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Micromechanics-Based Durability Study of Polyvinyl Alcohol-Engineered Cementitious Composite

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The durability of engineered cementitious composites (ECC) reinforced with polyvinyl alcohol (PVA) fiber is investigated in this paper. ECCs have been realized as ductile strain-hardening cementitious composites with tensile strain capacity up to 5%. This material is being applied in new construction and for the repair and retrofit of structures. A micromechanics-based approach is adopted in the present durability study. The micromechanics-based model relates the fiber, matrix, and interface parameters to composite properties through knowledge of microdeformation mechanisms beyond the elastic stage. Composite property changes resulting from environmental loading are expected to be a manifestation of changes in properties at the fiber, matrix, and/or interface level. This concept is examined in this paper by experimentally determining the changes in the fiber and fiber-matrix interface properties with specimens exposed to accelerated testing and correlating such changes to changes in the ductility of composites exposed to the same accelerated testing conditions. The accelerated test used in this study is a hot water immersion test simulating a long-term hot and humid environment. It is found that the fiber-matrix interface chemical bond increases while the apparent fiber strength decreases when the exposure time reaches 26 weeks. Correspondingly the composite ductility also decreases. The micromechanical model provides a rational means of interpreting and correlating the data from these two levels of testing. Despite the deterioration, PVA-ECC is found to retain tensile ductility more than 200 times that of normal concrete or normal fiber-reinforced concrete after exposure to an equivalent of 70 years or more of hot and humid environmental conditions.

Keywords: cementitious; durability; fiber-reinforced concrete; test.

INTRODUCTION

In the past decade, high-performance fiber-reinforced cementitious composites (HPFRCC) have evolved with intensified research. Very high ductility HPFRCC can now be routinely processed. This advance is due to the development in fiber, matrix, and composite processing technology, as well as better understanding of the fundamental micromechanics governing composite behavior, particularly the interaction among fiber, matrix, and interface properties.[1-4]

Engineered cementitious composites (ECC), a special type of HPFRCC containing a small amount (typically less than 2.5% by volume) of short random fibers, have been realized. ECC with tensile strain capacity reaching several percent[5] are designed with micromechanical principles. Micromechanical parameters associated with fiber, matrix, and interface are combined to satisfy a pair of criteria, the first crack stress criterion and steady state cracking criterion,[5,6] to achieve the strain hardening behavior. A high-performance polyvinyl alcohol fiber-reinforced engineered cementitious composite (PVA-ECC)[7] for structural applications has been developed. Although a large amount of PVA-ECC research[8-11] has been carried out, little is known about the durability of PVA-ECC.

While PVA fibers have been in use for some time and the experience of durability of fiber-reinforced concretes (FRC) containing PVA fibers has been positive,[12] the need to assess the durability performance of PVA-ECC becomes increasingly important as these materials are targeted for use in load-bearing structural members.[13-20] PVA-ECC structural members may be exposed to environments that could lead to modifications in the material microstructure and hence changes in the composite properties. Furthermore, the fibers are expected to carry loads and are therefore intrinsic to the structural response. This aspect is very different from those FRC in which the fibers only serve to reduce shrinkage cracking but are not expected to carry externally applied loads.

From a micromechanical viewpoint, composite durability can be related to changes in micromechanical parameters associated with properties of the fiber, matrix, and/or the fiber-matrix interface. Change in the fiber and/or fiber-matrix interface leads to modifications in the bridging properties of the composite. In turn, because the bridging properties directly influence the pseudo strain-hardening behavior of ECC, the magnitudes of composite ultimate tensile strength and/or tensile strain capacity can be altered. As an example, if a ductile building column or a bridge deck section is designed using the large strain capacity of the PVA-ECC, then changes in fiber, matrix, or fiber-matrix interface properties over the service life leading to a reduction in this strain capacity could significantly modify the designed structural performance of the column or bridge deck.

At the present time, the durability of most construction material, including fiber-reinforced cementitious composites, is assessed based on experimental accelerated tests. While this type of investigation is necessary and provides a valuable database of material durability, there are several shortcomings of this approach including: a) even with an "accelerated" test, it takes a relatively long time to develop a good material durability performance database; b) an accelerated test must be conducted for each material composition; and c) the information is difficult to use in addressing the source or mechanism(s) of deterioration, which leads to; d) difficulty in taking corrective measures by means of re-engineering of the material.

An objective of this study is to establish the methodology of micromechanics-based durability assessment for PVA-ECC. The theoretical component is based on the suite of micromechanical models constructed by Kanda and Li[21] for PVA-ECC materials. These models include the stress-crack

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opening relationship (σ-δ curve) and conditions for pseudo strain-hardening expressed in terms of micromechanical parameters. In the present work, the dependence of micromechanical parameters on environmental exposure is explicitly recognized. Once the data on fiber, matrix, and interface properties as a function of exposure time to a given environment are available from experiments, they can be used as inputs to the micromechanical models to predict the long-term performance of the composite properties. The durability of composites with different fiber content or aspect ratio may still be assessed using the same model and the same set of environment sensitive input parameters.

In this paper, to demonstrate the validity of this approach, the model-predicted composite properties will be compared with those obtained experimentally by exposing the composite to the same environmental conditions. An assessment will be made regarding the micromechanism(s) responsible for composite property degradation, if any. This information will be useful toward making needed changes in fiber, matrix, and/or interfaces to engineer a durable composite.

In the following, the background on accelerated testing and pertinent micromechanics theories are presented. In this paper, focus is placed on long-term hot and humid environmental loading, even though the broader framework described previously is applicable to other types of environmental exposures. The experimental investigations at the fiber bridging (fiber and interface level) and on the composite level are then discussed. The subsequent sections provide analyses of these experimental results using the micromechanics theory of ECC materials. Conclusions are then drawn on the durability of PVA-ECC, the effectiveness of the micromechanics-based durability assessment approach, and on strategies in designing durable ECC.

RESEARCH SIGNIFICANCE

This paper presents a new methodology in durability assessment of fiber-reinforced cementitious composites based on micromechanical models and knowledge of environmental sensitivity of composite components. The new methodology is expected to provide useful guidance for material design and engineering of durable ultra ductile cementitious composites. The research findings also confirm that adequate tensile strain capacity over 200 times that of normal FRC is retained, despite some reduction in the ductility of PVA-ECC under long-term hot and humid environmental loading. Therefore, PVA-ECC is demonstrated to be suitable for a broad range of structural applications where long-term ductility must be maintained.

FRAMEWORK OF STUDY

Accelerated aging tests for fiber-reinforced cementitious composites

The processes that cause changes in composite mechanical properties as a result of natural weathering are very complex and depend on the chemical composition of the fiber and the matrix as well as how they interact. The goal of laboratory accelerated aging test is to accurately simulate the effect of long-term natural weathering using controlled laboratory experiments. In the past, environmental durability of FRC has been assessed by researchers using four basic accelerated aging methods—wet-dry cycling, hot water immersion, freezing-and-thawing testing, and carbonation aging. All four test methods were designed to represent in-place exposure. Wet-dry cycling tests simulate the effect of rain and heat cycles. Hot water immersion tests simulate the long-term effects of hot and humid environments. Freezing-and-thawing tests simulate the climatic changes in winter. Carbonation aging tests simulate the ingress of carbon dioxide into the composite with time.

The effect of hot water immersion on the composite's microstructure and mechanical properties is time dependent. Natural fiber composites (such as cellulose) are extremely susceptible to short-term exposure and as a result lose mechanical strength because these fibers are particularly sensitive to alkali attack.[22] Also, the effect of long-term hot water immersion on the mechanical property on glass, carbon, aramide, PVA, polyethylene, acrylic, and carbon fiber-reinforced composites has been examined.[23-27] A hot water immersion test has been adopted as a typical method of accelerated aging for simulating the effects of long-term environmental weathering on fiber reinforced composites.

In this study, the hot water immersion test technique recommended by the Building Material Industry Society of Japan[27] is adopted. This method of accelerated test for the durability of fiber-reinforced cementitious composites is expected to be accepted by Japanese Industrial Standards (JIS). The accelerated test is carried out with composites immersed in 60 °C water for 4, 13, 26, and 52 weeks. It has been found that the bending toughness of PVA reinforced cementitious composites after 7.7 days of acceleration test corresponds to the bending performance after 3 years of outdoor exposure in Japan.

Theoretical guidelines for micromechanics-based durability study

Theoretical prediction of the mechanical durability of PVA-ECC is possible through the use of micromechanics. Micromechanics allows changes caused by natural weathering to the fiber, to the matrix, and at the fiber-matrix interface to be quantified. The fiber is characterized in terms of volume fraction V_f, fiber length L_f, diameter D_f, elastic modulus E_f, and tensile strength $\sigma_{fu}{}^N$. The matrix is characterized in terms of its fracture toughness K_m and elastic modulus E_m. The fiber-matrix interface is described by the frictional stress τ_o, chemical bond G_d, and apparent fiber strength $\sigma_{fu}{}^{APP}$. The apparent strength $\sigma_{fu}{}^{APP}$ denotes the reduced fiber strength when the fiber is embedded in a cementitious matrix.[28] Because the low tensile strain capacity of most cementitious materials is identified as the bottleneck property to achieving superior structural performance, the micromechanical model utilized herein is mainly focused on achieving pseudo strain-hardening in tension in ECC materials.

A fundamental requirement for pseudo strain-hardening[6,29] is that steady-state cracking occurs, which necessitates the crack

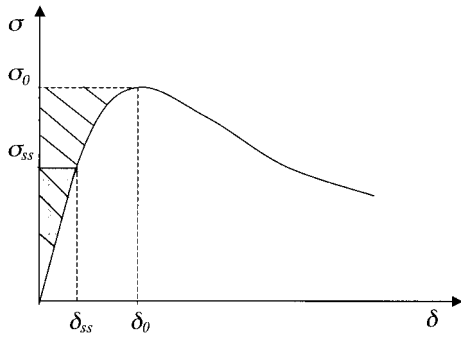

Fig. 1—Typical stress versus crack-opening $\sigma(\delta)$ curve representing fiber bridging property of cementitious composites. Shaded area represents maximum crack tip fracture energy that would result in steady-state flat crack initiated at steady-state stress σ_{ss}. Hatched area represents maximum complementary energy of the composite.

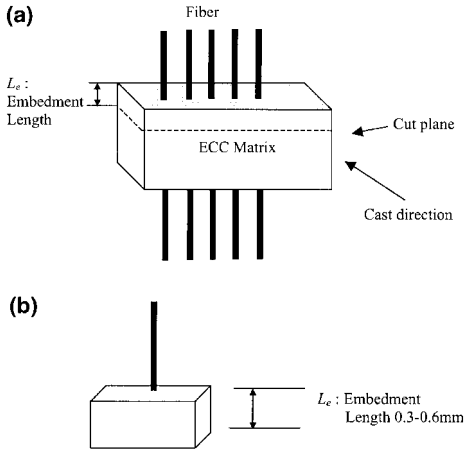

Fig. 2—Pullout specimen configuration: (a) cast specimen with multiple fibers; and (b) cut specimen with a single fiber.

tip toughness J_{tip} (shaded area, Fig. 1) to be less than the complementary energy J_b' (hatched area, Fig. 1) calculated from the bridging stress σ versus crack opening δ curve

$$J_{tip} = \frac{K_m^2}{E_m} \leq \sigma_o \delta_o - \int_0^{\delta_o} \sigma(\delta) d\delta \equiv J_b' \quad (1)$$

where σ_0 is the maximum bridging stress corresponding to the opening δ_0. J_{tip} approaches the matrix toughness K_m^2/E_m at small fiber content, appropriate for ECC, because less than 2.5% fiber by volume is used. The matrix fracture toughness K_m and Young's modulus E_m are sensitive to the details of mixture proportions, such as water-cement ratio (w/c) and sand content. High complementary energy is favorable to multiple cracking and high ductility of the composite.

Equation (1) is obtained by considering the balance of energy changes during extension of the steady-state flat crack. The stress-crack opening relationship $\sigma(\delta)$, viewed as a constitutive law of fiber-reinforced composites, is derived by using analytic tools of fracture mechanics, micromechanics, and probability theory. Specifically, the energetics of tunnel crack propagation along the fiber-matrix interface is used to quantify the debonding process and the bridging force of a fiber with a given embedment length.[30] Probability theory is introduced to describe the random nature of preexisting flaws and the random location and orientation of fibers.[31,32] The random orientation of fibers also necessitates the accounting for the mechanics of interaction between an inclined fiber and the matrix crack.[33] Details of these micromechanics analyses can be found in Li and Leung,[3] Li and Wu[4], Kanda and Li,[21] and Lin, Kanda, and Li.[30]

Environmental loading may lead to changes in fiber, matrix, and/or interface properties, so that the condition for strain hardening, as expressed in Eq. (1) may be satisfied in the short term but may not be satisfied in the long term. Satisfaction of Eq. (1) is necessary to achieve ECC behavior, otherwise, normal tensile softening FRC behavior results. As a result, an initially ductile composite may lose tensile strain capacity over time under environmental exposure.

Table 1—Properties of PVA fiber

Nominal fiber strength σ_{fu}^N, MPa	Apparent fiber strength σ_{fu}^{APP}, MPa	Diameter D_f, μm	Length L_f, mm	Young's modulus E_f, GPa	Elongation, %
1631	1035	39	12	38.9	6.4

Table 2—PVA-ECC composition

w/c	S/C	FA/C	SP	Viscosity agent, %	Defoamer, %	Fiber, volume %
0.42	1.0	0.11	1.2	0.049	0.048	2

Notes: FA = fly ash Type II; S = sand; C = cement; SP = superplasticizer (high-range water-reducing admixture).

EXPERIMENTAL PROGRAM

Material

The specific PVA fiber used in the present study has mechanical and geometrical properties described in Table 1. The fibers are coated with an oiling agent that reduces the hydrophilicity of the fiber surface. The main components of the dry mix consist of normal portland cement, fine sand, and fly ash Type II.

The chemical additives used are a dry viscosity agent (methyl cellulose) and high-range water-reducing admixture to adjust the workability. A small amount of defoamer was added to control the microvoids generated by the methyl cellulose. The complete matrix composition used in the PVA-ECC for this study is summarized in Table 2. The fiber volume fraction in the composite is 2%.

Fiber-matrix interface property and apparent fiber strength determination

The fiber-matrix interface properties (frictional bond τ_0 and chemical bond G_d) were determined based on single fiber pullout tests. The specimen configuration and dimensions are shown in Fig. 2 using a technique described in detail in Katz and Li.[34] Continuous fibers were taped to a plastic mold for alignment control. The matrix was prepared and poured into the mold. Vibration was applied for less than 2 min. A Plexiglas plate was then placed over the rectangular specimen to compact the material. The specimens were demolded after 24 h. After demolding, the specimens (Fig. 2(a)) were cured in a water tank at 20 °C for 28 days. The cured specimens were then immersed in hot water at 60 °C for 0, 4, 13, and 26 weeks. Upon removal from the hot water tank, the specimens were cut with a diamond saw under running water to the desired thickness (Fig. 2(b)), which was also the fiber embedment length.

The pullout tests were conducted on a fiber tester with the configuration shown in Fig. 3. A 10 N load cell was used to

Table 3—Effect of hot water immersion on micromechanical parameters, complementary energy J_b', and tensile strain capacity of composites

Acceleration age, weeks	τ_o, MPa	G_d, J/m^2	σ_{fu}^{APP}, MPa	σ_{fu}^{N}, MPa	E_f, GPa	Fiber elongation, %	J_b', J/m^2	J_b'/J_{tip}	Strain capacity ε_{cu}, %
0	2.11 ± 0.22	2.49 ± 0.88	1035 ± 144	1631 ± 57	38.9 ± 2.0	6.35 ± 0.32	16.22	3.25	4.47 ± 1.24
4	2.19 ± 0.17	2.59 ± 1.02	993 ± 19	1619 ± 48	38.3 ± 1.9	6.12 ± 0.30	13.77	2.75	3.18 ± 0.92
13	1.92 ± 1.06	2.49 ± 1.36	1055 ± 156	1620 ± 58	37.7 ± 2.5	6.12 ± 0.22	19.29	3.87	4.06 ± 1.48
26	2.30 ± 0.19	3.83 ± 0.87	930 ± 179	1616 ± 63	37.0 ± 2.8	6.16 ± 0.24	8.50	1.83	2.72 ± 0.67

Note: $J_{tip} \sim 5$ J/m^2 assumed for J_b'/J_{tip} calculations.

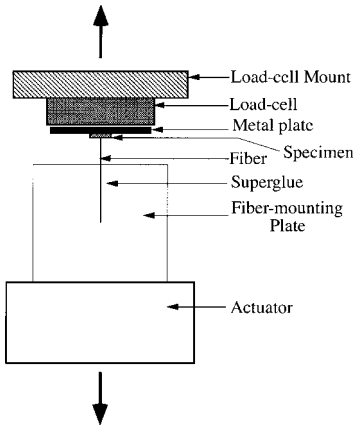

Fig. 3—Setup of single fiber pullout test.

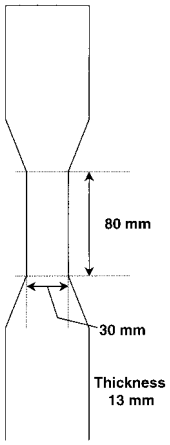

Fig. 4—Specimen configuration for uniaxial tensile test.

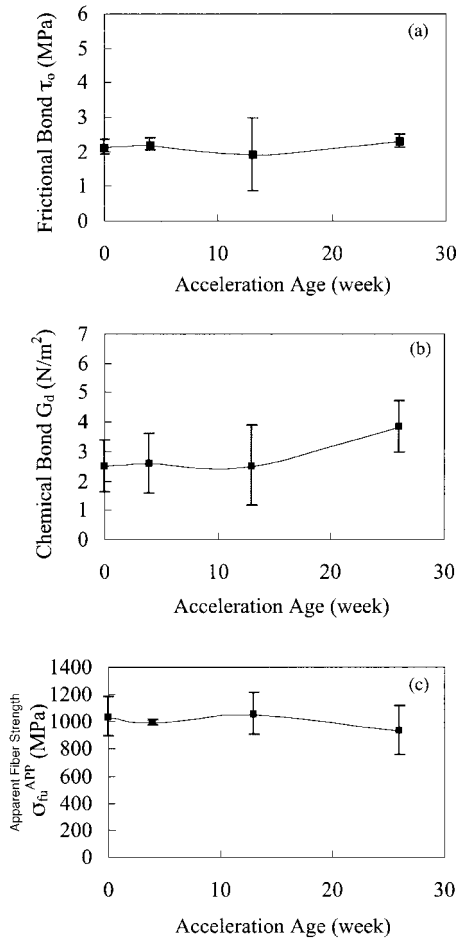

Fig. 5—Effect of hot water immersion on: (a) frictional bond; (b) chemical bond; and (c) apparent fiber strength.

measure the pullout load of the fibers with a displacement rate of 0.2 mm/min. These results were used to determine τ_0 and G_d using the procedure described by Katz and Li.[34] Pull-to-break tests were conducted on specimens with longer embedment length to determine the apparent fiber strength σ_{fu}^{APP}.

At least seven specimens were tested for the fiber-matrix interface property determination and at least eight specimens were tested for apparent fiber strength determination.

Fiber nominal strength determination

To determine the fiber nominal strength, fibers were immersed in hot water at 60 °C for 0, 4, 13, and 26 weeks. After removal from the hot water tank, single fibers were glued across 1 mm gaps cut with a special punch in graph paper strips. The fibers were then conditioned for 24 h at 20 °C and 65% relative humidity (RH). The instrument used to test the fiber was a fiber tester. The rate of extension was 0.5 mm/min; the breaking loads were then calculated from traces for at least 10 individual fibers from each sample.

Composite uniaxial tensile test

For determining the tensile stress-strain curve of composites, dumbbell-shaped specimens shown in Fig. 4 were prepared. The tested section length was 80 mm and the cross section was 13 x 30 mm. After 28 days curing in a water tank at 20 °C, the specimens were immersed in hot water at 60 °C for 0, 4, 13, and 26 weeks. Three specimens were tested at each age, using a material testing machine with displacement rate at 0.2 mm/min. Because the fiber length is 12 mm long, the relatively small cross section of the tensile specimens will most likely result in fiber orientation between one- and two-dimensionally random. The tensile properties measured are therefore expected to have higher values than those from tests with truly three-dimensionally random fiber orientation.

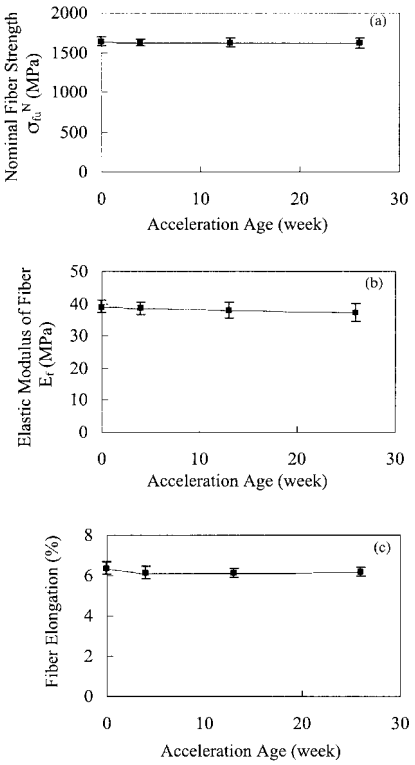

Fig. 6—Effect of hot water immersion on fiber properties: (a) norminal strength; (b) elastic modulus; and (c) elongation.

EXPERIMENTAL RESULTS AND DISCUSSION

Figure 5 shows the effect of hot water immersion tests on the interfacial parameter, frictional bond τ_0, chemical bond G_d, and apparent fiber strength σ_{fu}^{APP}. Figure 6 shows the environmental loading effect on fiber parameters: nominal fiber strength σ_{fu}^{N}, elastic modulus of fiber E_f, and fiber elongation. Complete data on these properties are tabulated in Table 3. The value of J_b is calculated from these micromechanical parameters (using Eq. (1)). With J_{tip} assumed at 5 J/m^2 (based on a previous study[35]) unaffected by environmental loading, J_b'/J_{tip} retains about 3 between 0 and 13 weeks of hot water immersion. However, it decreases to 1.83 after 26 weeks. This significant decrease in J_b'/J_{tip} results mainly from the increase in G_d and the decrease in σ_{fu}^{APP} at 26-week immersion.

The influence of hot water immersion on fiber-matrix interaction behavior can be appreciated by comparing Fig. 7(a) with Fig. 7(b). Figure 7(a) is a scanning electron microscopy (SEM) image of the rupture end for the fiber after 26 weeks of hot water immersion, showing delamination failure. Delamination failure was not observed after hot water immersion for 0, 4, and 13 weeks as shown in Fig. 7(b).

The composite tensile stress-strain curves after hot water immersion for 0, 4, 13, and 26 weeks are shown in Fig. 8. Both the first crack stress and the ultimate tensile strength corresponding to the maximum tensile bridging stress appear to increase with time of exposure. Tensile strain-hardening behavior was observed for every specimen. The average tensile strain capacity value is shown in Table 3. Figure 9 shows the trend of strain capacity change with age. A large variation in the tensile strain capacity at given immersion time was observed. A tendency of reduced tensile strain capacity with acceleration age was noticed, however, especially from 13 to 26 weeks.

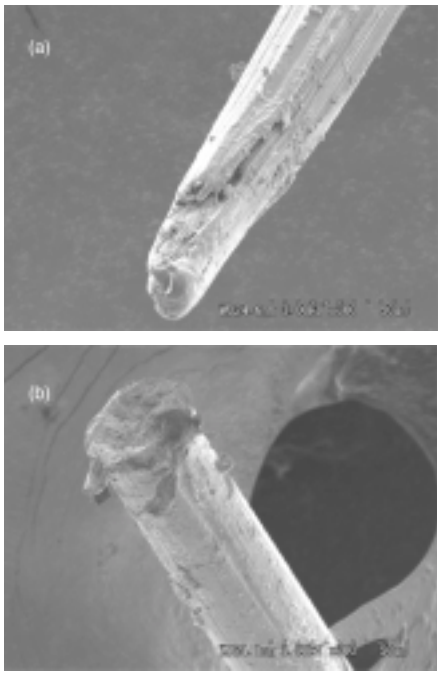

Fig. 7—Effect of hot water immersion on fiber pullout behavior from single fiber tests: (a) fiber delamination after hot water immersion for 26 weeks; and (b) fiber pulled out intact for specimens exposed to 0, 4, and 13 weeks.

From the experimental results reported previously, it is apparent that a correlation exists between the low J_b'/J_{tip} value and the low tensile strain capacity at 26 weeks of exposure. It suggests that after immersing the composite specimens in hot water for 26 weeks, the fiber bridging property has deteriorated through an increase in the chemical bond G_d of the fiber-matrix interface combined with a decrease in the apparent fiber strength σ_{fu}^{APP}. This combination of changes in G_d and σ_{fu}^{APP} results in a $\sigma(\delta)$ curve that has small complementary energy J_b' (Fig. 1). Consequently, the condition for strain hardening as expressed in Eq. (1) is more readily violated in such composites after long-term exposure, leading to unsaturated multiple cracking and associated reduced strain capacity. The SEM observation on the nature of fiber damage for the specimen exposed for 26 weeks (Fig. 7(a)) further supports this contention.

If there were no variation in bridging properties in the composite material from point to point in a uniaxial tensile specimen, and that initial flaw size and matrix toughness J_{tip} were uniform in the specimen, Eq. (1) would predict that saturated multiple cracking should be attained when $J_b'/J_{tip} = 1$. Due to an unavoidable variation in material properties in a specimen, however, the value of J_b'/J_{tip} required for multiple crack saturation is expected to be higher. Based on an experimental correlation between the intensity of multiple crack saturation and the J_b'/J_{tip} value of an ECC, Kanda and Li[21] estimated that a value of $J_b'/J_{tip} = 3$ is necessary to achieve saturated multiple cracking. The experimental data reported in the last two columns of Table 3 is consistent with this estimate. For specimens immersed in hot water between 0 and 13 weeks, J_b'/J_{tip} is between 2.75 and 3.87. For specimens immersed in hot water for 26 weeks, J_b'/J_{tip} drops to 1.83, significantly below the estimated required value of 3 for saturated multiple cracking.

From the previous discussions and referencing Table 3, long-term hot water immersion appears to mainly influence

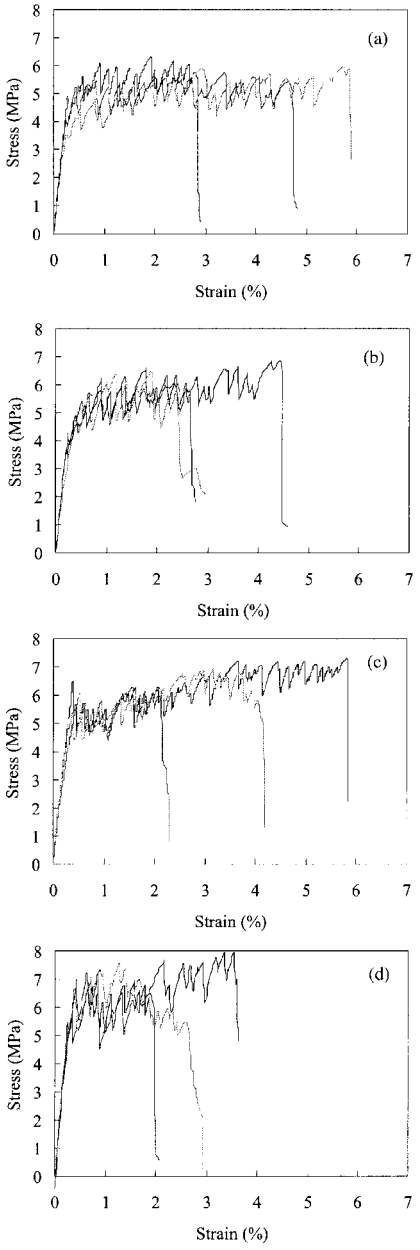

Fig. 8—Effect of hot water immersion on tensile stress-strain curve of composites with: (a) 0 weeks; (b) 4 weeks; (c) 13 weeks; and (d) 26 weeks of exposures. In each case, three samples are tested.

G_d and σ_{fu}^{APP}, while other micromechanical parameters are much less affected. The changes in G_d and σ_{fu}^{APP} may have resulted from a change in interfacial condition or in the surface coating of the fiber. For example, Li et al.[36] observed the delamination of the fiber tip with pullout test of noncoated PVA fiber that has high interfacial bond (τ_o, G_d). The nature of delamination is similar to that shown in Fig. 7. Bentur[26] examined the interfacial microstructure change of glass fiber-reinforced composites with humid environmental loading. He concluded that the humid environment promoted the formation of calcium hydroxide at the interface between glass fiber and matrix, resulting in a high interfacial bond strength and a brittle composite. A similar scenario may have occurred in the PVA-ECC composites investigated herein.

Despite a reduction in ductility, the PVA-ECC composites after 26 weeks of hot water immersion (equivalent to more than 70 years of natural weathering[27,37]) still retain tensile strain-hardening behavior and tensile strain capacity of 2.7% on average. This ductility remains over 200 times higher than that in normal concrete and conventional FRC composites with no environmental exposure. For this reason, it is expected that the PVA-ECC composites investigated are suitable for long-term applications in hot and humid environments if the structure is designed based on long-term mechanical properties.

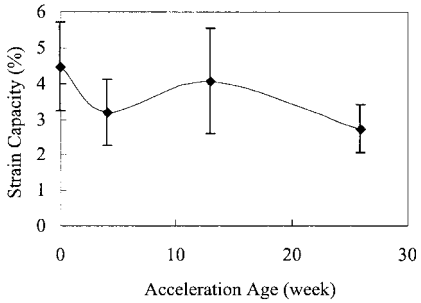

Fig. 9—Influence of hot and humid environmental loading on composite tensile strain capacity.

CONCLUSIONS AND FURTHER DISCUSSIONS

The following conclusions can be drawn from the current study:

1. The micromechanics-based model provides a useful link between changes at the fiber and interface level due to environmental exposure, to changes in composite ductility. Specifically, a rational interpretation of observed property changes at the composite level in terms of changes in fiber and interface parameters is provided;

2. Under hot water immersion conditions, the increase of chemical bond between the PVA fiber and mortar matrix and the reduction in apparent fiber strength are identified as dominant factors governing the long-term durability of PVA-ECC;

3. The micromechanics-based durability model provides a systematic approach for designing durable ECC composites. In the present investigation, the effective guidance for retaining high J_b through control of G_d and σ_{fu}^{APP} is revealing; and

4. Long-term hot water immersion leads to a reduction (from 4.5% averaged for specimens with no aging) in the tensile strain capacity of PVA-ECC. It retains 2.7% on average, however, and shows tensile strain-hardening behavior at 26 weeks of aging. PVA-ECC composites are durable under long-term hot and humid environmental loading as long as this long-term value of strain capacity is used in structural design.

In this paper, the fiber and interfacial parameters were examined after exposure to environmental loading. The matrix toughness J_{tip} was assumed constant. Katz and Bentur[23] reported that the strength of plain cement matrix increase and matrix pores decrease in size with hot and humid environmental loading. This observation suggests that J_{tip} may increase with time, leading to violation of the condition for strain hardening represented by Eq. (1). If so, the values of J_b'/J_{tip} reported in Table 3 should be further reduced with larger reduction for those specimens subjected to longer environmental exposure. Composite ductility deterioration due to matrix toughness increase cannot be ruled out. While this does not contradict any of the previous conclusions, a new series of tests is being carried out to investigate the change in J_{tip} under the same environmental conditions.

This micromechanics-based durability study indicated that it is important to resist changes in the micromechanical parameters G_d and σ_{fu}^{APP} for durable PVA-ECC design. The PVA fibers used are coated with an oiling agent. It is expected that improving control of the oiling agent (amount and type) could be one of the best solutions to retain these parameters, and this should be investigated experimentally.

The durability of PVA-ECC material was examined under long-term hot and humid environmental loading in this study. In the future, the effects of carbonation aging, wet-dry cycling, and freezing-and-thawing exposures should be examined to understand the durability of ECC composites under a broader range of environmental conditions. The proposed micromechanics-based durability assessment approach should remain useful for these studies.

In some structural applications, it is expected that the PVA-ECC may be used beyond the elastic state under service loads. The material may therefore be exposed to long-term environmental loading in the microcracked state. Hence, future durability studies should include specimens preloaded to the strain-hardening range prior to accelerated aging tests.

Finally, it should be noted that the present test results both at the fiber and interface level, as well as at the composite level, show fairly large variations. While the general trends are not expected to change, better constraint in numerical values for the measured material parameters should benefit from improved testing procedures and from using a larger number of specimens.

REFERENCES

1. Aveston, J.; Cooper, G.A.; and Kelly, A., "Single and Multiple Fracture," *Proceedings of Properties of Fiber Composites*, National Physical Laboratory, IPC Science and Technology Press, Guildford, UK, 1971, pp. 15-24.

2. Naaman, A. E., and Homrich, J. R., "Tensile Stress Strain Properties of SIFCON," *ACI Materials Journal*, V. 86, No. 3, May-June 1989, pp. 244-251.

3. Li, V. C., and Leung, C. K. Y., "Steady State and Multiple Cracking of Short Random Fiber Composites," *Journal of Engineering Mechanics*, ASCE, V. 188, No. 11, 1992, pp. 2246-2264.

4. Li, V. C., and Wu, H. C., "Conditions for Pseudo Strain-Hardening in Fiber Reinforced Brittle Matrix Composites," *Applied Mechanics Reviews*, V. 45, No. 8, Aug. 1992, pp. 390-398.

5. Li, V. C., "Engineered Cementitious Composites—Tailored Composites Through Micromechanical Modeling," *Fiber Reinforced Concrete: Present and the Future*, N. Banthia, A. Bentur, and A. Mufti, eds., Canadian Society for Civil Engineering, Montreal, 1998, pp. 64-97.

6. Li V. C., "From Micromechanics to Structural Engineering—The Design of Cementitious Composites for Civil Engineering Applications, *Journal of Structural Mechanics and Earthquake Engineering*, V. 10, No. 2, 1993, pp. 37-48.

7. Li, V. C.; Wang, S.; and Wu, C., "Tensile Strain-Hardening Behavior of PVA-ECC," *ACI Materials Journal*, V. 98, No. 6, Nov.-Dec. 2001, pp. 483-492.

8. Li, V. C., and Kanda, T., "Engineered Cementitious Composites for Structural Applications," *Journal of Materials in Civil Engineering*, V. 10, No. 2, May 1998, pp. 66-69.

9. Li, V. C.; Horii, H.; Kabele, P.; Kanda, T.; and Lim, Y. M., "Repair and Retrofit with Engineered Cementitious Composites," *International Journal of Engineering Fracture Mechanics*, V. 65, No. 2-3, 2000, pp. 317-334.

10. Zhang, J., and Li, V. C., "Monotonic and Fatigue Performance of Engineered Fiber Reinforced Cementitious Composite in Overlay System with Deflection Cracks," *Journal of Cement and Concrete Research*, V. 32, No. 3, 2002, pp. 415-423.

11. Fischer, G., and Li, V. C., "Effect of Matrix Ductility on Deformation Behavior of Steel Reinforced ECC Flexural Members under Reversed Cyclic Loading Conditions," *ACI Structural Journal*, V. 99, No. 6, Nov.-Dec. 2002, pp. 781-790.

12. Akers, S. A. S., and Studinka, J. B., "Aging Behaviour of Cellulose Fibre Cement Composites in Natural Weathering and Accelerated Tests," *The International Journal of Cement Composites and Light Weight Concrete*, V. 11, No. 2, May 1989, pp. 93-97.

13. Li, V. C., "Reflection on the Research and Development of Engineered Cementitious Composites," *Proceedings of the JCI International Workshop on Ductile Fiber Reinforced Cementitious Composites*, Oct. 2002, pp. 1-21.

14. Kanda, T.; Saito, T.; Sakata, N.; and Hiraishi, M., "Fundamental Properties of Direct Sprayed ECC," *Proceedings of the JCI International Workshop on Ductile Fiber Reinforced Cementitious Composites*, Oct. 2002, pp. 133-141.

15. Martinola, G., and Bauml, M. F., "Optimizing ECC in Order to Prevent Shrinkage Cracking," *Proceedings of the JCI International Workshop on Ductile Fiber Reinforced Cementitious Composites*, Oct. 2002, pp. 143-152.

16. Martinola, G.; Bauml, M. F.; and Wittmann, F. H., "Modified ECC Applied as an Effective Chloride Barrier," *Proceedings of the JCI International Workshop on Ductile Fiber Reinforced Cementitious Composites*, Oct. 2002, pp. 171-180.

17. Kunieda, M.; Kamada, T.; and Rokugo, K., "Size Effects on Flexural Failure Behavior of ECC Members," *Proceedings of the JCI International Workshop on Ductile Fiber Reinforced Cementitious Composites*, Oct. 2002, pp. 229-238.

18. Kabele, P., "New Developments in Analytical Modeling of ECCs Structural Behavior," *Proceedings of the JCI International Workshop on Ductile Fiber Reinforced Cementitious Composites*, Oct. 2002, pp. 239-248.

19. Fischer, G.; Fukuyama, H.; and Li, V. C., "Effect of Matrix Ductile on the Performance of Reinforced ECC Column Members under Reversed Cyclic Loading Conditions," *Proceedings of the JCI International Workshop on Ductile Fiber Reinforced Cementitious Composites*, Oct. 2002, pp. 269-278.

20. Billington, S. L., and Yoon, J., "Cyclic Behavior of Precast Post-Tensioned Segmental Concrete Columns with ECC," *Proceedings of the JCI International Workshop on Ductile Fiber Reinforced Cementitious Composites*, Oct. 2002, pp. 279-288.

21. Kanda, T., and Li, V. C., "A New Micromechanics Design Theory for Pseudo Strain Hardening Cementitious Composite," *Journal of Engineering Mechanics*, ASCE, V. 125, No. 4, 1999, pp. 373-381.

22. Sharman, W. R., "Durability of Fibre Cement Sheet Claddings," *New Zealand Concrete Construction*, V. 27, Aug. 1983, pp. 3-7.

23. Katz, A., and Bentur, A., "Effect of Matrix Composition on the Aging of CFRC," *Cement and Concrete Composites*, V. 17, 1995, pp. 87-97.

24. Majumdar, A. J., "The Role of the Interface in Glass Fibre Reinforced Cement," *Cement and Concrete Research*, V. 4, 1974, pp. 247-266.

25. Majumdar, A. J., and Nurse, R. W., "Invited Review: Glass Fiber-Reinforced Cement," *Material Science and Engineering*, V. 15, 1974, pp. 107-127.

26. Bentur, A., "Mechanisms of Potential Embrittlement and Strength Loss of Glass Fiber Reinforced Cement Composites," *Proceedings of Durability of Glass Fiber Reinforced Concrete Symposium*, Chicago, Ill., 1985, pp. 109-123.

27. "Research on the Evaluation Method of the Durability of Fiber Reinforced Concrete," Building Material Industry Society of Japan, 2001.

28. Kanda, T., and Li, V. C., "Effect of Apparent Fiber Strength and Fiber-Matrix Interface on Crack Bridging in Cement Composites," *Journal of Engineering Mechanics*, ASCE, V. 125, No. 3, 1999, pp. 290-299.

29. Marshall, D., and Cox, B. N., "J-Integral Method for Calculating Steady-State Matrix Cracking Stress in Composites," *Mechanics of Materials*, V. 7, No. 8, 1988, pp.127-133.

30. Lin, Z.; Kanda, T.; and Li, V. C., "On Interface Property Characterization and Performance of Fiber Reinforced Cementitious Composites," *Concrete Science and Engineering*, RILEM, V. 1, 1999, pp. 173-184.

31. Wu, H. C., and Li, V. C., "Stochastic Process of Multiple Cracking in Discontinuous Random Fiber Reinforced Brittle Matrix Composites," *International Journal of Damage Mechanics*, V. 4, No. 1, 1995, pp. 83-102.

32. Wang, Y.; Backer, S.; and Li, V. C., "A Statistical Tensile Model of Fiber Reinforced Cementitious Composites," *Composites*, V. 20, No. 3, 1989, pp. 265-274.

33. Li, V. C.; Wang, Y.; and Backer, S., "Effect of Inclining Angle, Bundling, and Surface Treatment on Synthetic Fiber Pull-Out from a Cement Matrix," *Composites*, V. 21, No. 2, 1990, pp. 132-140.

34. Katz, A., and Li, V. C., "A Special Technique for Determining the Bond Strength of Carbon Fibers in Cement Matrix by Pullout Test," *Journal of Materials Science Letters*, V. 15, 1996, pp. 1821-1823.

35. Li, V. C.; Mishra, D. K.; and Wu, H. C., "Matrix Design for Pseudo-Strain-Hardening Fiber-Reinforced Cementitious Composites," *Materials and Structures*, RILEM, V. 28, No. 183, 1995, pp. 586-595.

36. Li, V. C.; Wu, C.; Wang, S.; Ogawa, A.; and Saito, T., "Interface Tailoring for Strain-Hardening PVA-ECC," *ACI Materials Journal*, V. 99, No. 5, Sept.-Oct. 2002, pp. 463-472.

37. Proctor, B. A.; Oakley, D. R.; and Litherland, K. L., "Developments in the Assessment and Performance of GRC Over 10 Years," *Composites*, Apr. 1982, p. 173.