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Development of lightweight engineered cementitious composite for durability enhancement of tall concrete wind towers

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ABSTRACT

Recently, concrete (especially high strength concrete) is considered the most suitable material for building tall wind turbine towers. However, concrete is prone to cracking and the durability of tall concrete towers can be compromised when large cracks (> 300 μm) occur on their exterior surfaces. In this study, a lightweight engineered cementitious composite (ECC), reinforced by high tenacity polypropylene fiber, was developed based on performance driven design approach to serve as protective coatings on the tall concrete towers. By using fly ash cenospheres as lightweight filler material, a lightweight ECC with a density of 1810 kg/m^3 can be achieved. Guided by micromechanics-based design theory, this newly developed ECC can achieve a tensile strength above 2 MPa, tensile ductility above 2%, and maximum crack width of 100 μm in both direct tension and flexural fatigue tests. The high ductility and excellent crack control of ECC coating can improve the cracking resistance of the hybrid tall ECC/concrete towers, therefore enhancing their durability and extending their service life.

1. Introduction

Concrete has been a popular material for tall tower structures, especially wind turbine towers. The Concrete Center in the UK reported that concrete wind turbine towers with a height of up to 100 m and rotor diameter of up to 140 m, can be constructed on site using the slip-form construction method [1,2]. The towers can also be assembled using prefabricated segments. Jimeno [3] reported that Inneo, a Spanish company, had been using pre-cast technology to erect a wind turbine tower in one day. Acciona, a major wind turbine manufacturing company, has invested in mega-wind farms with 120-m-high concrete wind turbine towers in Brazil [4]. To achieve even taller and more powerful wind turbine towers, high-strength concrete (HSC) becomes a more attractive material [5]. Due to its high stiffness, HSC can help achieve the deflection limit of tall wind turbine towers and avoid excitation of resonant oscillations from wind, earthquakes and blade operations when the height of a wind turbine tower reaches 150 m. In addition, HSC's higher elastic modulus can reduce tower dimensions and wall thickness, allowing for a more cost-effective tower design.

While concrete make tall wind turbine towers feasible, its tendency of cracking raises durability concerns [6,7]. Cracks on the concrete cover provide pathways for aggressive chemicals such as chlorides to reach the steel reinforcement and accelerate concrete deterioration [8–10]. As a result, both the durability and long-term performance of a tall concrete wind turbine tower can be compromised, and expensive maintenance and undesirable downtime are required. These concerns are exacerbated by flexural and fatigue loading, and especially if the tower is located in an aggressive environment such as a coastal region for capturing high-speed wind.

To address this durability concern, engineered cementitious composites (ECC), a high-performance fiber reinforced cementitious composite, has been developed based on performance driven design approach (PDDA) [11,12]. In this study, ECC is proposed to be used as a protective coating on the exterior of concrete wind turbine towers (Fig. 1), in which concrete is responsible for providing the required stiffness of tall tower structures while ECC is responsible for ensuring the durability performance. The concept of a dual-layer system has already been implemented in pavement overlay [13] and permanent formwork [14], in which polyvinyl alcohol fiber reinforced ECC (PVA-ECC) was used. Unlike concrete, PVA-ECC exhibits self-controlled crack widths under increasing tensile load and fatigue load. When cracked, the cracks in PVA-ECC are limited to less than 50–100 μm [15], depending on mix composition. According to Wang et al., 1997 [16], a crack width, which does not exceed 100 μm, has little effect on concrete permeability. The tight crack width of ECC also contributes to a low chloride diffusion coefficient [17] and dramatically slows the rate of corrosion of steel reinforcement under the most aggressive exposure environment [18]. These prior works suggest that ECC can serve as an

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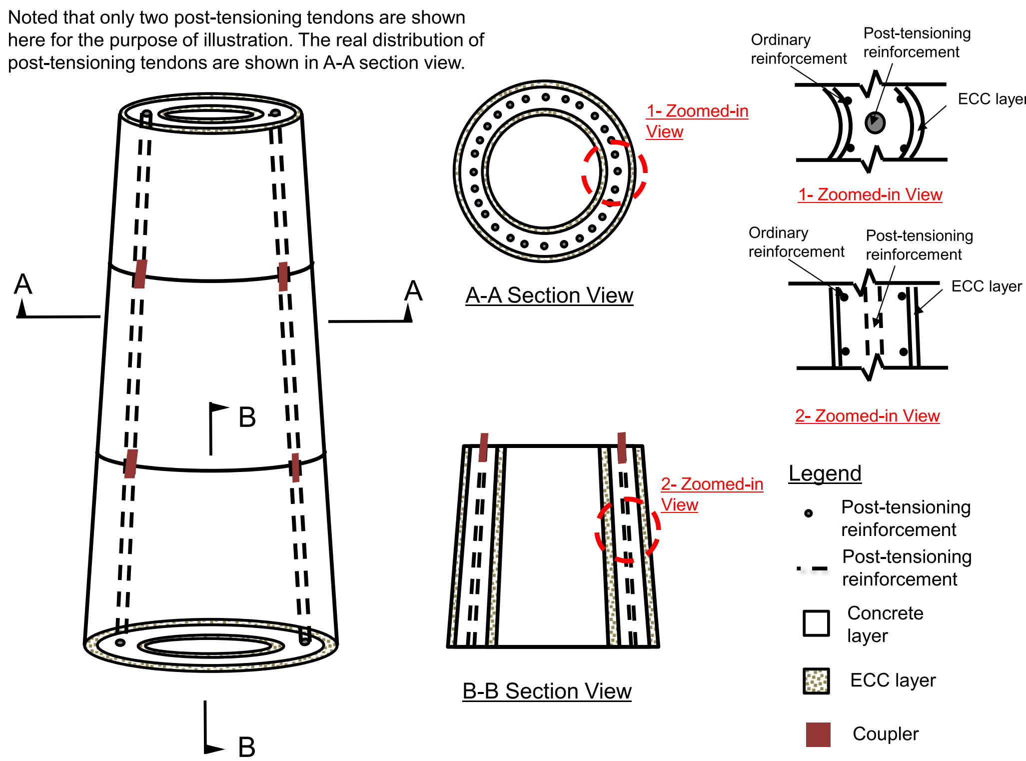

Fig. 1. Schematic design of tall hybrid ECC/concrete wind towers.

effective protective coating for tall concrete wind turbine towers.

Instead of casting ECC coating on concrete wind turbine towers, the ECC coating can be pre-fabricated and used as a permanent formwork to construct ECC/concrete wind turbine tower segments. Therefore, a lightweight ECC is more desirable since it can avoid the use of heavy lifting cranes. In this paper, a lightweight ECC is developed to meet the needs of a hybrid ECC/concrete wind turbine tower design. The equilibrium density of this ECC should be 1680–1920 kg/m^3 to be classified as lightweight [19]. A high tensile ductility of above 2% (normal concrete has 0.01% tensile ductility) is specified to meet the flexural performance of ECC with crack width less than 100 μm to maintain the durability performance. Since this ECC only serves as protective coating on tall concrete tower, its compressive strength can be designed to be suitable for minimum structural use as permanent formworks, such as allowing for handling and assembling on site. ACI 213 [19] specifies a minimum 28-day compressive strength of 17 MPa for lightweight concrete in structural applications. After identifying the lightweight ECC that achieves all the aforementioned criteria, flexural and fatigue tests are carried out to verify its durability performance as a protective coating on tall concrete wind turbine towers.

In addition, to maintain ECC's superior durability performance under various loading conditions, to which wind turbine towers may be exposed, and to explore the feasibility of using less expensive fibers compared to commonly used PVA fibers [20], this paper will focus on the development of high tenacity polypropylene (HTPP) fiber reinforced lightweight ECC.

2. Experimental program

2.1. Material design

To achieve lightweight cementitious materials, fly ash cenospheres (FAC) have been previously studied and used as a lightweight filler [21,22]. Hanif et al. [23] have summarized the advantages of using FAC in cementitious materials compared to other lightweight fillers. By using FAC, various other advantages can be achieved in cementitious materials, such as low thermal conductivity [24,25], high compressive strength [26,27], high elastic modulus [28], and high flexural and tensile strengths [29–31], the latter is achieved by its compatible use with fibers. These advantages, especially the enhanced mechanical properties and compatibility when used with fibers, are beneficial in developing a FAC-based lightweight ECC protective coating to enhance the durability of tall wind towers. The chemical composition and particle size distribution of the FAC provided by Cenostar Corporation, USA are shown in Table 1 and Fig. 2, respectively. The bulk density of the FAC is 380 kg/m^3.

As mentioned previously, high tenacity polypropylene (HTPP) fibers (from Polymer Group Inc., USA) are used to produce lightweight ECC in this paper. The mechanical and geometric properties of HTPP fibers are listed in Table 2. The other materials used in the lightweight ECC are Type I/II ordinary portland cement (OPC, Lafarge North America), water, and Class F fly ash (FA). The chemical compositions and particle size distributions of OPC and FA are also summarized in Table 1 and Fig. 2, respectively. The addition of FAC creates the difficulties during mixing due to its absorptive nature. Therefore, high-range water-reducing admixture (HRWR, ADVA 190, from Grace Concrete Product) is added to achieve optimal workability and ensure robust properties of the lightweight ECC.

To achieve the desired tensile properties, a micromechanics-based design theory has been used as a guide to material compositions in this study [32–34]. The essence of this design theory is to allow for a systematic and effective tailoring of ECC for a high ductility and other special attributes by controlling the composite matrix, the fiber, and the fiber/matrix interface. By deliberately allowing cracks to grow out from

Table 1
Chemical composition of cement, fly ash (FA), and fly ash cenosphere (FAC).

Composition (wt%)	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O
Cement	19.3	4.1	3.5	67.6	1.8	0.3	0.7
FA	42.2	22.5	9.2	15.7	3.2	1	1.5
FAC	61.9	27.7	3.9	1	1.2	1.3	2.8

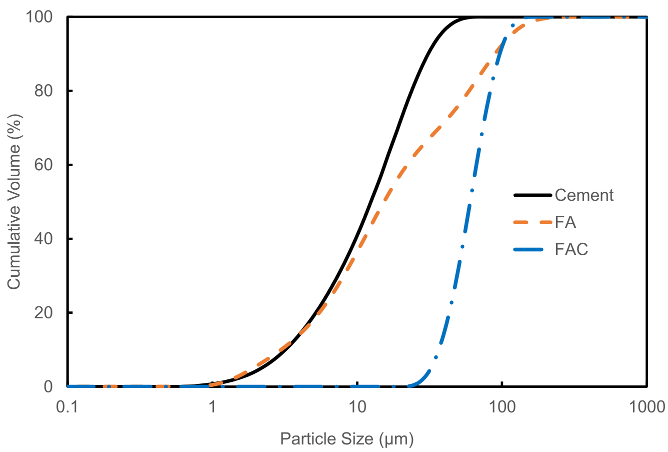

Fig. 2. Particle size distribution of cement, FA and FAC

pre-existing flaws with controlled crack opening, ECC can exhibit a high tensile ductility by two orders of magnitude compared to conventional concrete. The typical cracking pattern under uniaxial tension results in many closely spaced microcracks, with the crack width of less than 100 μm [34]. The ductility of ECC is the total sum of the distributed deformations resulting from these diffused microcracks. To attain the multiple cracking response in this controlled manner, ECC must meet the strength and energy criterions, the details of which can be found in Li 2012 [35].

For this lightweight ECC, FAC plays an important role in meeting strength and energy criteria. As hollow alumino-silicate spheres, FAC introduces voids to lightweight ECC. These voids can help lower the matrix toughness, which is preferable in ECC as the energy criterion for strain-hardening can be more easily met. Furthermore, the voids reduce the tensile stress level, which is needed to initiate cracking. When microcracks occur at lower tensile stress levels, a reduction of crack width can be expected when the interfacial bond property between fiber and matrix remains the same. However, the increase of FAC content also increases the porosity of the matrix due to its hollow particle nature, and in turn reduces the compressive strength [30]. Therefore, an optimal amount of FAC should be used in the lightweight ECC to achieve the desired tensile and compressive properties. Moreover, a minimum amount of FAC (10% of total volume) should be used to achieve the lightweight requirement. Therefore, three mix designs (Table 3) with different volumetric additions (10%, 15% and 20% of total volume for mix 1, 2 and 3, respectively) of FAC were used and compared in this paper to find the most suitable design that has optimal amount of FAC and meets all requirements.

2.2. Mixing and curing

The tensile properties of ECC are closely associated with the uniformity of fiber dispersion. Li and Li [36] have discovered the correlation between the rheological properties of ECC mortar before adding fibers and the uniformity of fiber dispersion after adding fibers. They also discovered that the optimal rheological properties for achieving uniform fiber dispersion can be quantified by the Marsh cone flow test. Felekoglu et al. [37] applied this concept and test method in HTPP fiber reinforced ECC and identified the most appropriate flow time of 25–35s for uniform fiber dispersion. The mixing procedure in this study was

Table 3
Mix proportions of lightweight ECC.

Mix ID	Cement	FA	FAC	Water	water/ solids ratio	HTPP Fiber Volume %	HRWR (kg/m^3)
1	1	2.79	0.22	0.93	0.23	2	7.4
2	1	2.79	0.36	0.97	0.23	2	7.7
3	1	2.79	0.51	1	0.23	2	7.9

modified based on Felekoglu et al. [37] to ensure the same rheological properties of ECC mortar before adding HTPP fibers.

A HOBART® floor mixer, with a capacity of 12 L, was used to mix ECC. The dry powder ingredients were prepared first in the mixer and mixed at 100 rpm for 2 min. Water and HRWR were then added into the dry mixture at 150 rpm for 3 min. These procedures intend to produce a consistent and uniform ECC mortar with optimal rheological properties. Finally, HTPP fibers were added and mixed at 300 rpm for 6 min to uniformly disperse the fibers, as recommended by Felekoglu et al. [37]. The fresh ECC was cast into molds with different shapes for different tests. After curing for 24 h in molds and covered with a plastic sheet, the specimens were demolded and cured in limewater at room temperature (23 ± 3°C) for 28 days.

2.3. Tests for basic material properties

Dogbone-shaped specimens were prepared for each mixture to test the direct tensile behavior of the lightweight ECC. The configurations of dogbone-shaped specimens and the setup of the tests are shown in Fig. 3. The specifications are in accordance with the Japanese Society of Civil Engineers (JSCE) recommendation for High Performance Fiber Reinforced Cementitious Composite (HPFRCC) specimens [38]. The direct tensile test was conducted under displacement control at a loading rate of 0.005 mm/s. This loading rate was chosen to simulate a quasi-static loading condition. Two external linear variable displacement transducers (LVDT), with a gage length of approximately 100 mm, were attached to the specimen (Fig. 3). Stress–strain curves were recorded to determine the behavior of specimens under direct tension. The peak stress and the corresponding strain value were used as tensile strength and tensile ductility, respectively. After direct tension test completed, the crack widths were measured by using a portable microscope with resolution of 10 μm, and the maximum crack width was recorded.

Three cube specimens, with the dimensions 50 × 50 × 50 mm^3, were made to obtain the compressive strength and to measure the equilibrium density. Compressive strength tests were performed at a loading rate of approximately 0.28 MPa/s, in accordance with ASTM C109 [39].

The equilibrium density of different mixtures was measured based on the conditions specified in ACI 213 [1]: after exposure to a relative humidity of 50 ± 5% and a temperature of 23 ± 2 °C for a period of time sufficient until there is no significant loss of weight (change less than 0.5%) in 28 days. The mixture that meets all design requirements was selected for the four bending and fatigue tests (section 2.4 and 2.5, respectively).

2.4. Four-point bending test

Two groups of beam members were prepared for a four-point bending test to study the flexural behavior of the hybrid ECC/concrete

Table 2
Mechanical and geometric properties of HTPP Fibers.

Fiber Type	Diameter (μm)	Length (mm)	Nominal Tensile Strength (MPa)	Young's Modulus (GPa)	Elongation (%)
HTPP	12	10	850	6	21

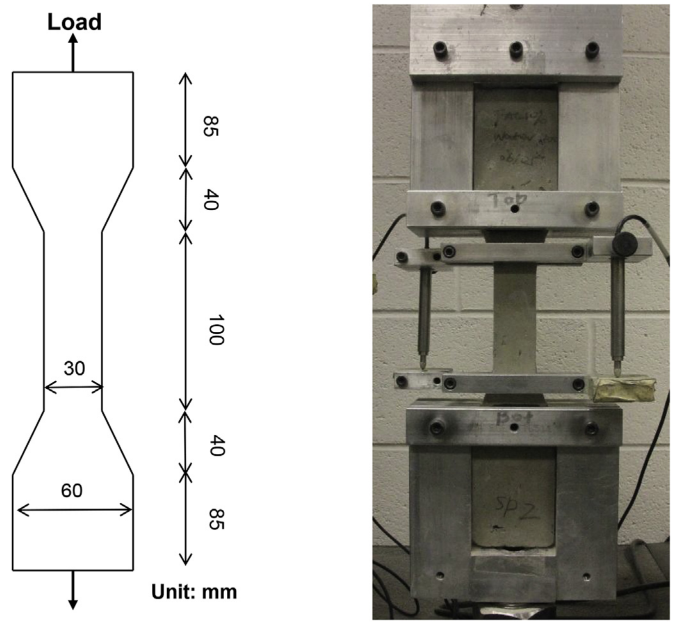

Fig. 3. Configurations of dogbone-shaped specimens (left) and test setup for direct tensile testing (right).

Table 4
Mix proportions of concrete.

Mix ID	Cement	Water	Natural Sand	Aggregate	HRWR
Concrete	1	0.36	1.65	2.4	0.09

dual-layer system. Each group has three members. The first group is the control group of 102 × 102 × 356 mm (height × width × length) plain concrete beam. The materials used in concrete are type I/II ordinary portland cement, water, natural sand (with particle size from 75 μm to 9.5 mm), and limestone coarse aggregate (with particle size from 9.5 mm to 37.5 mm). The mix proportions of the concrete are listed in Table 4. The compressive strength of concrete after 28-day water curing is 80 MPa and the elastic modulus is 42 GPa. The second group is a 102 × 102 × 356 mm hybrid ECC/concrete beam, consisting of a 26 mm thick lightweight ECC coating and a 76 mm thick concrete layer (Fig. 4). To avoid the delamination between ECC and concrete layer, transverse grooves adopted from Leung and Cao [40] were introduced to the surface of the ECC layer before casting concrete. According to Leung and Cao [40], this surface treatment is effective in diffusing major cracking in concrete into multiple fine cracks in the ECC layer without delamination. The concrete layer was then cast on the ECC layer 24 h after the casting of the ECC layer. After demolding, the dual-layer beam was placed in limewater for 28 days before testing.

The test setup is shown in Fig. 4, which follows the ASTM C1609 standard test procedure [41]. A constant mid-point net deflection rate of 50 μm/min was employed in the test, as recommended by ASTM C1609. The mid-point net deflection was measured and recorded using two potentiometers mounted on either side of the beam (one is shown in Fig. 4 and the other is on the backside).

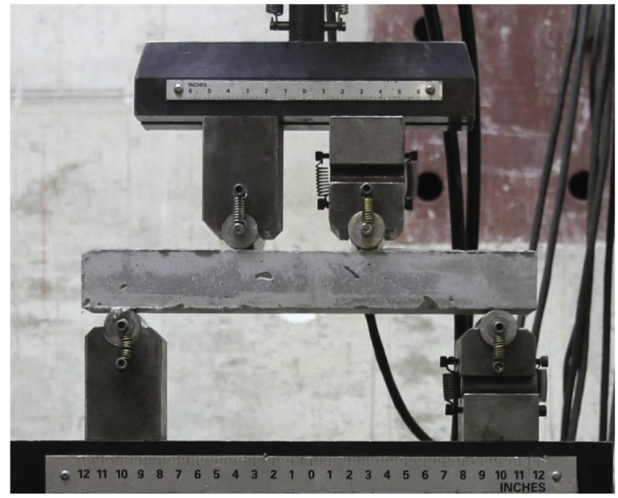

Fig. 5. Flexural fatigue test setup.

2.5. *Fatigue test*

The specimen preparation and test setup for fatigue test are based on Qian et al. [42] and are shown in Fig. 5. The test specimens are 38 × 76 × 304 mm (height × width × length). The span between the two far supports is 254 mm. Four-point bending was conducted at a constant moment span length of 84 mm. The monotonic test was carried out under displacement control at a rate of 0.5 mm/min to determine the flexural strength of the lightweight ECC.

For the fatigue test, the specimen was subjected to a static preloading stage to 50% of the flexural strength, followed by a fatigue loading stage. The preloading also used displacement control at a rate of 0.5 mm per minute; no micro-cracks were observed during the preloading stage. Fatigue cycles began after preloading, with loading control by a sinusoidal waveform at a frequency of 8 Hz. The fatigue load ratio (maximum flexural stress over flexural strength) was chosen to be 0.7, 0.8 and 0.9. The minimum flexural stress was kept at 20% of

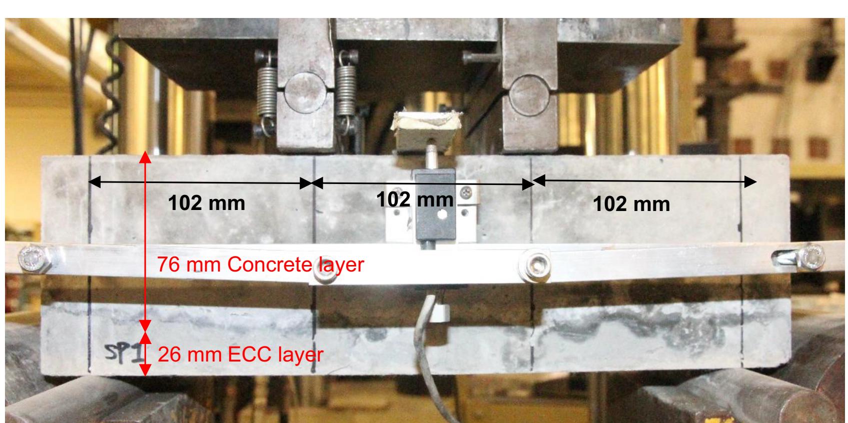

Fig. 4. Flexure test setup for four point bending test.

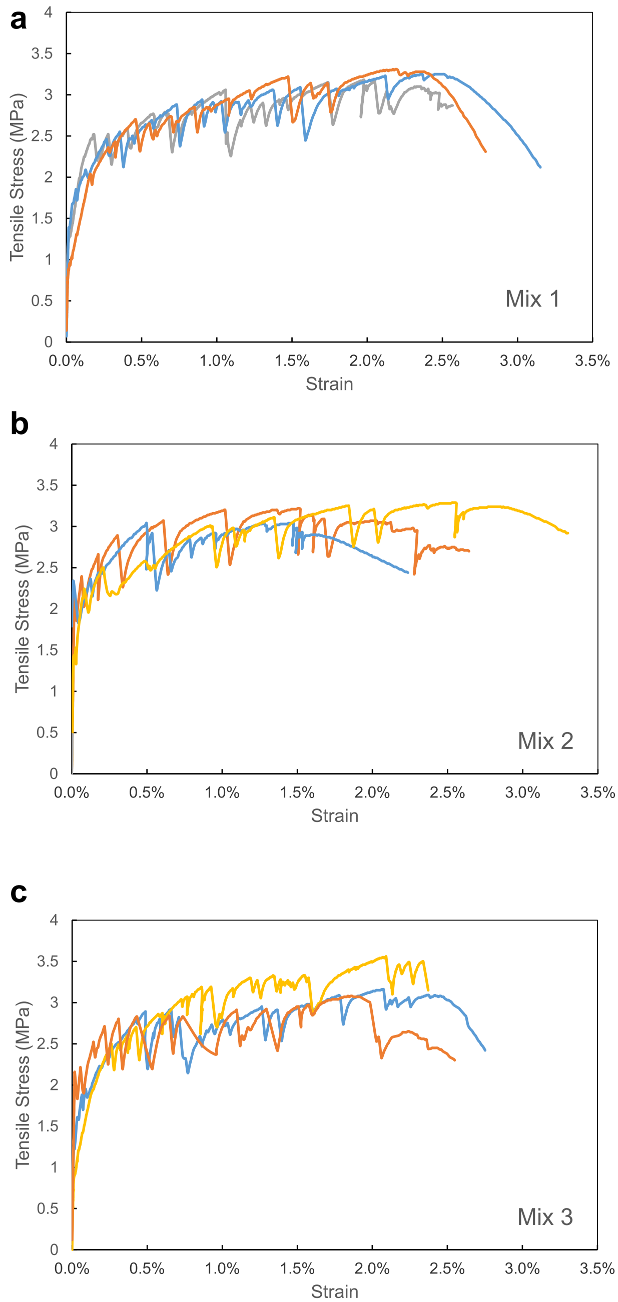

Fig. 6. Stress-strain curve of Mix 1 (a), Mix 2 (b), and Mix 3 (c).

the maximum flexural stress.

The fatigue life (the number of cycles at which the specimen fails) for each maximum flexural stress was recorded and was used to construct the fatigue stress-fatigue life (S—N) relation. For the measurement of crack width, the test was paused and the crack width was measured using the same portable microscope in Section 2.3. The maximum crack width and the corresponding number of cycles were recorded to construct a relationship between crack width evolution and number of cycles. Both results of fatigue life and crack width evolution were compared with concrete beams.

3. Results and discussion

The basic material properties of ECC are summarized in Section 3.1. The tensile properties of all ECC mixtures are obtained from direct tensile test and the results are shown in Fig. 6. The flexural behavior of the hybrid ECC/concrete beam is obtained from the four-point bending test and the results are shown in Fig. 7. The flexural fatigue behavior and the crack evolution of the lightweight ECC are obtained from fatigue test and the results are shown in Fig. 10.

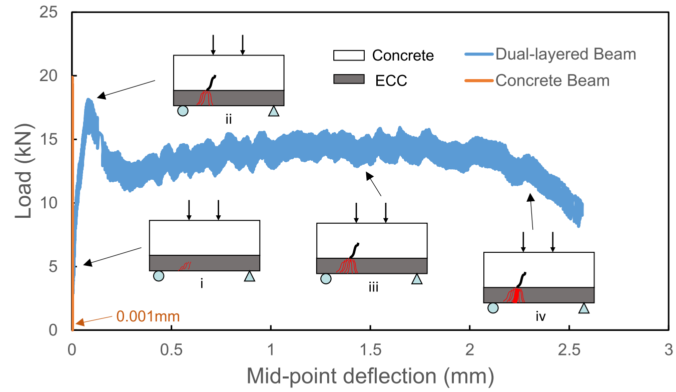

Fig. 7. The comparison of load – mid-point deflection between plain concrete beam and hybrid ECC/concrete beam and crack evolution for dual-layered beam.

3.1. Basic material properties of lightweight ECC

The basic material properties of all ECC mixtures are listed in Table 5, and their stress-strain curves are shown in Fig. 6. Only Mix 1 meets all the criteria listed in Table 5, and therefore was selected for four-point bending and fatigue tests. The equilibrium density is 1810 kg/m^3, which can be classified as lightweight [19], and the compressive strength is 30–32 MPa after 28-day water curing, almost twice the minimum compressive strength of lightweight structural concrete specified in ACI 213 [19]. The tensile ductility reaches 2.3–2.5%, which is more than 200 times that of regular concrete. Its tensile strength is above 3 MPa and maximum crack width is 100 μm, which has little effect on concrete permeability [17]. Based on the values of stress and strain where first cracking occurs, the elastic modulus is found to be 9 GPa (Fig. 6a). To avoid confusion, the term lightweight ECC used in this paper refers to this particular mixture.

By comparing the properties of different mixture designs, the following observations can be made about the additions of FAC. The density and compressive strength decrease with increasing FAC. Further, the matrix toughness and cracking stress level are lowered due to FAC's hollow structure thus acting as pre-existing flaws in the ECC matrix. According to micromechanics-based design theory [32–34], the energy criterion for strain-hardening can be more easily met by the reduced toughness from the use of FAC makes production of ECC, and the reduced tensile stress level is favorable for ECC for achieving a lower crack width. For Mix 1, where 10% FAC is added volumetrically, the maximum crack width of 100 μm can be achieved. However, the maximum crack width increases with the increase of FAC content (as seen in Table 5). The widening of crack widths may be attributed to the weakened interfacial bond between fibers and matrix as excessive FAC increases the porosity of the matrix [30,31].

3.2. Flexural behavior of the hybrid ECC/concrete beam

The typical load vs. mid-point deflection curve for the hybrid ECC/ concrete beam is shown in Fig. 7. The schematic crack evolution of the dual-layered beam is also shown as insets in this figure. Microcracks start forming in the ECC coating when the load reaches 5 kN (Fig. 7i). With the increase of the load, more microcracks form at the ECC coating. The drop of load after reaching the peak load of 18 kN occurs when a major crack is formed in the concrete (Fig. 7ii). At this point, the tensile stress on the bottom of the concrete section is found to be

Table 5
Basic material properties of lightweight ECCs.

Mix ID	Equilibrium Density (kg/m^3)	Compressive Strength (MPa)		Tensile Strength (MPa)		Tensile Ductility (%)		Maximum Crack Width (μm)	FAC (%)
		Mean	SD	Mean	SD	Mean	SD		
Design Criteria	1680–1920	≥17		NA		≥2		≤100	≥10
1	1810	31.17	1.04	3.17	0.15	2.37	0.15	100	10
2	1750	28.67	2.52	3.07	0.06	1.87	0.55	120	15
3	1680	22.33	1.53	3.17	0.29	1.95	0.13	130	20

6.1 MPa, using transformed-section method. This value is slightly larger than the tensile stress on the bottom of plain concrete based on the four-point bending test for plain concrete, which is found to be 5.8 MPa. The slightly larger tensile stress found in the concrete section of dual-layered beam compared to the plain concrete is attributed to the fact that the concrete crack initiation is restrained by ECC coating. The plateau after the peak load in this curve indicates that this major crack is arrested by the ECC coating (Fig. 7iii). The presence of the plateau also signifies that the carrying capacity of the beam does not drop immediately and the beam fails in a ductile manner. The decreasing load during the end of the test means that a localized fracture occurred at one of the existing microcracks in the ECC coating (Fig. 7iv). No delamination occurs during the test. In contrast, the peak load for the plain concrete member is followed by a sudden drop at a mid-point deflection of less than 0.001 mm. It indicates that concrete member without ECC coating fails in a brittle manner.

Fig. 8 shows the crack pattern in both the concrete and ECC layers; the major crack in concrete was arrested by the ECC coating and was turned into multiple tight microcracks. The multiple crack formation on the ECC coated concrete specimen is the result of a transverse opening of the concrete crack at the ECC/concrete interface. The microcracks in the ECC coating prior to fracture localization is similar to those in the dogbone shaped specimen in the direct tensile test (Fig. 8). In contrast, a localized crack was formed in the control plain concrete beams. Therefore, the dual-layer system, with the tight crack openings in its ECC layer, ensures the durability of wind turbine towers under extreme flexural loading conditions.

It should be noted that all beam members were intentionally tested without any ordinary steel reinforcement, which is mainly used for crack control and handling prefabricated segments in wind tower design (post-tensioning reinforcement is used to connect all precast segments) [43]. With the help of the excellent crack control and the tensile ductility supplied by the lightweight ECC coating, ordinary steel reinforcement for crack control can be reduced, as well as construction cost.

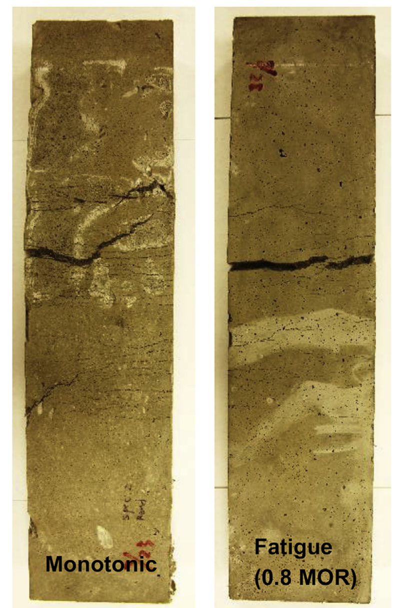

Fig. 9. Crack pattern at failure for lightweight ECC under flexural monotonic bending and fatigue loading at 80% of flexural strength.

3.3. Flexural fatigue behavior and crack evolution of lightweight ECC

The lightweight ECC exhibits multiple-cracking behaviors under both monotonic and fatigue bending tests (Fig. 9), while concrete always fails by sudden fracture localizations [42]. Less microcracks were observed for the lightweight ECC under fatigue loading, such as at 80% of the flexural strength, than under monotonic bending. This is because when at a lower stress (fatigue test), less cracks can be activated. It is more difficult for ECC beams to reach saturated multiple cracking under lower fatigue stress levels. Finally, fracture localization occurs at one of the existing microcracks.

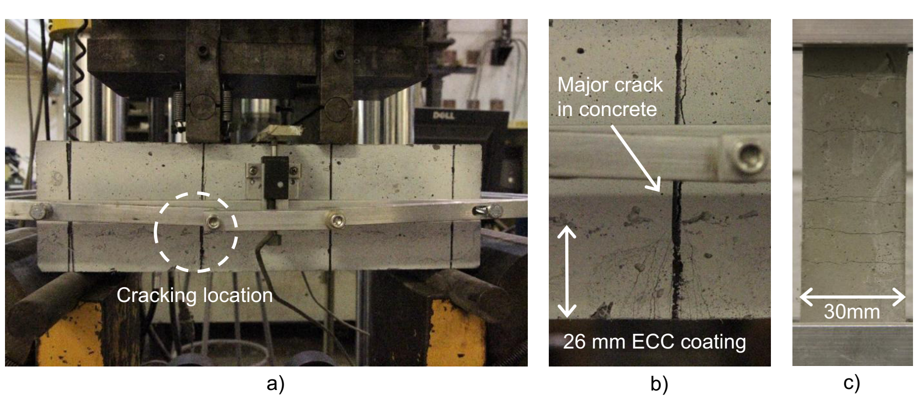

Fig. 8. a) Cracking Location on Dual-layered Beam Member, b) Single Major Cracking in Concrete Transitions into Multiple Microcracks in ECC, c) Multiple Microcrack from Direct Tensile Test.

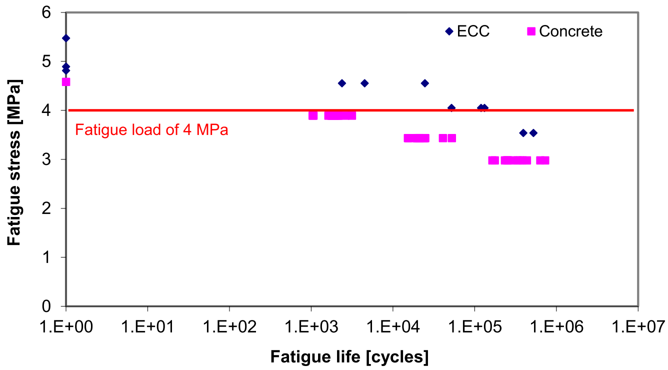

Fig. 10. S-N relationship for ECC and concrete.

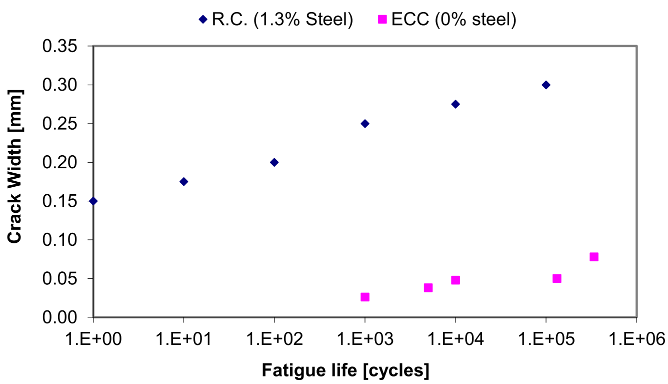

Fig. 11. Crack evolution for LW-HTPPECC and RC

Fig. 10 summaries the S—N relation of ECC and concrete, and the result shows that ECC has a better flexural fatigue resistance than concrete. The S—N relation of concrete is from Oh [44]. According to Fig. 10, ECC exhibits longer fatigue life than concrete under the same fatigue load. For example, ECC shows fatigue life of 10^5 cycles for a flexural fatigue stress of 4 MPa, while fatigue life of concrete is only around 2000 cycles. These results indicate that ECC exhibits a fatigue life 50 times that of normal concrete at this fatigue stress level.

Comparison of crack width evolution between concrete and the lightweight ECC is shown Fig. 11. The data of concrete is taken from Balaz and Eligehausen [45], in which they used steel reinforced concrete (RC), with a reinforcement ratio of 1.3%. To make a fair comparison, both ECC and RC were tested under a fatigue load ratio of 0.7. According to Balaz and Eligehausen [45], only one crack was observed in RC, which is expected. In ECC members, multiple microcracks were observed, with the maximum crack width remained below 50 μm throughout its fatigue life up to 10^5 cycles. However, the crack width at 3.3×10^5 cycles was 78 μm. This is because one of the microcracks had already started localizing and the fatigue life of this specimen was around 3.9×10^5 cycles. Therefore, the crack width of ECC remains more controlled throughout its fatigue life. For concrete, the crack width increased throughout its fatigue life. When the number of cycles reached 10^5, the crack width exceeded 300 μm, which marks the end of the nominal service life of tall concrete tower structures [46] and repair is required [47].

It should be noted that the RC specimen had a steel reinforcement ratio of 1.3%, while ECC had no steel reinforcement. The crack width evolution data support the concept that the use of ECC eliminates the need for ordinary reinforcement while providing better crack control than the reinforced concrete.

As stated previously, the tight crack width contributes to a low chloride diffusion coefficient and delays the initiation of steel corrosion [17], which contributes to extending the service life of concrete wind turbine towers. If the threshold value of 300 μm is considered the end of service life, the evolution of crack width can be used to predict the service life of tall wind turbine towers. Due to the scope of this paper, detailed estimation and comparison of service life in terms of fatigue life predication and chloride-induced corrosion of reinforced ECC/concrete wind turbine towers will be included in another manuscript [48], together with the corresponding life cycle cost (LCC) analysis.

4. Conclusions

With the guidance of performance driven design approach and micromechanics-based theory, a lightweight high tenacity polypropylene fiber reinforced engineered cementitious composite (ECC) has been developed by using low-density fly ash cenospheres (FAC). After meeting all the design requirements, this lightweight ECC is suggested for use as a protective coating on tall concrete wind turbine towers for enhanced durability. In contrast to concrete, it shows a controlled crack pattern, which results in closely spaced microcracks of maximum crack widths below 100 μm under uniaxial tension. Its compressive strength is almost twice the minimum required value of lightweight structural concrete, hence is appropriate for pre-fabricated coating being used as a permanent formwork during construction. Its ductility is more than 200 times than that of normal concrete. The hybrid ECC/concrete dual-layer system exhibits better ductility performance than the monotonic concrete system by transforming major cracks in the concrete layer into multiple microcracks in the ECC layer without any delamination. When subject to flexural fatigue loading, ECC shows a longer fatigue life than concrete. It also requires fewer repairs during its fatigue life since it maintains a constant crack width substantially less than 300 μm.

In addition to the mechanical and durability advantages of ECC/concrete dual-layer system, the results of this study suggest that economic advantages can also be achieved by this dual layer system. As the hybrid tower system can resist bending fatigue loading and exhibits better crack control without ordinary steel reinforcement, thereby reducing the construction cost. The enhanced durability could reduce maintenance costs. Moreover, with taller wind turbine towers and longer service life, the total energy production could increase. Therefore, it is worthwhile to carry out a life cycle cost analysis in a future study to demonstrate its economic advantage.

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References

[1] Concrete Wind Towers: concrete solutions for offshore and onshore wind farms, Ref. TCC/02/04, (2005) 1-904818-34-Xcopyright at The Concrete Centre.
[2] The Concrete Center, Concrete Towers for Onshore and Offshore Wind Farms". Technical Report, Camberley, Surrey, (2007).
[4] ACCIONA Windpower Signs a Contract to Supply 93 MW of Wind Power for Brazil, (2013) Retrieved March 26, 2016 http://www.acciona.windpower.com/pressroom/news/2014/january/acciona-windpower-signs-a-contract-to-supply-93-mw-of-wind-power-for-brazil/.
[5] Iowa State Engineers Design, Test Taller, High-strength Concrete Towers for Wind Turbines, (2013) Retrieved March 26, 2016, from http://www.news.iastate.edu/news/2013/05/14/concreteturbinetowers.
[3] J. Jimeno, Concrete Towers for Multi-megawatt Turbines", windsystemsmag.Com, February, (2012), pp. 40–45.
[6] P.K. Mehta, R.W. Burrows, Building durable structures in the 21st century, Concr. Int. 23 (3) (2001) 57–63.
[7] S. Abbas, M.L. Nehdi, M.A. Saleem, Ultra-high performance concrete: mechanical performance, durability, sustainability and implementation challenges, Int. J. Concrete Struct. Mater. 10 (3) (2016) 271–295.
[8] X. Shi, N. Xie, K. Fortune, J. Gong, Durability of steel reinforced concrete in chloride environments: an overview, Construct. Build. Mater. 30 (2012) 125–138.
[9] G. Carlos, Berrocal, ignasi fernandez, karin lundgren, ingemar löfgren, corrosion-induced cracking and bond behaviour of corroded reinforcement bars in SFRC,

Compos. B Eng. 113 (15 March 2017) 123–137.
[10] C. Tennakoon, A. Shayan, J.G. Sanjayan, A. Xu, Chloride ingress and steel corrosion in geopolymer concrete based on long term tests, Mater. Des. 116 (2017) 287–299.
[11] V.C. Li, Integrated structures and materials design, RILEM J. of Materials and Structures 40 (4) (2007) 387–396.
[12] V.C. Li, Performance driven design of fiber reinforced cementitious composites, in: R.N. Swamy (Ed.), Proceedings of 4th RILEM International Symposium on Fiber Reinforced Concrete, Chapman and Hall, 1992, pp. 12–30.
[13] J. Zhang, V.C. Li, Monotonic and fatigue performance in bending of fiber reinforced engineered cementitious composite in overlay system, J. of Cement and Concrete Research 32 (No.3) (2002) 415–423.
[14] Qingxu Jin, K. Christopher, Y. Leung, Changli Yu, Effect joining method for pseudo-ductile permanent formwork, Mater. Struct. 46 (3) (2013) 345–360.
[15] V.C. Li, Tailoring ECC for special attributes: a review, Int'l J. Concrete Structures and Materials 6 (No.3) (August, 2012) 135–144.
[16] K. Wang, D.C. Jansen, S.P. Shah, A.F. Karr, Permeability study of cracked concrete, Cement Concr. Res. 27 (3) (1997) 381–393.
[17] M. Sahmaran, M. Li, V.C. Li, Transport properties of engineered cementitious composites under chloride exposure, ACI Mater. J. 104 (No. 6) (November, 2007) 604–611.
[18] S. Miyazato, Y. Hiraishi, Transport properties and steel corrosion in ductile fiber reinforced cement composites, Proceedings of the Eleventh International Conference on Fracture, Turin, Italy, Mar. 20-25, 2005 (CD-ROM).
[19] ACI 213R-03. Guide for Structural Lightweight-aggregate Concrete.
[20] E.-H. Yang, Designing Added Functions in Engineered Cementitious Composites, PhD Thesis (Civil Engineering) The University of Michigan, 2007.
[21] J.Y. Wang, M.H. Zhang, W. Li, K.S. Chia, J.Y.R. Liew, Stability of cenospheres in lightweight cement composites in terms of alkali-silica reaction, Cement Concr. Res. 42 (2012) 721–727.
[22] J.Y. Wang, Y. Yang, J.Y.R. Liew, M.H. Zhang, Method to determine mixture proportions of workable ultra lightweight cement composites to achieve target unit weights, Cement Concr. Compos. 53 (2014) 178–186.
[23] Asad Hanif, Zeyu Lu, Li Zongjin, Utilization of fly ash cenosphere as lightweight filler in cement-based composites – a review, Construct. Build. Mater. 144 (2017) 373–384.
[24] Vanessa Rheinheimer, Yunpeng Wu, Tao Wu, Kemal Celik, Junyan Wang, Laura De Lorenzis, Peter Wriggers, Min-Hong Zhang, J. Paulo, M. Monteiro, Multi-scale study of high-strength low-thermal-conductivity cement composites containing cenospheres, Cement Concr. Compos. 80 (2017) 91–103.
[25] Yunpeng Wu, Jun-Yan Wang, J. Paulo, M. Monteiro, Min-Hong Zhang, Development of ultra-lightweight cement composites with low thermal conductivity and high specific strength for energy efficient buildings, Construct. Build. Mater. 87 (2015) 100–112.
[26] F. Blanco, P. García, P. Mateos, J. Ayala, Characteristics and properties of lightweight concrete manufactured with cenospheres, Cement Concr. Res. 30 (2000) 1715–1722.
[27] A. Hanif, S. Diao, Z. Lu, T. Fan, Z. Li, Green lightweight cementitious composite incorporating aerogels and fly ash cenospheres – mechanical and thermal insulating properties, Construct. Build. Mater. 116 (2016) 422–430.
[28] X. Liu, M.H. Zhang, K.S. Chia, J. Yan, J.Y.R. Liew, Mechanical properties of ultralightweight cement composite at low temperatures of 0 to -60 C, Cement Concr. Compos. 73 (2016) 289–298.
[29] J.Y. Wang, K.S. Chia, J.Y.R. Liew, M.H. Zhang, Flexural performance of fiber reinforced ultra lightweight cement composites with low fiber content, Cement Concr. Compos. 43 (2013) 39–47.
[30] A. Hanif, Z. Lu, M. Sun, P. Parthasarathy, Z. Li, Green lightweight ferrocement incorporating fly ash cenosphere based fibrous mortar matrix, J. Clean. Prod. 159 (2017) 326–335.
[31] X. Huang, R. Ranade, Q. Zhang, W. Ni, V.C. Li, Mechanical and thermal properties of green lightweight engineered cementitious composites, J. Constr. Building Mater. 48 (2013) 954–960.
[32] V.C. Li, C. Wu, S. Wang, A. Ogawa, T. Saito, Interface tailoring for strain-hardening PVA-ECC, ACI Mater. J. 99 (No. 5) (2002) 463–472.
[33] V.C. Li, On Engineered Cementitious Composites (ECC) – a review of the material and its applications, J. Adv. Concr. Technol. 1 (3) (2003) 215–230.
[34] T. Kanda, V.C. Li, Practical design criteria for saturated pseudo strain hardening behavior in ECC, J. Adv. Concr. Technol. 4 (No. 1) (Feb. 2006) 59–72.
[35] V.C. Li, Tailoring ECC for special attributes: a review, Int'l J. Concrete Structures and Materials 6 (3) (2012) 135–144.
[36] M. Li, V.C. Li, Rheology, fiber dispersion, and robust properties of Engineered Cementitious Composites, Mater. Struct. 46 (2013) 405–420.
[37] B. Felekoglu, K. Tosun-Felekoglu, R. Ranade, Q. Zhang, V.C. Li, Influence of matrix flowability, fiber mixing procedure, and curing conditions on the mechanical performance of HTPP-ECC, Compos. B Eng. 60 (2014) 359–370.
[38] JSCE, Recommendations for design and construction of high performance fiber reinforced cement composites with multiple fine cracks (HPFRCC). Concrete Committee, Rokugo K. (chair), Jap. Soc. Civ. Eng. (March; 2008) 212.
[39] ASTM C109. Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. Or [50-mm] Cube Specimens).
[40] C.K.Y. Leung, Q. Cao, Development of pseudo-ductile permanent formwork for durable concrete structures, RILEM Mater Struct 43 (7) (2010) 993–1007.
[41] ASTM C1609, Standard Test Method for Flexural Performance of Fiber-reinforced Concrete with Third-Point Loading, American Society for Testing and Materials, West Conshohocken, PA, 2010.
[42] S.Z. Qian, V.C. Li, H. Zhang, G.A. Keoleian, Life cycle analysis of pavement overlays made with Engineered Cementitious Composites, J. Cement Concrete Composites 35 (2013) 78–88.
[43] M.W. LaNier, Evaluation of Design and Construction Approaches for Economical Hybrid Steel/Concrete Wind Turbine Towers", Technical Report NREL/SR-500-36777, National Renewable Energy Laboratory, Golden, Colorado, 2005.
[44] B.H. Oh, Fatigue life distributions of concrete for various stress levels, ACI Mater. J. 88 (2) (1991) 122–128.
[45] G. Balaz, R. Eligehausen, Cracking behaviour under non-monotonic loading - literature review-, Int. Conf. Bond Concr. from Res. to Pract. (1992) 29–38.
[46] C. Andrade, C. Alonso, F.J. Molina, Cover Cracking as a Function of Bar Corrosion: Part I – Experimental Test" Materials and Structures vol. 26, (1993), pp. 453–464.
[47] CICIND - International Committee on Industrial Chimneys "Model Code for Concrete Chimneys, (August 2001).
[48] Jin, Qingxu, Li, Victor, Life Cycle Analysis of Hybrid Tall ECC/concrete Wind Turbine Towers Using Various ECC Designs. (Under development for submission).