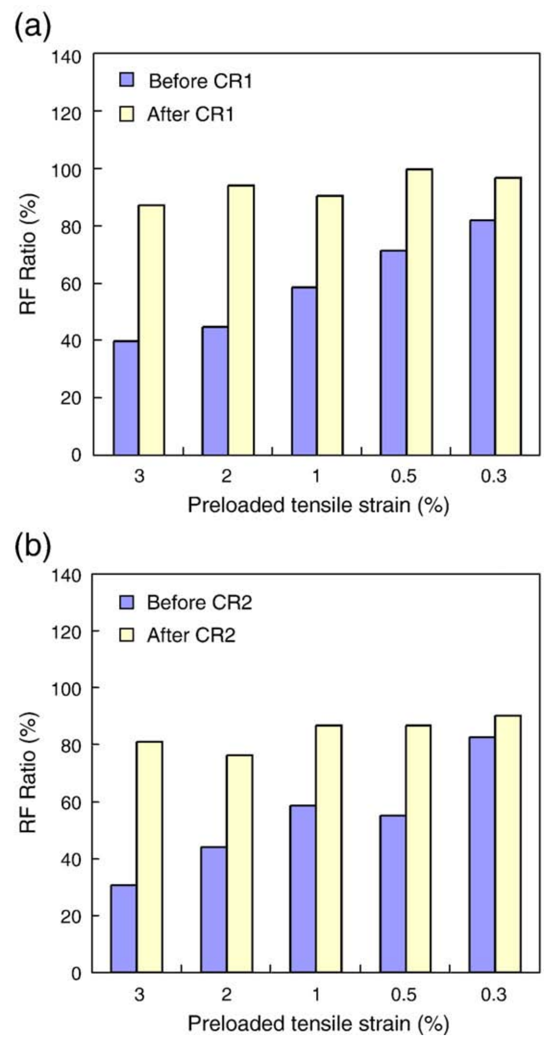

Fig. 7. Extent of self-healing in ECC under cyclic wetting and drying. (a) Extent of self-healing in ECC under CR1 (water/air cycle). (b) Extent of self-healing in ECC under CR2 (water/hot air cycle).

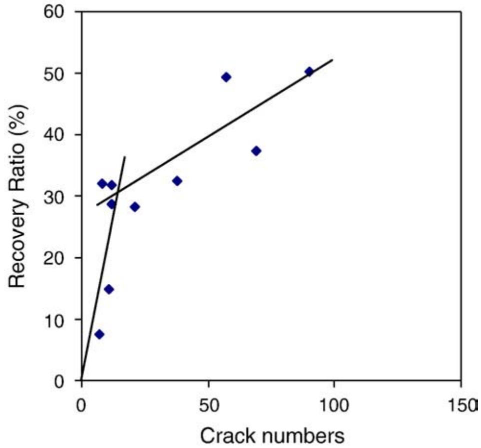

Fig. 8. Rebound in resonant frequency versus number of cracks within the ECC specimen.

were deliberately made to exhibit tension-softening response typical of normal fiber reinforced concrete so that a single crack of controlled crack width can be introduced. Each specimen was first preloaded under uniaxial tension to produce a single crack with a crack width between 0 μm and 300 μm. Resonant frequency and permeability coefficient were measured after preloading and exposure to CR1, to monitor the self-healing of specimen with different crack widths.

3. Results and discussion

3.1. Effect of crack width on self-healing

Fig. 4 shows the resonant frequency of single-crack specimens before and after wet–dry cycles as a function of crack width. The *y*-axis gives the resonant frequency of specimens before and after the prescribed wet–dry conditioning, normalized by the resonant frequency of uncracked (virgin) material. Therefore, the RF ratio of 100% represents a total recovery of the resonant frequency. It is expected that further hydration and moisture content changes during the specimen conditioning regimes may contribute to some fraction of the resonant frequency recovery. To account for this, the averaged resonant frequency of virgin uncracked specimens under the same 10 cyclic conditioning regimes (10 cycles of CR1) was used in the normalization. Each data point represents at least two test results.

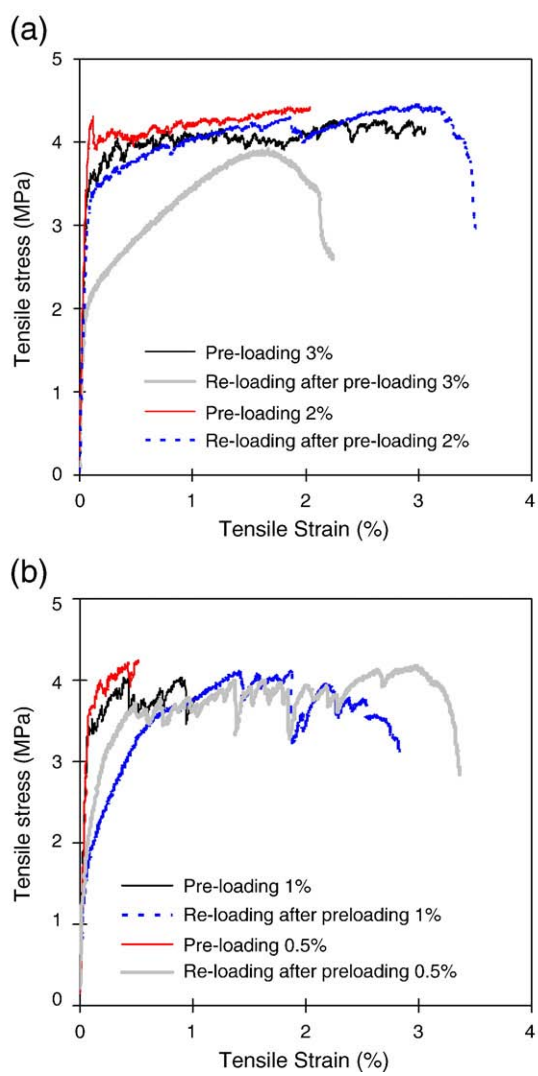

Fig. 9. Preloading and reloading after 10 CR1 (water/air) cycles tensile stress–strain relations of ECC specimens. (a) Specimen with preloading to above 1%. (b) Specimens with preloading to 1% or below.

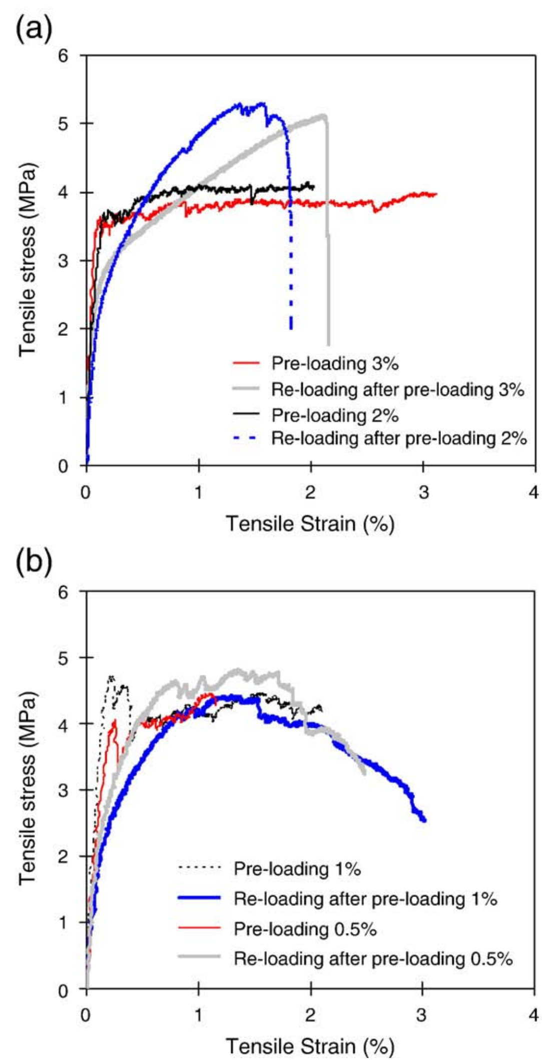

Fig. 10. Preloading and reloading after 10 CR2 (water/hot air) cycles tensile stress–strain relations of ECC specimens. (a) Specimen with preloading to above 1%. (b) Specimen with preloading to 1% or below.

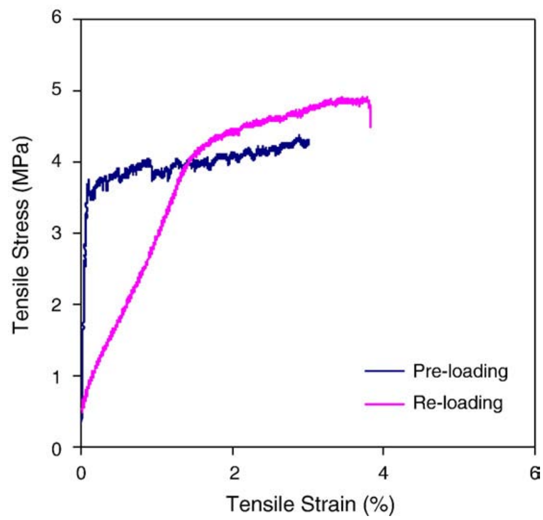

Fig. 11. Preloading and reloading without self-healing tensile stress–strain curve of ECC specimen.

As seen in Fig. 4, the resonant frequency of specimens after 10 cyclic wet–dry exposures can recover up to 100% of the uncracked value provided that crack widths are kept below 50 μm. With an increase of crack width; however, the degree of material damage indicated by the drop in resonant frequency increases and the extent of self-healing diminishes. When the crack width exceeds 150 μm, the specimen resonant frequency remains unchanged even after undergoing the wet–dry cycle conditioning, signifying the difficulty of repairing microstructural damage within these cracked materials.

Along with the resonant frequency monitoring, permeability tests were conducted on those single cracked specimens after 10 wet–dry cycles. Fig. 5 summarizes the permeability coefficient of preloaded specimen after 10 cyclic conditioning exposures as a function of crack width. Although it is known [19,20] that self-healing can occur during the very act of performing a permeability test, the data shown here were initial values so that permeability changes during the test were deliberately excluded. Thus any self-healing detected here were primarily due to the wet–dry cycle exposures. From Fig. 5, it can be seen that after conditioning, the permeability of specimens with crack widths below 50 μm is essentially identical to that of the virgin uncracked specimens, which represents an almost full recovery of transport property, permeability. With increasing crack width, the permeability increases exponentially, with little or no recovery after the ten wet–dry cycles.

The resonant frequency measurements (Fig. 4) and the permeability measurements (Fig. 5) together suggest that autogenous self-healing within cement-based materials in both mechanical and transport properties can be achieved, provided that damage must be restricted to very tight crack widths, below 150 μm and preferably below 50 μm, at least under 10 wet–dry cycles exposure regime. This extremely tight crack width is difficult to attain reliably in most conventional concrete materials, even when steel reinforcement is used. However, ECC materials with inherent tight crack width control easily meet this rigorous requirement.

3.2. Self-healing of ECC

From Fig. 6(a) and (b), it can be seen that the resonant frequencies of all preloaded ECC specimens gradually recovers under cyclic wetting and drying. At least two specimens were tested for each strain level. The shaded band indicates the range of resonant frequencies of virgin ECC specimens which had undergone the same cyclic wetting and drying conditioning regime. The resonant frequencies for all specimens stabilize after 4 to 5 cycles. Specimens subjected to higher tensile strains exhibit a lower initial frequency after cracking, due to a slightly wider crack width and a much larger number of cracks (Table 2), and ultimately lower recovery values after wetting–drying cycles.

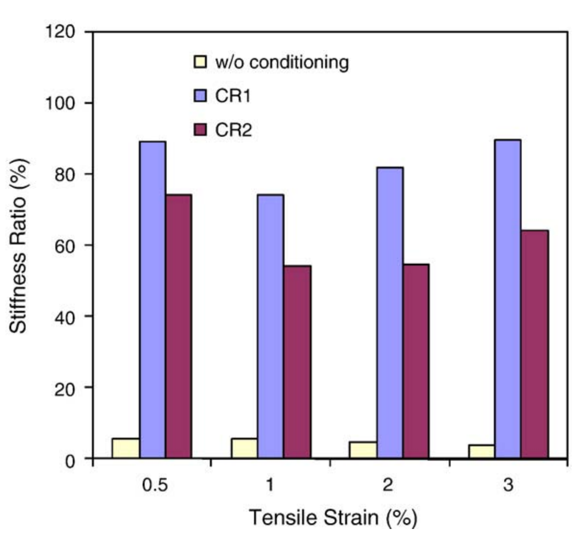

Fig. 12. Stiffness recovery of ECC under different conditioning regime.

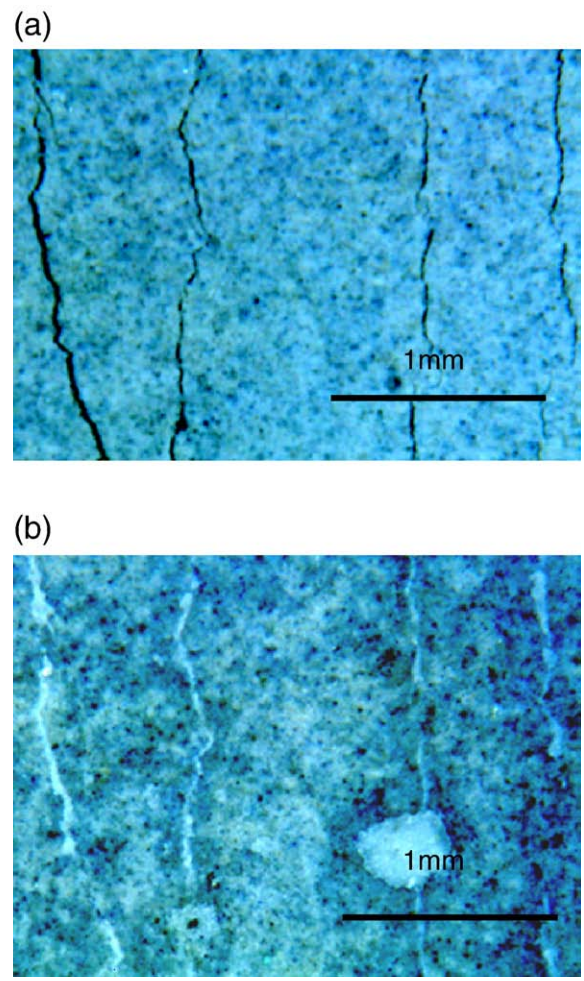

Fig. 13. Microcracks in ECC before and after self-healing. (a) Before self-healing. (b) After self-healing.

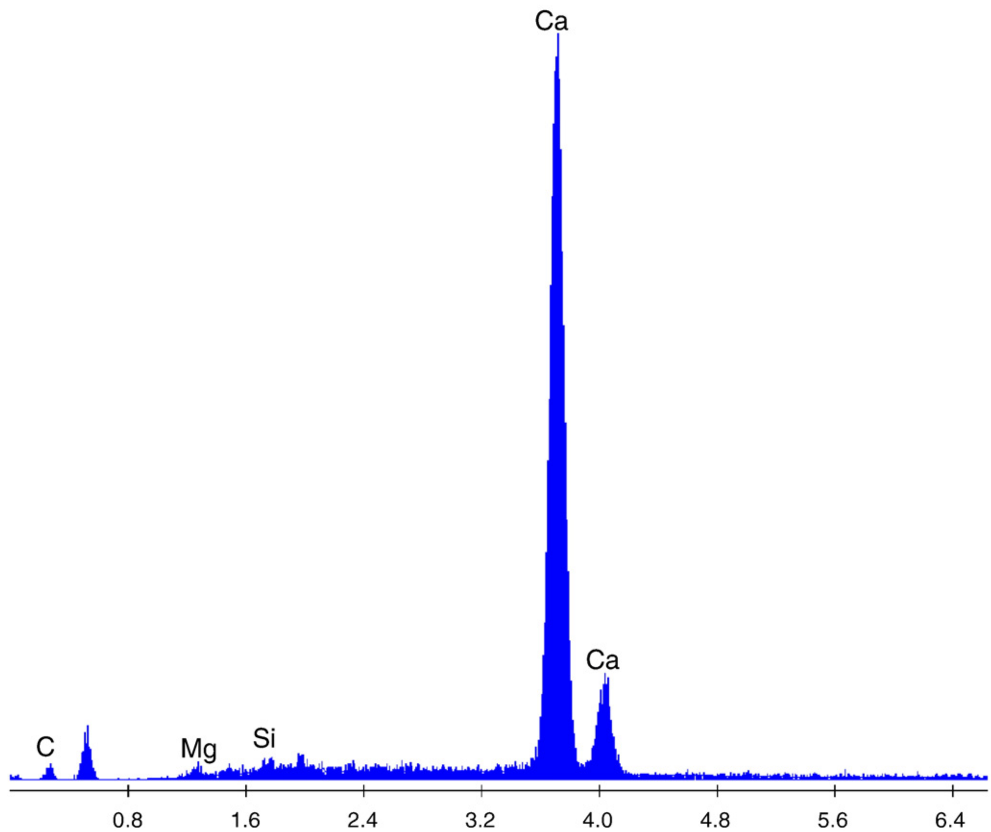

Fig. 14. Chemical composition of self-healed products.

Fig. 7(a) shows the extent of self-healing in preloaded ECC specimens, expressed in RF ratios before and after CR1 conditioning. It was found that the RF ratios vary between 40% (for specimens preloaded to 3%) and 82% (for specimens preloaded to 0.3%) before conditioning. After the wet–dry cycles, the RF ratios increased to 87%–100%. For CR2 specimens (Fig. 7(b)), the RF ratios dropped to 31% (for specimens preloaded to 3%) to 83% (for specimens preloaded to 0.3%) before conditioning. After the wet–dry cycles, the RF ratios increased to 77%–90%. The lesser amount of self-healing in the CR2 regime compared to that in CR1 regime is likely due to less uniform rehealing products formed inside the cracks. However, more study is needed to confirm the effect of temperature on self-healing.

Of particular interest is the relation between the extent of self-healing and level of strain in the preloaded ECC specimens under CR1. Pre-loaded testing series with tensile strain of 0.5% exhibited a reduction in resonant frequency of only 18%, while those pre-loaded to 3% strain showed an initial reduction of 60%. Self-healing in 0.5% strained specimens showed resonant frequencies returned back to 100% of initial values, while specimens pre-loaded to 3% strain returned to only 87% of initial frequencies. This phenomenon is captured in Fig. 8 that highlights the rebound in resonant frequency as a function of the number of cracks within the ECC specimens. As the number of cracks increases, the recovery ratio (the amount of rebound after CR1) also increases. This means that the more damage experienced in the form of crack numbers, the more opportunity of crack healing the specimen presents. However, the ultimate self-healed condition may not be as complete as in specimens strained to a lower deformation. This is likely due to the probabilistic existence of larger crack widths that limit the amount of self-healing for highly strained specimens.

Figs. 9 and 10 show the preloading tensile stress–strain curves of ECC specimens as well as the reloading tensile stress–strain curves of self-healed ECC specimens after conditioning cycles CR1 and CR2, respectively. In these plots, the permanent residual strain introduced in the preloading stage is not accounted for in the stress–strain curve during the reloading stage. This gives a conservative measurement of the tensile strain capacities of rehealed specimens. For the CR1 test series, the first-cracking strength of nearly all specimens after self-healing falls below the first-cracking strength of the virgin specimens (before any damage was induced). The tensile strain capacity after self-healing for these specimens ranges from 1.7% to 3.1%. For the CR2 test series, once again the first-cracking strength of all specimens after self-healing remains below the first-cracking strength of virgin specimens. The tensile strain after self-healing for CR2 specimens ranges from 0.8% to 2.2%. However, the ultimate strengths after self-healing are actually higher than those of the pre-loaded specimens, especially for the specimens pre-loaded to 2–

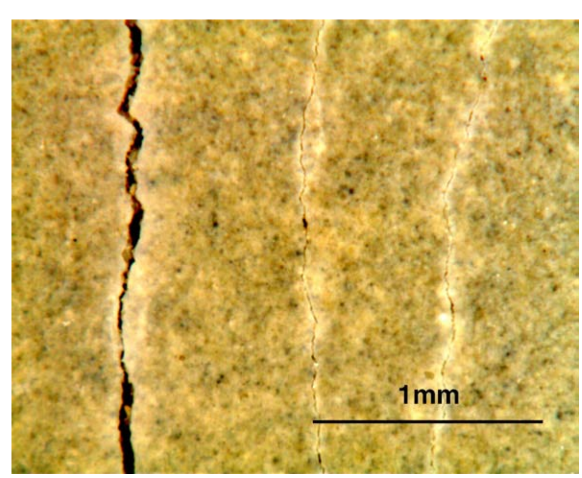

Fig. 15. Cracks through self-healed material due to reloading after wet–dry cycles.

3%. The higher temperature in the wet–dry conditioning regiment for CR2 may have led to hydration of unreacted cement and fly ash and an increase in fiber/matrix bond that is responsible for the higher ultimate strength of the rehealed specimens. Similarly, the same effect could have led to an increase in matrix toughness that limits the amount of multiple cracking [21] responsible for tensile ductility. The exact mechanism(s) causing the difference in reheal behavior under CR1 and CR2 requires further study, but is beyond the scope of this paper.

Fig. 11 shows the tensile properties of ECC specimens that have been preloaded to 3% strain levels, then unloaded, and immediately reloaded without any wet–dry cycle conditioning. As expected, there is a remarkable difference in initial stiffness between a virgin specimen and a pre-loaded damaged specimen with no self-healing. This is due to the re-opening of cracks within pre-loaded specimen during reloading. The opening of these cracks offers little resistance to load. However as the opening returns to the original crack width, more and more bridging fibers across the cracks will be re-engaged. Further loading then causes the strain-hardening and multiple-cracking process to resume.

By comparing the material stiffness of self-healed specimens in Figs. 9 and 10 with the material stiffness of the re-loaded specimens without self-healing in Fig. 11, it can be seen that a significant recovery of the stiffness of ECC specimens after self-healing is present. This result is captured in Fig. 12 that shows the stiffness ratio (tensile stiffness of specimens during reloading normalized by that of virgin specimens) after CR1 and CR2 conditioning. The stiffness ratio for specimens without undergoing conditioning and therefore have no self-healing are also shown for reference. It is seen that the recovery in material stiffness is distinctive for both conditioning regimes, even for specimens pre-damaged by as much as 3% preloading strain. These results confirm without a doubt that self-healing of ECC material results not only in sealing of cracks, but also in the rehabilitation of tensile properties to some degree, in this case the initial stiffness of the material under tensile load. This finding in recovery of tensile stiffness is consistent with the rebound of resonant frequency observed in the self-healed ECC specimens (Fig. 8). Resonant frequency is directly related to the dynamic modulus, or stiffness, of a material. Together, these test results lend support to the contention that self-healing in a mechanical property sense is achievable in ECC.

The microstructures of ECC specimens before and after self-healing are shown in Fig. 13(a) and (b). It can be seen that abundant white residue is present along the crack lines after wet–dry conditioning cycles. Further, from EDX analysis results (Fig. 14), it was found that the majority of the self-healed products are characteristic of calcium carbonate crystals.

Fig. 15 shows an ECC specimen subjected to tensile loading after undergoing self-healing through the CR1 conditioning regime. This specimen was preloaded to 2% strain before being exposed to wet–dry cycles. Again, the distinctive white self-healed product can be observed

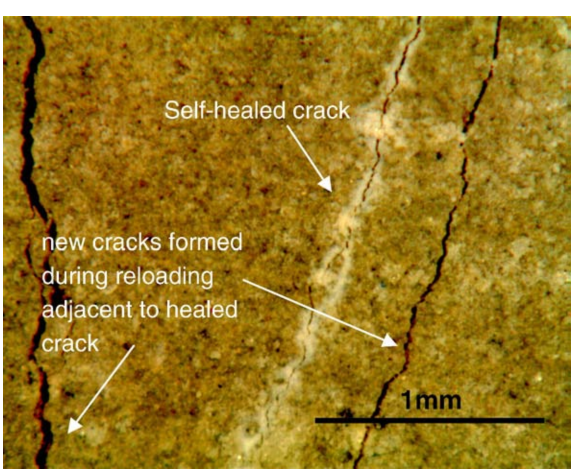

Fig. 16. Cracks through virgin ECC material adjacent to a self-healed crack held tight by self-healing material.

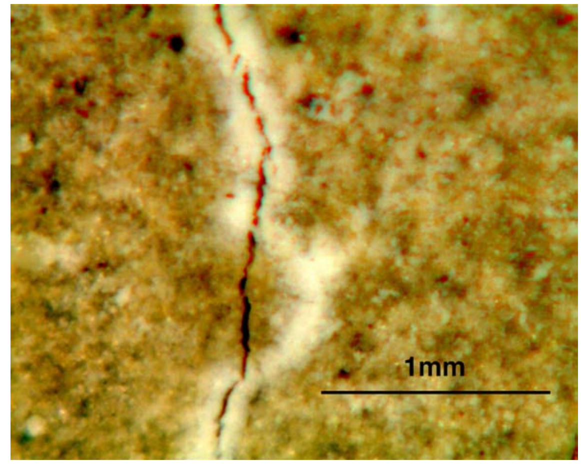

Fig. 17. Meandering new crack path partially deviating from previously self-healed crack.

in these photos. Further, it can be seen that the majority of cracks which form in this self-healed specimen tend to follow the previous crack lines and propagate through the self-healed material. This is not surprising due to the relatively weak nature of calcium carbonate crystals in comparison to hydrated cementitious matrix. The lower first cracking strength in the rehealed specimen (Figs. 9 and 10) can also be attributed to the fact that the first crack in the rehealed specimen on reloading starts from the self-healed material (calcium carbonate) which has a lower strength compared to adjacent hydrated cementitious matrix. Incomplete healing may also be responsible for the lower first crack strength. However, this is not always the case. As can be seen in Figs. 16 and 17, new cracks and crack paths have been observed to form adjacent to previously self-healed cracks which now show little or no new cracking. The possibility of this event depends heavily upon the cracking properties of the matrix adjacent to the self-healing, and the quality of the self-healing material itself. However, this phenomenon serves as a testament to the real possibilities of full recovery of mechanical properties via self-healing within ECC material. Certainly, the rehealed crack shown in Fig. 16 was transmitting tensile load high enough to cause new cracking in its neighborhood.

4. Conclusions

From this work, three broad conclusions can be drawn regarding the self-healing of ECC materials subject to wet–dry cycles. Foremost, the deliberate strategy used to enhance self-healing through design of cementitious materials (ECC) with inherently tight crack widths is effective. Second, self-healing in both transport property and mechanical properties is shown to be achievable. Third, the use of resonant frequency has been established as a non-destructive test method to uniquely determine the level of damage (i.e. strain deformation) to which a specimen has been subjected. While the relatively simple technique was primarily used within this study to quantify self-healing, or “reverse damage”, it has promising prospects in future research to quantify the extent of damage within ECC subjected to unknown strain levels. Based on limited EDX study, the mechanism of self-healing in ECC is the growth of calcites inside the tight cracks. However, more detailed studies are undergoing to confirm this. Additionally, a number of other specific conclusions can be drawn.

(1) The crack widths within cement-based materials must be controlled to below 150 μm, preferably below 50 μm, in order to engage noticeable self-healing behavior.
(2) Four to five cycles of wet–dry conditioning is necessary to attain the full benefit of self-healing.
(3) Self-healing in specimens subject to a tensile strain of 0.3% and 3% brought the resonance frequencies back to 100% and 76% of

initial values, respectively. This exhibits the relation between the extent of self-healing within cracked ECC specimens, and the level of strain damage to which they have been subjected.

(4) Self-healing can distinctly enhance the stiffness of cracked ECC resulting in true mechanical self-healing of the composite.

(5) Effects of temperature during self-healing can lead to an increase of the ultimate strength and as light decrease of tensile strain capacity of ECC. The quality of self-healing with CR2 at higher temperature appears lower than that with CR1, based on the resonant frequency test as well as the stiffness test results.

(6) For ECC specimens subjected to pre-load straining of a high level, even up to 2% or 3%, the material can still retain a tensile strain capacity of 1.8% to 3.1% after self-healing. That is, the tensile ductility characteristic of ECC is retained. The self-healed ECC material remains ductile.

Acknowledgements

This research was partially funded through an NSF MUSES Biocomplexity Program Grant (CMS-0223971 and CMS-0329416), an NSF Civil Infrastructure Grant CMMI 0700219, and a China National Scholarship. MUSES (Materials Use: Science, Engineering, and Society) supports projects that study reducing adverse human impact on the total, interactive system of resource use, the design and synthesis of new materials with environmentally benign impacts on biocomplex systems, as well as maximizing the efficient use of individual materials throughout their life cycles.

References

[1] C.A. Clear, The effects of autogenous healing upon the leakage of water through cracks in concrete, Cement and Concrete Association Technical Report No. 559, 1985.

[2] C. Edvardsen, Water permeability and autogenous healing of cracks in concrete, ACI Materials Journal 96 (1999) 448–455.

[3] P.S. Mangat, K. Gurusamy, Permissible crack widths in steel fiber reinforced marine concrete, Journal of Materials and Structures 20 (1987) 338–347.

[4] W. Ramm, M. Biscoping, Autogenous healing and reinforcement corrosion of water-penetrated separation cracks in reinforced concrete, Journal of Nuclear Engineering and Design 179 (1998) 191–200.

[5] H. Reinhardt, M. Joos, Permeability and self-healing of cracked concrete as a function of temperature and crack width, Journal of Cement and Concrete Research 33 (2003) 981–985.

[6] P. Schiessl, N. Brauer, Influence of autogenous healing of cracks on corrosion of reinforcement, Durability of Building Materials and Compoments 7 1 (1996) 542–552.

[7] S.S. Sukhotskaya, V.P. Mazhorova, Y.N. Terekhin, Effect of autogenous healing of concrete subjected to periodic freeze–thaw cycles, Journal of Hydrotechnical Construction 17 (1983) 294–296.

[8] S. Granger, A. Loukili, G. Pijaudier-Cabot, G. Chanvillard, Experimental characterization of the self-healing of cracks in an ultra high performance cementitious material: mechanical tests and acoustic emission analysis, Cement and Concrete Research (2007) 519–527.

[9] S. Jacobsen, J. Marchand, H. Homain, SEM observations of the microstructure of frost deteriorated and self-healed concrete, Journal of Cement and Concrete Research 25 (1995) 1781–1790.

[10] S. Jacobsen, J. Marchand, L. Boisvert, Effect of cracking and healing on chloride transport in OPC concrete, Journal of Cement and Concrete Research 26 (1996) 869–881.

[11] S. Jacobsen, E.J. Sellevold, Self healing of high strength concrete after deterioration by freeze/thaw, Journal of Cement and Concrete Research 26 (1996) 52–62.

[12] C. Aldea, W. Song, J.S. Popovics, S.P. Shah, Extent of healing of cracked normal strength concrete, Journal of Materials In Civil Engineering 12 (2000) 92–96.

[13] V.C. Li, S. Wang, C. Wu, Tensile strain-hardening behavior of polyvinyl alcohol engineered cementious composite (PVA-ECC), ACI Materials Journal 98 (2001) 483–492.

[14] E. Yang, Y. Yang, V.C. Li, Use of high volumes of fly ash to improve ECC mechanical properties and material greenness, ACI Materials Journal 104 (2007) 620–628.

[15] V.C. Li, On engineered cementitious composites (ECC) — a review of the materials and its applications, Journal of Advanced Concrete Technology 1 (2003) 215–230.

[16] Y. Yang, M. Lepech, V.C. Li, Self-healing of ECC under cyclic wetting and drying, Proceedings of Int'l Workshop on Durability of Reinforced Concrete under Combined Mechanical and Climatic Loads, Qingdao, China, 2005, pp. 231–242.

[17] K. Wang, D.C. Jansen, S.P. Shah, A.F. Karr, Permeability study of cracked concrete, Journal of Cement and Concrete Research 27 (1997) 381–393.

[18] J.N. Cernica, Geotechnical Engineering, Holt, Reinhart & Winston, New York, 1982.

[19] M.B. Weimann, V.C. Li, Drying Shrinkage and Crack Width of ECC, BMC 7, Poland, 2003, pp. 37–46.

[20] Lepech, M.D., A Paradigm for Integrated Structures and Materials Design for Sustainable Transportation Infrastructure, Ph.D. Dissertation, Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, 2006.

[21] Wang, S., Micromechanics Based Matrix Design for Engineered Cementitious Composites, Ph.D. Dissertation, Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, 2005.