Keynote Address

Re-engineering concrete for resilient and sustainable infrastructure

Victor C. Li
University of Michigan, USA

Keywords:

ABSTRACT: This paper considers the requirements of construction materials to support civil infrastructure resiliency and sustainability. Relevant properties of a re-engineered ductile concrete, named Engineered Cementitious Composite (ECC), are reviewed under this framework. Based on a growing body of experimental data, it is suggested that the tensile and compressive ductility, the damage tolerance and tight crack width characteristics, and the self-healing functionality of ECC provides the foundation of a materials technological platform that contributes to structural durability and resiliency. The technology is undergoing a transition from laboratory studies to full-scale field applications. The state-of-the art of ECC technology is illustrated with highlights of an application in bridge deck retrofit aimed at enhancing infrastructure sustainability, and an application in a new building design aimed at enhancing building resiliency under earthquake loading.

1 INTRODUCTION

Civil infrastructures are products. Like all other products, the need for their design for sustainability is increasingly recognized. Unlike most other products however, civil infrastructures, such as building and transportation systems, and water and energy systems, are typically large in size and are supposed to last as much as a hundred years or more. They are often seen as public monuments. Their large size implies large material flow, and their long lasting nature implies a long life cycle, during which multiple repair events may be needed. Both features carry serious implications on sustainability in terms of material production, construction and reconstruction, reduced operation/occupation (down-time for maintenance) and associated economic and environmental costs. Suitable civil infrastructure design can have large and lasting impacts on the quality of life of citizens in developing and developed countries.

Civil infrastructures are often public assets. We depend on them to sustain our everyday activities. The importance of their resiliency to extreme loads whether natural or manmade, is well known. A lack of resiliency goes beyond the concern for public safety, but could lead to severe interruption of daily life and business that can have significant economic impacts, especially in dense urban communities.

It is perhaps obvious that civil infrastructures should be designed to be both sustainable and resilient, while being economical (part of being sustainable). In a recent article by Peng et al. (2012), it is argued that true sustainability should embody resiliency. While few will argue against this philosophy of integrated sustainability and resiliency, the question is how to achieve this in practice. This is a subject of active research.

For concrete infrastructure, there is intrinsic challenge due to the brittle characteristic of concrete material. Despite the common practice of steel reinforcement, severe damage or even collapse of infrastructure continues to occur in major seismic events, requiring expensive and lengthy periods of recovery, not to mention the loss of life. Under normal service loads, the problem of cracking continues to afflict both new and old structures, leading to poor durability and repeated repair requirements. These considerations suggest that we are far from the ideal of being able to build civil infrastructures that are both resilient and sustainable, despite a significant amount of research on structural safety design and on high performance concrete materials.

Much of the research that has gone into concrete materials over the last two decades have focused on either making concrete stronger (typically meaning higher compressive strength) or making concrete greener (typically using recycled ingredients and/or reducing the cement content). It is generally recognized that concrete with higher compressive strength actually becomes more brittle, and that greener concrete is not equivalent to more durable concrete. The challenge of creating damage tolerant concrete that supports infrastructure resiliency and sustainability remains.

This paper overviews the material characteristics required to support sustainability and resiliency of civil infrastructure systems. It is suggested that a newly developed ductile concrete named Engineered Cementitious Composites (ECC) provides a viable platform to meet this ambitious goal. Recent field applications of this material are used to illustrate how specific features of ECC are utilized to realize the infrastructure design goals of simultaneous resiliency and sustainability.

2 REQUIREMENTS FOR MATERIAL CHARACTERISTICS TO SUPPORT INFRASTRUCTURE SUSTAINABILITY AND RESILIENCY

The global construction and reconstruction of concrete infrastructures result in enormous flows of materials between natural and human systems. To support the sustainability of infrastructure, it is necessary for concrete material to be green with low embodied energy and carbon emissions in its production process. While this is a necessary condition, it is not sufficient. A green concrete that requires repeated repairs in the resulting infrastructure not only leads to increased volume of material used in the whole life cycle, but also negatively affects the use pattern of the infrastructure. For example, based on a detailed life cycle model, Keoleian et al. (2005) found that the use phase dominates over other phases of the life-cycle of a bridge deck; repair events and associated traffic impacts lead to primary energy consumption and equivalent carbon dioxide emission that overwhelms all other phases (material production for the initial construction, construction, transport and end of life demolition). This study highlights the important contributions of concrete infrastructure durability to sustainability indicators. For truly sustainable infrastructure design, an ideal concrete material should be both green in production and durable in use.

While a number of definitions on infrastructure resiliency have been offered, perhaps the concepts advanced by Bruneau et al. (2003) is most helpful for the present discussion. They stated that three characteristics must be met for an infrastructure to be resilient:

a) Reduced failure probability
b) Reduced consequences from failure
c) Reduced time (and cost) to recovery

Figure 1 (adapted from Bruneau et al., 2003) illustrates how the quality of an infrastructure degrades to 50% due to a major loading event at t_0, and gradually recovers to full functionality at time t_1. The green dashed line represents the quality profile of a more resilient infrastructure that degrades less by the same loading event, and recovers to 100% functionality at a time period below that of (t_1 - t_0).

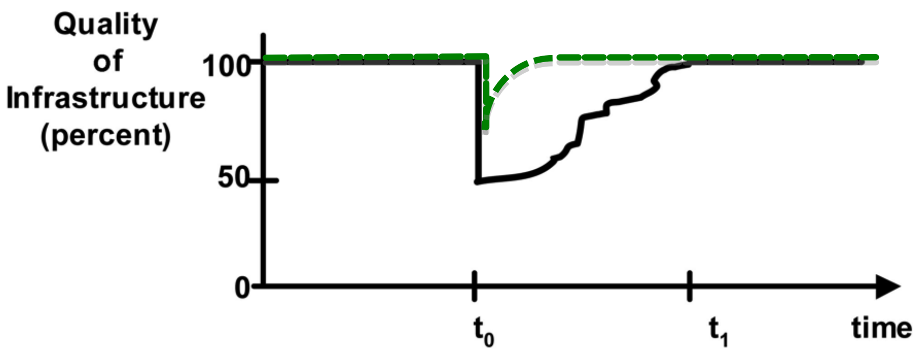


Figure 1 A resilient infrastructure degrades less and recovers faster after a major loading event (adapted from Bruneau et al., 2003)

From a concrete material standpoint, high material tensile ductility can be utilized to design structures with reduced structural failure probability (see e.g. Gencturk, 2013). This is particularly true as most concrete structural collapses result from brittle fracture rather then concrete compressive crushing. Further, material damage tolerance can directly contribute to reducing the consequences of failure (Gencturk, 2013, Fukuyama et al., 2000 and Billington and Yoon, 2004); controlled damage may lower the material and structural stiffness but retain load carrying capacity. Finally, if concrete crack width can be controlled so that they experience self-repair without external intervention, the recovery period will be shortened and repair cost will be reduced. A concrete that is ductile, damage tolerant and possesses the ability to undergo self-healing will contribute to enhancing infrastructure resiliency.

To summarize, the requirements for a structural material to support civil infrastructure sustainability and resiliency are:

a) The material should be green
b) The material should possess tensile and compressive ductility in addition to strength
c) The material should exhibit damage tolerance when overloaded
d) The material should be durable and should limit crack width in support of structural durability
e) The material should self-repair when damaged

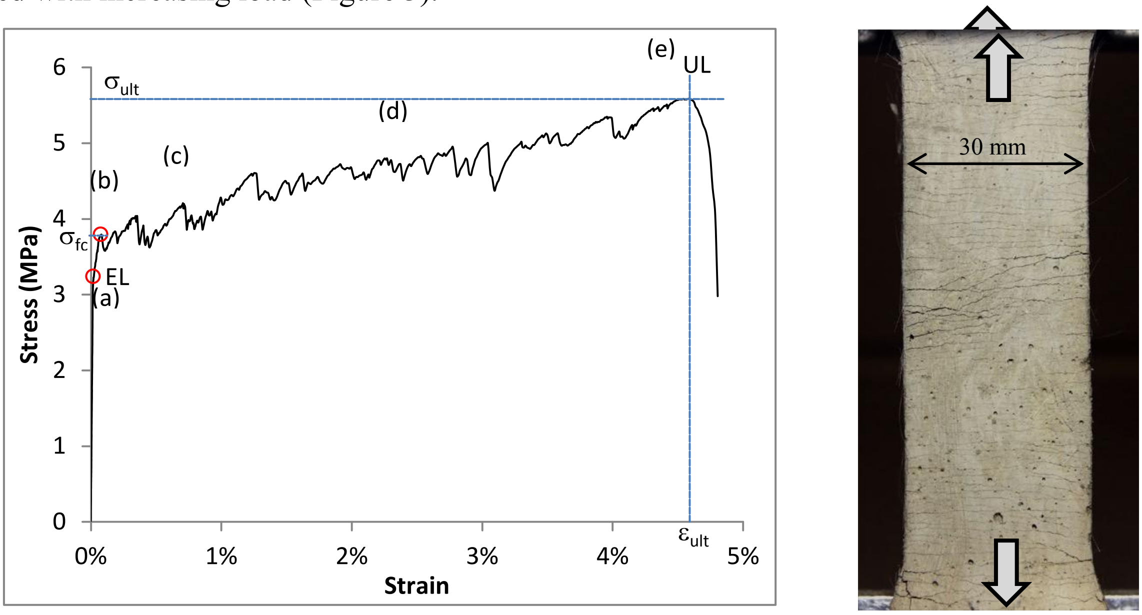
These requirements are difficult to meet, especially in a single material. The integration of these requirements, however, should be the goal of design for the next generation concrete. Implicit in the above, especially recognizing the large volume usage of concrete material in infrastructures is that these requirements need to be met with cost effectiveness in mind, in order for such a material to be meaningful in an industrial context. The pursuit of a single objective, for example, green or high strength, would not be adequate for future civil infrastructure systems demanding sustainability and resiliency.

3 A NEW CONCRETE FOR INFRASTRUCTURE SUSTAINABILITY AND RESILIENCY

A plausible technology platform to support infrastructure sustainability and resiliency is Engineered Cementitious Composite (ECC) (Li et al., 2001). The most important characteristic of ECC is its ability to strain-harden when deformed beyond the elastic limit under tensile or compressive loading. Under compression, the strain capacity is about twice that of normal concrete. Under tension, ECC exhibits over 3% strain, or more than 300 times the strain capacity of normal concrete.

A typical stress-strain curve of an ECC in tension is shown Figure 2. The elastic limit (EL), first cracking (σ_{fc}) strength, and ultimate limit UL at tensile strength σ_{ult} and strain capacity ε_{ult} are identified on this curve. Between the elastic and ultimate limits, multiple microcracking occurs, and gives rise to inelastic straining with increasing tensile stress. For this reason, the material is also known as Strain-Hardening Cementitious Composite (SHCC) (van Zijl et al., 2010). This strain-hardening branch on the stress-strain curve is typically absent in concrete materials, but is responsible for the unique tensile ductility and damage tolerance of ECC materials.

The development of crack pattern of an ECC (Lepech and Li, 2006) is unique among concrete materials. Instead of a single fracture leading to failure, distributed microcracking of tight cracks is associated with increasing load (Figure 3).



(a) (b)

Figure 2 ECC shows (a) high tensile ductility with over 3% strain capacity, and (b) multiple saturated multiple cracking

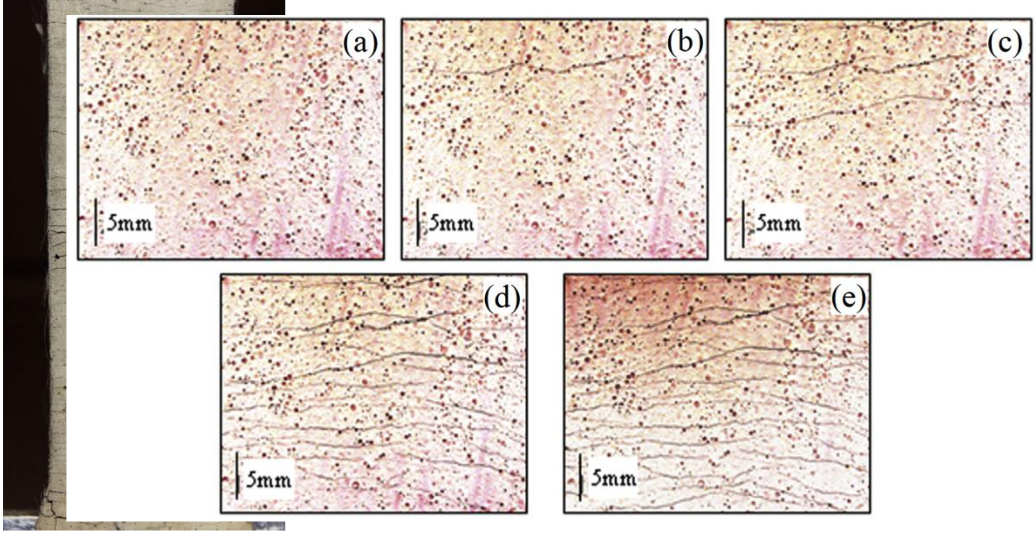


Figure 3 Development of crack pattern in ECC (Lepech and Li, 2006): Increasing number of cracks with limited crack width under increasing imposed tensile load. The five stages (a-e) of damage pattern correspond approximately to the loading stages indicated in Figure 2

The damage tolerance of ECC can be demonstrated by the response to uniaxial tensile loading of a double edge notched specimen. Figure 4 (Li, 2009) shows the distributed inelastic deformation away from the notched plane, a behavior distinctly absent for notch sensitive material such as normal concrete or ordinary fiber reinforced concrete.

Double edge specimens with different notch depths have been tested (Li, 2009). The tensile strengths of these specimens were found to remain essentially constant regardless of the notch depth.

The underlying principle of ECC design (Li, 2003, Yang and Li, 2010 and Li, 1997) is controlled load transfer between fiber and matrix, in such a manner that cracks emanating from initial defects in the composite matrix are bridged by fibers regardless of the length of the crack, and that tensile loading on fiber bridges are limited to below the bridging capacity. These requirements are embodied in a set of micromechanical tools that can be used to tailor fiber, matrix and fiber/matrix interface to attain the high tensile ductility (Li, 2012).

The same set of micromechanics tools can be utilized to control the width of the microcracks (Li, 2012). In ECC, microcracks are typically constrained to less than a hundred micron; in some cases as low as 20 microns depending on the fiber type, surface coating and interface tailoring.

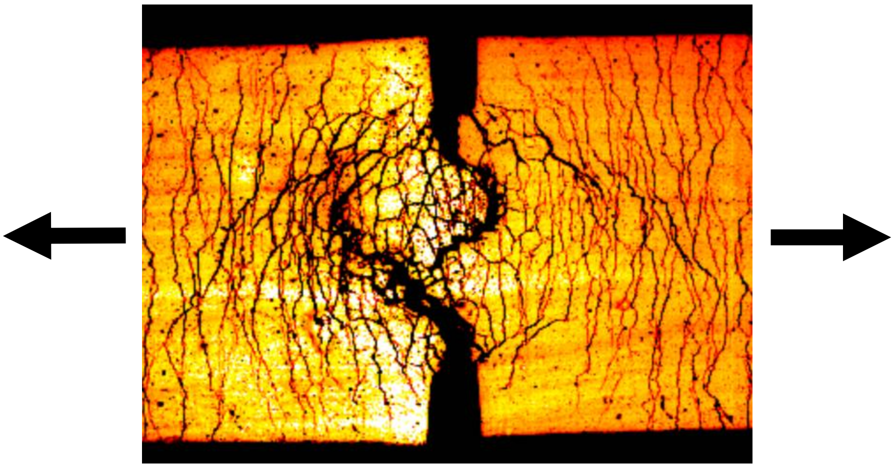
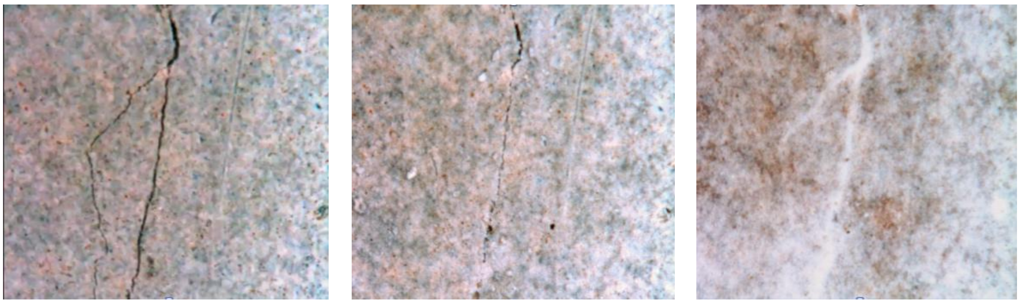


Figure 4 ECC shows high damage tolerance (Li, 2009) by diffusing inelastic deformation and delaying localization of fracture. The brittle fracture mode of failure is fully suppressed



(a) (b) (c)

Figure 5 ECC microcracks self-heal and recovers mechanical stiffness, strength and ductility: (a) load induced damage, (b) partial healing, (c) complete healing

The tight crack width of ECC can be exploited to aid in self-healing (Herbert and Li, 2013 and Yang et al., 2011) even after the composite has undergone imposed deformation of several percent. Self-healing occurs through a combination of continued hydration, pozollanic reaction, and calcite formation processes (Sakulich et al. 2010). Figure 5 shows the different stages of self-healing of preloaded specimens (to 3% in tension). Self-healing of the specimen took place by exposure to water and air.

A major drawback of ECC, similar to most high performance cementitious composites, is the fact that the material tends to have a higher cement content per unit weight of material, due to the elimination of coarse aggregates (Keoleian et al., 2005). This drawback impacts on economics, potential durability performance due to higher drying shrinkage, and on material greenness.

The concern on drying shrinkage of ECC has been addressed by several researchers (Yang, 2007a, Zhang et al., 2009 and Şahmaran et al., 2009). These researchers deploy shrinkage reducing, shrinkage compensating or internal curing agents to counteract the lack of internal shrinkage restraint by coarse aggregates. The resulting ECC has shrinkage similar to that of normal concrete.

The concerns on economics and material greenness have been addressed with material ingredient substitutions. For example, partial cement substitutions using fly ash, slags, or mine (iron ore) tailings have shown success (Huang et al., 2013a, Huang et al., 2013b, Huang et al., 2013c, Yang et al., 2007, Wang and Li, 2007, Lepech et al., 2008 and Zhou et al., 2010). Even total substitution of cement using fly ash base geopolymer has shown promise.

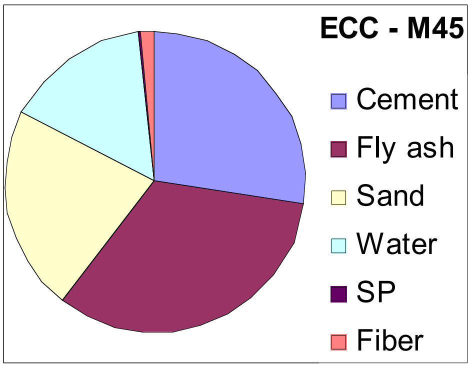


Figure 6 The weight fractions of ingredients in a "standard" ECC

Figure 6 shows the material composition of a "standard" ECC (M-45) that has been extensively studied. Yang et al. (2007) investigated ECCs with higher fly ash contents, and found that a F/C ratio up to 5.6 is feasible, although a reduction in compressive strength can be expected. However, they also demonstrated that an ECC with a F/C ratio of 2.8 could retain a tensile ductility of 3% and compressive strength of 35.2MPa at 28 days. Apart from enhancing economics and greenness, higher fly ash content and reduced cement content have been found to improve fresh properties, reduce drying shrinkage, heat of hydration as well as the width of the multiple microcracks.

Figure 7 (Huang et al., 2013a) shows the contributions to primary energy consumption and CO_2 emissions by the various material ingredients that make up ECC – M45 (Figure 6). The fly ash being a recycled material from coal-based power plants is assumed not to contribute to the carbon and energy footprints. From this figure, it can be seen that portland cement is the major contributor to CO_2 emission, whereas cement and PVA fiber contribute approximately equally to primary energy consumption. This implies that a more complete greening of ECC requires addressing also the fiber type used in ECC, despite its relatively small content in the composite.

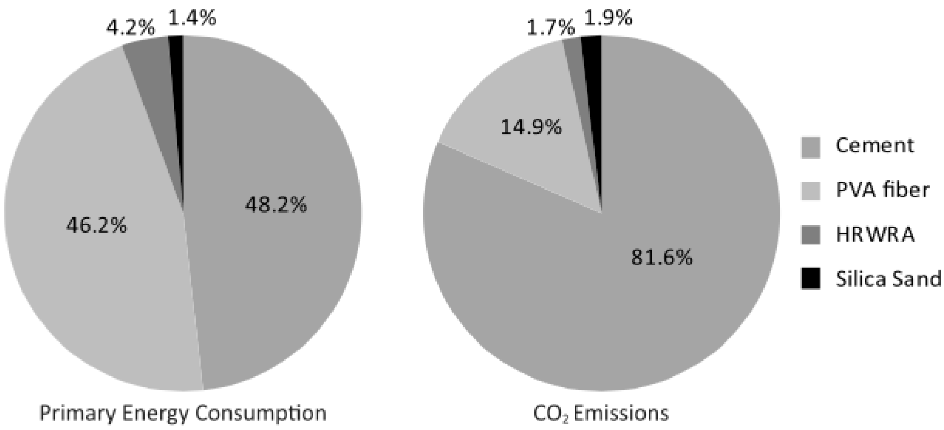


Figure 7 PVA fiber and portland cement dominates the carbon and energy footprints of ECC. These are targets for replacements to achieve greener ECCs

Primary energy consumption can be reduced by replacing PVA fiber with a density of 1.3gm/cc with PP fiber with a density of 0.9gm/cc. The reduction in density leads to a saving of about 30% purely because ECC tensile strength and ductility are governed by fiber volume fraction rather than weight fraction, assuming the same fiber content is employed. This is in addition to the lowering of energy in the production process of PP fiber when compared with PVA fiber. The development of ECC with PP fiber has been conducted by Yang (2007) and Felekoglu et al. (2014). Further reduction in carbon and energy footprints (and economic cost) can be achieved by the use of plant fibers that are renewable. Recent attempt (Soltan et al., 2015) to do exactly this indicates the feasibility of this approach, but a lowering of mechanical performance of the resulting ECC can be expected.

4 EXPERIMENTAL DEMONSTRATION OF STRUCTURAL RESILIENCY USING ECC

A variety of experimental testing of structural elements have demonstrated the ability of ECC to limit the amount of damage while maintaining structural load capacity, especially under simulated seismic loading (Fischer and Li, 2002, Fukuyama et al., 2000 and Billington et al., 2004).

Figure 8 (Fukuyama et al., 2000) shows the reinforcement detailing of a shear beam subjected to fully reversed cyclic loading. The level of damage experienced by the R/ECC beam is substantially smaller than that of the similarly reinforced R/C beam, with bond splitting and cover spalling completely suppressed (Figure 9). The hysteresis behavior of the R/ECC beam shows no pinching, but full loops, and stable load capacity up to a deflection angle of 5% radian (Figure 10).

The features of R/ECC with a large number of microcracks but no bond splitting and cover spalling, stable load and high energy absorption are common to many different experimental tests of R/ECC elements. They are the direct consequences of the high tensile ductility and damage tolerance of ECC material.

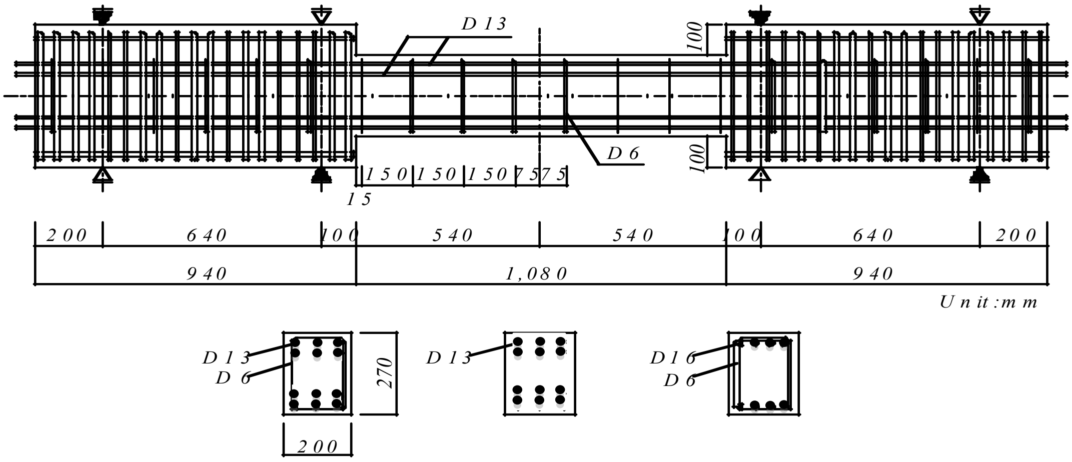
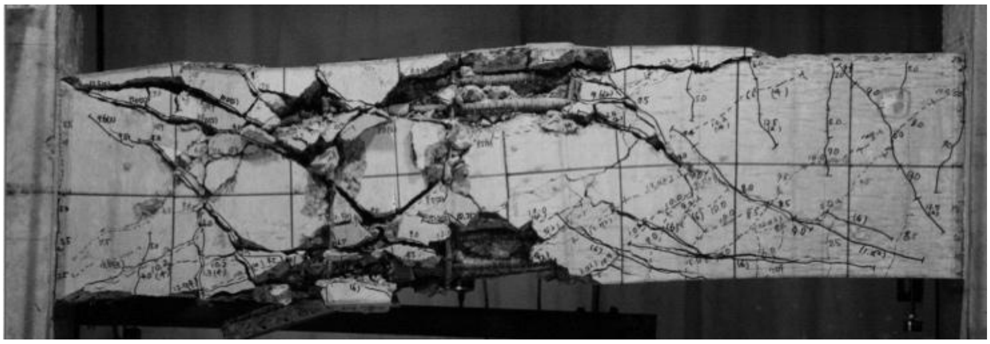
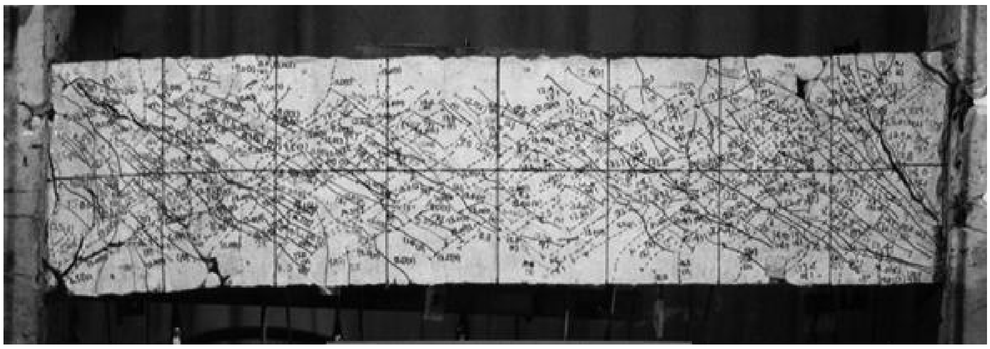


Figure 8 Reinforcement details of a beam subjected to fully reversed cyclic loads (Fukuyama et al., 2000)

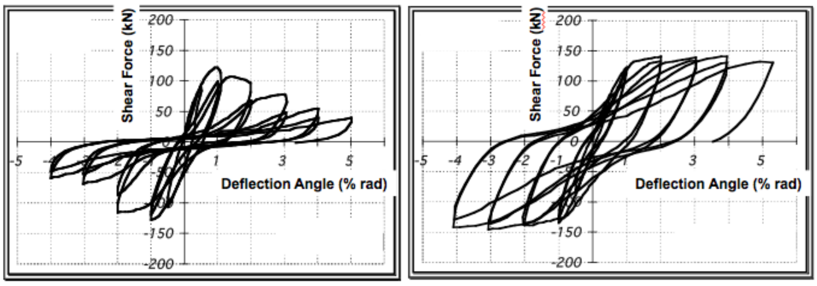


(a)



(b)

Figure 9 Damage level of (a) standard R/C member, and (b) R/ECC member, showing the suppression of bond splitting and cover spalling (Fukuyama et al., 2000)



(a) (b)

Figure 10 The hysteresis loops of (a) R/C member, and (b) R/ECC member. The latter shows no pinching and more stable load capacity even up to large deflection angle (Fukuyama et al., 2000)

In a study on the connection of a hybrid steel beam – R/C column subjected to reversed cyclic loading, Parra-Montesinosand Wight (2000) found that the ECC shear panel experienced the least amount of damage when compared with eight other specimens with different materials (FRC) and reinforcement (stirrups, steel band plates, steel box cover plates) combinations, despite the deliberate absence of joint transverse reinforcement.

A recent study by Gencturk (2013) led to the conclusion of lower initial cost of ECC frames designed for seismic loads as a result of reduction in material and labor cost associated with the elimination of transverse reinforcement in the ECC frames when compared with R/C frames. The life cycle cost was also found to be reduced due to increased capacity and reduced demand for ECC frames.

5 EXPERIMENTAL DEMONSTRATION OF STRUCTURAL DURABILITY USING ECC

A variety of material durability studies have been carried out, including resistance to frost (Sahmaran et al., 2012), freezing and thawing (Sahmaran et al., 2009), deicing salt scaling (Sahmaran and Li, 2007), hot and humid environment (Li et al., 2004), alkali silicate reaction (ASR) (Sahmaran and Li, 2008), fatigue failure (Suthiwarapirak et al., 2002), and abrasion and wear (Lepech and Li, 2006). These studies indicate that ECC has improved durability over that of normal concrete.

Beyond material durability, infrastructure sustainability demands that the material supports durability of the structure under load. In concrete structures, the presence of cracks and subsequent rise in the effective diffusion coefficient of chloride ions is a major cause of loss of structural durability in many parts of the world, especially in coastal regions where the structures are exposed to a salt environment, or in cold regions, where salt is used in winter seasons for deicing purpose. Structural durability requires limiting the migration of aggressive agents through the concrete cover in order to delay the corrosion of the reinforcing bars.

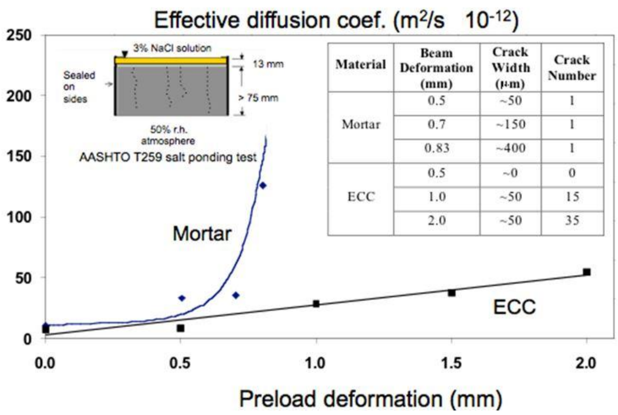


Figure 11 Measured effective diffusion coefficient of ECC shows a slower rise with preload deformation level when compared with mortar (Sahmaran et al., 2007)

Sahmaran et al. (2012) studied the effective diffusion coefficient of ECC subjected to a 3% NaCl solution ponding. The specimens were obtained from a beam that has been deliberated preloaded to beyond the elastic stage. In order words, the specimens subjected to NaCl ponding had experienced microcracking, thus simulating a loaded structural environment. Figure 11 shows the effective diffusion coefficient as a function of preload deformation. In the case of ECC, this coefficient increases linearly with the amount of preload deformation, due to the increase in the number of microcracks that maintain a crack width of about 50μm. In contrast, the control mortar specimen shows a highly nonlinear increase of this coefficient, resulting from the increase in width of a single crack. The much slower linear increase of the effective diffusion coefficient of ECC suggest that ion penetration would be significantly slower, resulting in a time delay in corrosion of rebar and a longer service life of the structure.

A complementary investigation (Miyazato and Hiraishi, 2005) measured the corrosion rate in mm/year of the reinforcing bar inside the preloaded R/ECC specimen subjected to a 28 days chloride accelerated environment. This accelerated environment includes cycles of 2 day wetting (saltwater shower 90% RH), and 5 day drying (60% RH) while the macro crack in the R/C and the microcracks in the R/ECC were kept open (not unloaded). The result is shown in Figure 12. In the case of R/ECC, a small amount of corrosion was found along the length of the rebar, especially at locations where microcracks formed. In contrast, the control R/C specimen showed very high corrosion rate at the single crack site, while the other parts of the rebar remain pristine. This suggests that R/ECC structural elements will have longer service life corresponding to a longer corrosion initiation period, when compared with standard R/C elements in a similarly aggressive environment. Further, Sahmaran et al. (2008) investigated the residual flexural load capacity of R/C and R/ECC beams subjected to accelerated corrosion by an electrochemical method. The result is summarized in Figure 13. They concluded that the corrosion propagation period was significantly prolonged due to the damage tolerant and spall resistance of ECC.

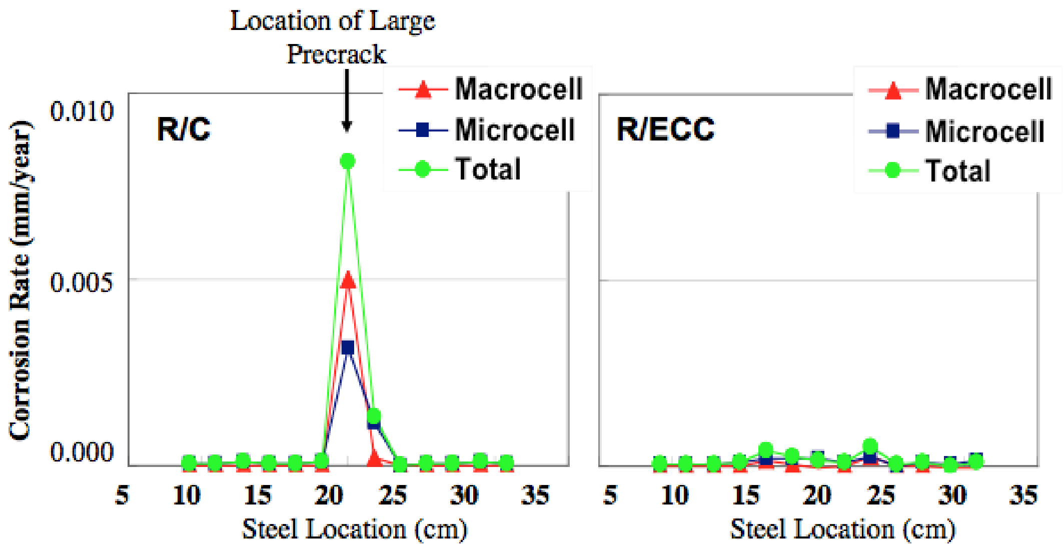


Figure 12 The measured corrosion rate in R/ECC beam subjected to an accelerated chloride environment is substantially lower than that of R/C beam. After Miyazato and Hiraishi (Miyazato and Hiraishi, 2005)

(a) ECC before accelerated corrosion

(b) ECC after 150 hours accelerated corrosion

(c) Mortar before accelerated corrosion

(d) Mortar after 50 hours accelerated corrosion

Figure 13 The damage tolerant behavior of ECC prolongs the corrosion propagation period and protects the beam element from failure, when subjected to an accelerated corrosion environment. After Sahmaran et al. (2008)

6 FIELD APPLICATIONS OF ECC

ECC has been applied in repair, retrofit, and new constructions. Repair applications include external walls of concrete buildings (Cheung et al., 2004), highway patch repair (Lepech and Li, 2006), railway infrastructure repair (Kunieda and Rokugo, 2006), irrigation canal repair (Uchida et al., 2008), and dam repairs (Uchida et al., 2008). Retrofit applications include bridge deck link-slabs (Lepech and Li, 2009), tunnel lining strengthening (Uchida et al., 2008) and viaduct deck-pier dampers for seismic retrofit. New constructions include exterior building insulation wall (Zhang, 2015), coupling beams in the core of tall buildings (Kanda et al., 2011) and composite bridge decks (Uchida et al., 2008). These applications cover the building and transportation, and water and energy domains. Application methods include cast-in-place, pre-cast, and spray (shotcrete). The Japan Society of Civil Engineers has published a recommendation document (Japan Society of Civil Engineers, 2008) for the design and application of this special class of ductile concrete materials.

One of the applications that best illustrate enhancement of infrastructure sustainability is the bridge deck retrofit in Southeast Michigan in the US (Figure 14), where ECC was applied as a deck link-slab replacing conventional expansion joints (Lepech and Li, 2009). This application was originally motivated by the frequent repair needs of expansion joints, the surrounding deck concrete and the steel or R/C girders supporting the deck below the joints. The combined traffic load and temperature load on the link slab demands a tensile strain capacity of 2%, which cannot be delivered by any concrete material reinforced or not. This is also an application that highlights a major value of ECC – high tensile ductility. High strength concrete material with normal ductility will not be able to meet the design requirement.

Figure 14 Application of ECC on deck retrofit of a highway bridge in Southeast Michigan

Figure 15 Bridge deck showing ECC link-slab (between dashed lines) after bridge re-opened to traffic

Figure 15 shows the bridge deck immediately after installation (2005) of the ECC link slab. Placement of the link slab was cast-in-place using a normal concrete ready-mix truck from a nearby batching plant. The total volume of ECC made for this application was 25.5m^3. While the ECC was designed to be self-consolidation, care was taken to ensure that the required crown of the roadway cross-section was maintained. Despite the severe winters in Michigan, the link-slab remains in working condition today with no maintenance since installation, offering confirmation of the durability of ECC material.

A detailed life-cycle analysis (Keoleian et al., 2005) was carried out for this bridge structure, comparing materials and energy inputs and waste and emissions for the case with conventional expansion joint and for the case with the ECC link-slab. The life-cycle model embodied a traffic model that accounts for changes in traffic due to reconstruction events during the 90 years service life assumed. Figure 16 shows the primary energy consumption and carbon emission results of this analysis. Savings of about 40% is obtained for the case when ECC link-slab is used to replace conventional expansion joint. The most important contributor to these savings derives from the differences in traffic patterns. In the case of the deck with ECC link-slab, the expected durability resulting from the reduced rate of re-bar corrosion and the spall resistance of ECC eliminated repair events and the associated traffic pattern interruptions. The second most important contributing factor to lowering the energy consumption and carbon emission derives from the lowering of the total amount of materials required over the service life as maintenance needs are reduced. This is despite the fact that the ECC used in this project and for the life-cycle analysis did not benefit from the greener versions that were later derived and described in an earlier section of this paper. The life-cycle analysis did not include costs associated with the repair of the supporting girder elements when conventional expansion joints fail. The economic and environmental savings would be even bigger had this been accounted for.

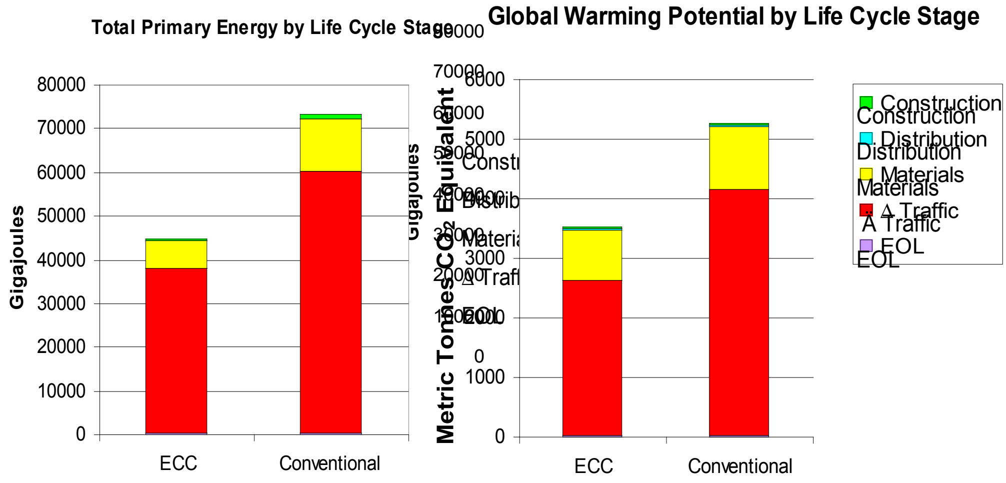
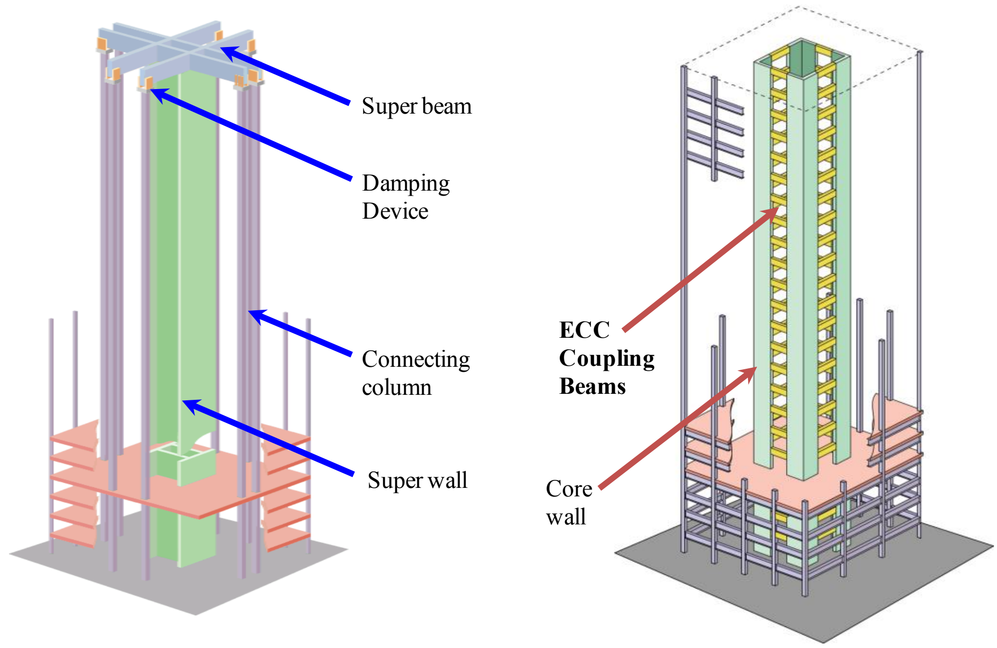


Figure 16 ECC link-slab extends service life and reduces primary energy consumption and carbon emission

One of the best illustration of the use of ECC in enhancing structural resiliency is the new building design created by Kajima Corporation in Japan (Kanda et al., 2011 and Yamamoto, 2008). In this new design, the structural load is mainly born by the core, made up of (two or four) ECC coupling beams on each floor between core-walls. The goal is to maximize floor space by eliminating the beams and columns commonly used in conventional rigid-frame structures. Although a similar goal was previously achieved using a superframe construction, the ECC coupling beam approach was considered easier to construct with dramatic labor saving, and also resulted in cost savings on the building unit level, even from an initial cost point of view.



(a) (b)

Figure 17 (a) Superframe design, and (b) ECC-coupling beam design of tall buildings realized by Kajima Corporation (Kanda et al., 2011)

Figure 17(a) shows the superframe approach which uses a super beam connected to the top of a pair of columns through dampers, to form a frame. Multiple pairs of superframes are deployed to achieve self-centering performance of the building during an earthquake. The super beams are about 3m in height and their weight requires construction of the beams on the building top. Figure 17(b) shows the new building design with ECC coupling beams. So far, three buildings in Japan has been constructed using this approach, including the Glorio-tower Roppongi (Figure 18(a)), the Nabule-Yokohma tower and residence (Figure 18(b)), and the 61 story Kitahama Tower in Osaka (Figure

18(c)), currently the tallest R/C structure in Japan. These buildings may be considered one of the first applications of ECC in enhancing infrastructure resiliency.

The ECC coupling beams were designed to meet three criteria: (a) shear or bond splitting failure must be fully suppressed, (b) load capacity remains stable even when the member drift angle reaches 4%, and (c) residual crack width after unloading must be limited to less than 0.3mm. Structural experiments similar to those described in Figures 8-10 confirmed the desired failure mode, hysteresis behavior and cracking behavior. The structural design strategy ensured member ductility and energy absorption for imposed seismic load profile.

The ECC coupling beams were precast off-site to ensure high quality control of these critical structural elements. They were cast together with part of the floor slab to safeguard a more gradual transition from the high performance ECC coupling beam to the standard R/C floor slab. The precast coupling beams with protruding re-bars were dropped into location at each floor before the core-wall was cast (Figure 19).

Kanda et al. (2011) reported no visible damage to the Glorio-tower and Nabule-Yokohma tower near Tokyo after the large Tohoku earthquake excitation in 2011.

(a) (b) (c)

Figure 18 (a) The Glorio-tower Roppongi, (b) the Nabule-Yokohma tower and residence, and (c) the Kitahama Tower in Osaka are recent tall buildings using ECC coupling beams for structural resiliency
(Kanda et al., 2011 and Yamamoto, 2008)

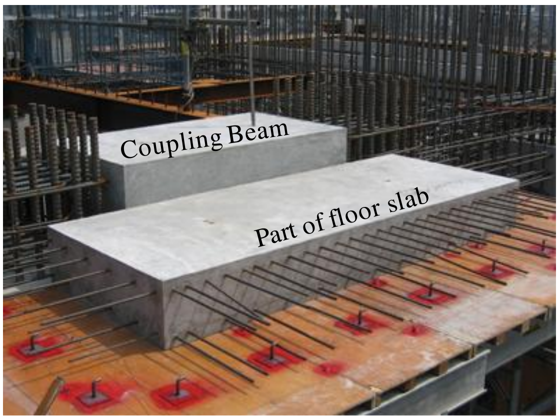


Figure 19 Precast ECC coupling beam dropped into location during building construction (Kanda et al., 2011)

7 CONCLUSION

In keeping with the goals of the global sustainable development efforts, next general civil infrastructure must be designed for sustainability. For truly sustainable infrastructures, they must also be resilient. These targets may initially appear contradictory since sustainability is often associated with less material consumption, while resiliency is often associated with more material for construction. However, it is argued that simultaneous sustainability and resiliency of civil infrastructure is not only necessary, but it is also feasible.

One approach to simultaneously attaining infrastructure sustainability and resiliency challenge is through advanced concrete technology. A re-engineered concrete that is green, ductile, damage tolerant, durable in use, and possesses the ability to self-heal when damaged, can serve this purpose. A growing body of experimental data collected under extreme durability testing conditions and mechanical test conditions suggests that Engineered Cementitious Composites (ECC) may provide a feasible platform to meet the infrastructure sustainability and resiliency challenge.

While continued refinement and improvements of ECC can be expected, this material is already emerging in a variety of full-scale structures, including in the building and transportation infrastructure, and the energy and water infrastructure domains. The field experiences gained in structural design, large scale material mixing, and construction methods, provide a valuable foundation for continued future development and broad deployment of this new technology.

8 REFERENCES

Billington SL and Yoon JK (2004) Cyclic response of unbonded posttensioned precast columns with ductile fiber-reinforced concrete. *Journal of Bridge Engineering* **9(4)**: 353-363.

Bruneau SEC, Eguchi RT, Lee GC, O'Rourke TD, Reinhorn AM, Shinozuka M, Tierney K, Wallace WA and von Winterfeldt D (2003) A framework to quantitatively assess and enhance the seismic resilience of communities. *Earthquake Spectra: November 2003* **19(4)**, 733-752.

Cheung AKF, Cheung CYN and Leung CKY (2004) A protective pseudo-ductile cementitious layer for external walls of concrete buildings. *Proceedings of the Fourth International Conference on Concrete under Severe Conditions (CONSEC04)*, edited by Oh BH, Sakai K, Gjorv OE and Banthia N, 1192-1199.

Felekoğlu B, Tosun-Felekoğlu K, Ranade R, Zhang Q and Li VC (2014) Influence of matrix flowability, fiber mixing procedure and curing conditions on the mechanical performance of HTPP-ECC. *J. Composites, Part B: Engineering* **60:** 359-370.

Fischer G and Li VC (2002) Effect of matrix ductility on deformation behavior of steel reinforced ECC flexural members under reversed cyclic loading conditions. *ACI Structural J.* **99(6)**:781-790.

Fukuyama H, Matsuzaki Y, Sato Y, Iso M and Suwada H (2000) Structural performance of engineered cementitious composite elements. *Composite and Hybrid Structures, 6th ASCCS International Conference on Steel-Concrete Composite Structures, 2000*.

Fukuyama H, Sato Y, VC Li, Matsuzaki Y and Mihashi H (2000) Ductile engineered cementitious composite elements for seismic structural applications. *CD Proceedings of the 12 WCEE*, Paper, 1672.

Gencturk B (2013) Life-cycle cost assessment of RC and ECC frames using structural optimization. *Earthquake Engng Struct. Dyn. 2013* **42**: 61-79.

Herbert EN and Li VC (2013) Self-healing of microcracks in Engineered Cementitious Composites (ECC) under a natural environment. *Materials* **6(7)**: 2831-2845.

Huang X, Ranade R and Li VC (2013a) Feasibility study of developing green ECC using Iron Ore Tailings (IOT) powder as cement replacement. *ASCE J. Materials* **25(7):** 923-931.

Huang X, Ranade R, Ni W and Li VC (2013b) Development of green engineered cementitious composites using Iron Ore Tailings as aggregates. *J. Construction and Building Materials* **44:** 757-764.

Huang X, Ranade R, Zhang Q, Ni W, and Li VC (2013c) Mechanical and thermal properties of green lightweight engineered cementitious composites. *J. Construction and Building Materials* **48**: 954-960.

Japan Society of Civil Engineers (2008) *Recommendations for Design and Construction of High Performance Fiber Reinforced cement Composite with Multiple Fine Cracks (HPFRCC)*, Concrete Library 127.

Kanda T, Nagai S, Maruta M and Yamamoto Y (2011) New high rise R/C structure using ECC coupling beams. *2nd Int'l RILEM Conference on Strain Hardening Cementitious Composites*, Rio de Janeiro, Brazil, 2011, 289-296.

Keoleian GA, Kendall A, Dettling JE, Smith VM, Chandler R, Lepech MD and Li VC (2005) Life cycle modeling of concrete bridge design: comparison of engineered cementitious composite link slabs and conventional steel expansion joints. *ASCE J. Infrastructure Systems* **11(1):** 51-60.

Kunieda M and Rokugo K (2006) Recent progress on HPFRCC in Japan required performance and applications. *Journal of Advanced Concrete Technology* **4(1)**: 19-33.

Lepech MD, Keoleian GA, Qian S and Li VC (2008) Design of green engineered cementitious composites for pavement overlay applications. *Int'l Association for Life Cycle Civil Engineering conference (IALCCE 08)*, Italy, 837-842.

Lepech MD and Li VC (2006) Long term durability performance of engineered cementitious composites. *Int'l J. for Restoration of Buildings and Monuments* **12(2)** 119-132.

Lepech MD and Li VC (2009) Application of ECC for bridge deck link slabs. *RILEM J. of Materials and Structures* **42(9):** 1185-1195.

Li VC (1997) Engineered Cementitious Composites (ECC) – tailored composites through micromechanical modeling. *Fiber Reinforced Concrete: Present and the Future*, Eds: Banthia N, Bentur A and A Mufti, Canadian Society of Civil Engineers, 1997.

Li VC (2003) On Engineered Cementitious Composites (ECC) – A review of the material and its applications. *J. Advanced Concrete Technology* **1(3):** 215-230.

Li VC (2009) Damage tolerant ECC for integrity of structures under extreme loads. *Structures 2009, Proc., ASCE Structures Congress*, Austin, Texas, April-May, 2009, 2209-2218.

Li VC (2012) Tailoring ECC for special attributes – a review. *J. of Concrete Structures and Materials* **6(3)**: 135-144.

Li VC, Horikoshi T, Ogawa A, Torigoe S and Saito T (2004) Micromechanics-based durability study of polyvinyl alcohol-engineered cementitious composite. *ACI Materials J.* **101(3)**: 242-248.

Li VC, Wang S and Wu C (2001) Tensile strain-hardening behavior of polyvinyl alcohol engineered cementitious composite (PVA-ECC). *ACI Materials Journal 2001* **98(6)**:483-492.

Miyazato S and Hiraishi Y (2005) Transport properties and steel corrosion in ductile fiber reinforced cement composites. *Proceedings of the Eleventh International Conference on Fracture 2005*.

Ohno M and Li VC (2014) A feasibility study of strain hardening fiber reinforced fly ash-based geopolymer composites. *J. Construction and Building Materials* **57C**: 163-168.

Parra-Montesinos G and Wight JK (2000) Seismic response of exterior RC column-to-steel beam connections. *ASCE Journal of Structural Engineering* **126(10)**: 1113-1121.

Peng T, Lemay L and Hansen J (2012) Resilience is the new sustainability. *Concrete in Focus*, Published by National Ready Mixed Concrete Association (NRMCA), 10-29, Jan-Feb 2012.

Şahmaran M, Lachemi M, Hossain KMA and Li VC (2009) Internal curing of engineered cementitious composites for prevention of early age autogenous shrinkage cracking. *J. Cement and Concrete Research* **39(10):** 893-901.

Sahmaran M, Lachemi M and Li VC (2009) Assessing the durability of Engineered Cementitious Composites (ECC) under freezing and thawing cycles. *J. of ASTM Int'l* **6(7)**: 1-13.

Sahmaran M, Ozbay E, Yucel HE, Lachemi M and Li VC (2012) Frost resistance and microstructure of engineered cementitious composites: nfluence of fly ash and micro poly-vinyl-alcohol fiber. *J. Cement and Concrete Composites* **34**, 156-165.

Sahmaran M, Li M and Li VC (2007) Transport properties of engineered cementitious composites under chloride exposure. *ACI Materials J.* **104(6)**: 604-611.

Sahmaran M and Li VC (2007) De-icing salt scaling resistance of mechanically loaded engineered cementitious composites. *J. Cement and Concrete Research* **37(7):** 1035-1046.

Sahmaran M and Li VC (2008) Durability of mechanically loaded engineered cementitious composites under highly alkaline environment. *J. Cement and Concrete Composites* **30(2):** 72-81.

Sahmaran M, Li VC and Andrade C (2008) Corrosion resistance performance of steel-reinforced engineered cementitious composites beams. *ACI Materials J.* **105(3)**: 243-250.

Sakulich AR, Kan L and Li VC (2010) Microanalysis of autogenous healing products in Engineered Cementitious Composites (ECC). *Microscopy and Microanalysis* **16**: 1220-1221.

Soltan D, Savastano G and Li VC (2015) Preliminary study of curaua fiber reinforced cement based composite. Submitted for publication in *Industrial Crops and Products Journal*, 2015.

Suthiwarapirak P, Matsumoto T and Kanda T (2002) Flexural fatigue failure characteristics of an engineered cementitious composite and polymer cement mortars. *J. Materials, Conc. Struc. Pavements, JSCE* **718(57):** 121-134.

Uchida Y, Fischer G, Hishiki Y, Niwa J and Rokugo K (2008) Review of Japanese recommendations on design and construction of different classes of fiber reinforced concrete and application examples. *Proc. of 8th International Symposium on Utilization of High strength and High-performance Concrete*, Tokyo: JCI, 92-110.

van Zijl G, Greeff PA and Wittmann FH (2010) *Durability of Strain-Hardening Fibre-Reinforced Cement-Based Composites (SHCC): State of the Art Report, Vol. 4*. Springer Science & Business Media, 2010.

Wang S and Li VC (2007) Engineered cementitious composites with high volume fly ash. *ACI Materials J.* **104(3)**: 233-241.

Yamamoto Y (2008) Application example of high strength – high performance concrete – The Kitahama Tower. *Construction Technology*, Dec 2008, 20-21 (in Japanese).

Yang EH (2007a) *Designing Functionalities into ECC Materials via Micromechanics*. PhD Thesis in partial fulfillment of the PhD degree, Dept. of Civil and Environmental Engineering, Univ. of Michigan, Ann Arbor, 2007.

Yang EH (2007b) *Designing Added Functions in Engineered Cementitious Composites*. The University of Michigan, PhD Thesis (Civil Engineering), 2007, 276p.

Yang EH and Li VC (2010) Strain-hardening fiber cement optimization and component tailoring by means of a micromechanical model. *J. Construction and Building Materials* **24**: 130-139.

Yang EH, Yang Y and Li VC (2007) Use of high volumes of fly ash to improve ECC mechanical properties and material greenness. *ACI Materials J.* **104(6)**: 620-628.

Zhang J (2015) *Private communications*, 2015.

Zhang J, Gong C, Guo Z and Zhang M (2009) engineered cementitious composite with characteristic of low drying shrinkage. *Cement and Concrete Research* **39(4)**: 303-312.

Zhou J, Qian S, Beltran MGS, van Breugel GYK and Li VC (2010) Development of engineered cementitious composites with limestone powder and blast furnace slag. *Materials and Structures* **43(6)**: 803-814.