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Engineered Cementitious Composites (ECC) for Applications in Texas

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16. Abstract
The objective of this project was to identify the applications of ECC that are suitable for the Texas transportation system. To achieve this goal, the following three activities were conducted: 1) literature review and data analysis, 2) survey on ECC state-of-the-practice, and 3) cost-benefit analysis through life-cycle cost analysis (LCCA) and life-cycle assessment (LCA). Comprehensive information about ECC including the materials properties, mixture designs, field applications, and survey results are synthesized. The results of LCA and LCCA for the applications to pavement overlay and bridge link slab demonstrate that the use of ECC is beneficial in the aspects of the agency cost, user cost, greenhouse gas emission, and energy consumption. Based on the findings from these activities, recommendations for ECC applications in Texas are provided. The priority applications for ECC are the following: 1) pavement overlay made of ECC, 2) ECC link-slab for bridge expansion joints, and 3) repair of existing concrete structures with ECC. A standard mixture proportioning composed of Portland cement, class F fly ash, sand, water, and PVA fiber is proposed. In addition, further research topics to facilitate practical applications of ECC in Texas are suggested.

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Chapter 1. Introduction

1.1 Overview

Engineered Cementitious Composites (ECC) are a special type of High-Performance Fiber-Reinforced Cementitious Composites (HPFRCC) that is characterized by high-ductility (3-5% of strain) and moderate tensile strength (4-6 MPa) with 1.5-2% fiber content by volume. Under tensile deformation, ECC shows a strain-hardening behavior and closely spaced microcracks after the first cracking. ECC has excellent shear capacity, improved damage tolerance, ability to control crack width, and synergistic interaction with reinforcing bars.

Basic components of ECC are Portland cement, water, fine aggregate, plasticizer, and fibers. Poly-vinyl-alcohol (PVA) fibers are typically used for ECC (known as PVA-ECC) because PVA fibers provide the higher and more consistent ductility improvement than other types of fibers. Coarse aggregate is not used in ECC mixtures, and in some cases, fly ash (typically type F) is added to reduce the amount of Portland cement. Because of the lack of coarse aggregate, the initial cost of ECC is higher than the regular concrete, and this has been one of the barriers to the widespread use of ECC. Lack of information and previous experience of using ECC are another barrier of using ECC. Some investigators have shown that the life-cycle cost and environmental impact of ECC can be lower than conventional concrete because of the extended service life and lower maintenance required. The properties and structural applications of ECC have been actively investigated by various engineers during the last two decades.

1.2 Objectives of the Research

The objective of this project is to identify the applications of ECC that are suitable for the Texas transportation system. The following fundamental information on ECC technology are provided to achieve this goal:

- Literature and survey results that demonstrate state-of-the-art and state-of-the-practice
- Principles of ECC technology: micromechanics, characteristics, and mixture design of ECC
- Reported applications of ECC and their long-term performance
- Cost-benefit analysis through life-cycle assessment
- Recommendations for Texas applications

The technology readiness level (TRL) of the requested proposal is ‘Level 1: Basic principles observed and reported’. Since ECC technology has more than twenty years of research history and pioneering applications, the TRL of ECC technology in Texas can rapidly rise with the information obtained from this research.

1.3 Work Scope

In order to evaluate the applicability of ECC to the Texas transportation system, the following tasks were conducted:

- Task 1: Project management
- Task 2: State-of-the-art and state-of-the-practice of ECC technology
- Task 3: Meta-analysis results on ECC raw materials, mechanical behavior, and performance
- Task 4: Information on the mixture design, processing, construction, and quality control of ECC
- Task 5: Case examples of ECC applications
- Task 6: Results of the state-of-practice survey on ECC applications
- Task 7: The life-cycle assessment (LCA) including cost-benefit analysis, social, and environmental impacts for selected case applications of ECC
- Task 8: Recommendations and considerations on the applications of ECC for Texas transportation system

The work consists of three activities: (1) literature review and data analysis (Tasks 2-5), (2) survey on ECC state-of-the-practice (Task 6), and (3) cost-benefit analysis (Task 7). The existing papers, reports, and standards are collected and reviewed in Task 2. Using the collected data from Task 2, the research team conducted in-depth meta-analyses on material characteristics of ECC (Task 3), mixture design & process, construction, and quality control (Task 4), and case examples of ECC applications (Task 5). In parallel to the literature review, the research team conducted a survey on ECC experiences for states, federal, and international agencies (Task 6). The cost-benefit analysis considering Texas environment, life-cycle cost, and environmental impact are conducted in Task 7. Task 8 synthesizes the findings through Task 2-7 and provides recommendations and considerations for ECC applications in Texas.

Chapter 2. State-of-the-Art of ECC Technology

2.1 Introduction to ECC Technology

Engineered Cementitious Composite (ECC) is another name for high-performance fiber reinforced cementitious composite (HPFRCC). ECC is characterized by high-ductility (3-5% of strain) and moderate tensile strength (4-6 MPa) with as little as 1.5-2% fiber contents by volume. Under tensile deformation, ECC shows a pseudo-strain-hardening behavior and closely spaced microcracks after first cracking. ECC has excellent shear capacity, improved damage tolerance, ability to control crack width, and synergistic interaction with reinforcing bars. The initial cost of ECC is higher than regular concrete, but the use of ECC may reduce the life-cycle cost and corresponding environmental impact and provide improved safety because of the superior ductility.

The use of fibers to reinforce a brittle material is dated back to Egyptian times. The ancient engineers added straws or horsehair into mud bricks as a reinforcement. Plain concrete is a brittle material, and its tensile strength is so low it is usually neglected in design of concrete structures. When fibers are added, the increase in tensile strength and ductility are substantial while the increase in compressive strength is not significant. Because of the changes in the tensile behavior, the flexural behavior also improves. The modern development of fiber reinforced concrete (FRC) was initiated in 1960's by Romauldi and co-workers (Romauldi and Batson 1963; Romauldi and Mandel 1964) who used short steel fibers in concrete. With the evolution of FRC technology, Lankard (1986) and Naaman (1992) attained a high tensile strength and strain-hardening behavior by using SIFCON (Slurry Infiltrated Fiber CONcrete).

The term 'ECC' was suggested by Li (1993), and the properties and structural applications of ECC have been actively investigated by various engineers during the last two decades. While various polymeric fibers including polyethylene (PE) and polypropylene (PP) have been used for ECC, ECC using poly-vinyl-alcohol (PVA) fiber (known as PVA-ECC) has the largest experimental dataset due to the higher and more consistent ductility improvement than other polymeric fibers (Yu et al. 2018a).

2.2 Mechanical Properties

2.2.1 Classification of FRC Behavior

Naaman and Reinhardt (2006) suggested a classification of FRC based on the tensile behavior. According to this model, after the proportional limit (point ① in Figure 2-1a and 2-1b), the tensile response of FRC can be divided into tensile strain hardening (Figure 2-1a) and tensile strain softening (Figure 2-1b) behavior. Similarly, the flexural behavior can be classified as deflection hardening (Figure 2-2 curve b) and deflection softening (Figure 2-2 curve a). Naaman and Reinhardt (2006) stated that the deflection hardening can be observed at both tensile softening and hardening FRCs, and suggested a FRC classification shown in Figure 2-3. FRC showing tensile hardening behavior is called HPFRCC. Fakharifar et al. (2014) and Wille et al. (2014) provided a graphical explanation for this classification as shown in Figure 2-4 (under tension) and Figure 2-5 (under bending), respectively.

Soranakom and Mobasher (2007a; 2007b; 2008) and Mobasher (2012) tried to correlate tensile and flexural responses of strain softening and strain hardening cement composites. They provided the equations predicting the moment-curvature behavior using the uniaxial stress-strain curves or vice versa. Instead of linear stress distribution assumption along with the depth of the beam, they used a uniaxial stress-strain model as the stress block. This approach is similar to the method recommended by RILEM TC 162-TDF (2003).

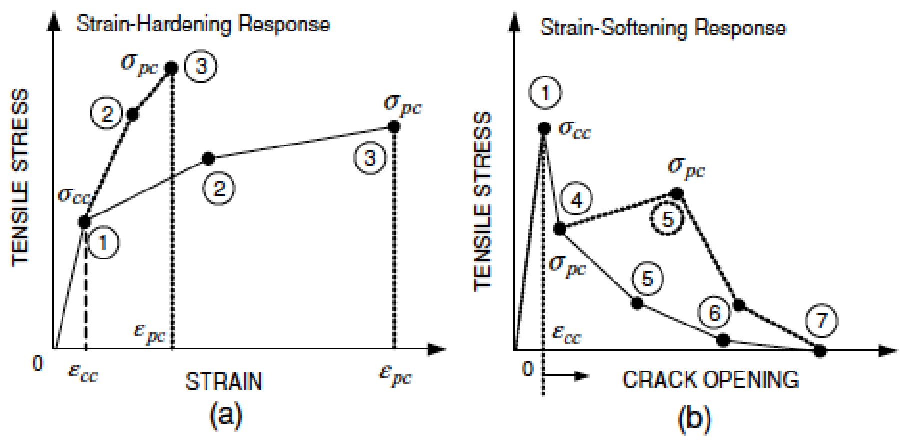

Figure 2-1. Typical Stress Strain Curve Response of a Strain Hardening and Strain Softening FRC Composite Subjected to Tension (Naaman and Reinhardt 2006)

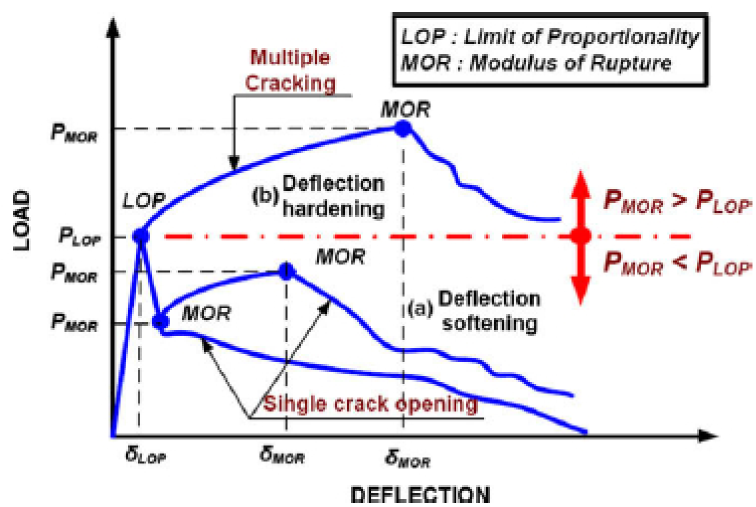

Figure 2-2. Typical Load-Deflection Response Curve of FRC Subjected to Bending (Kim et al. 2008)

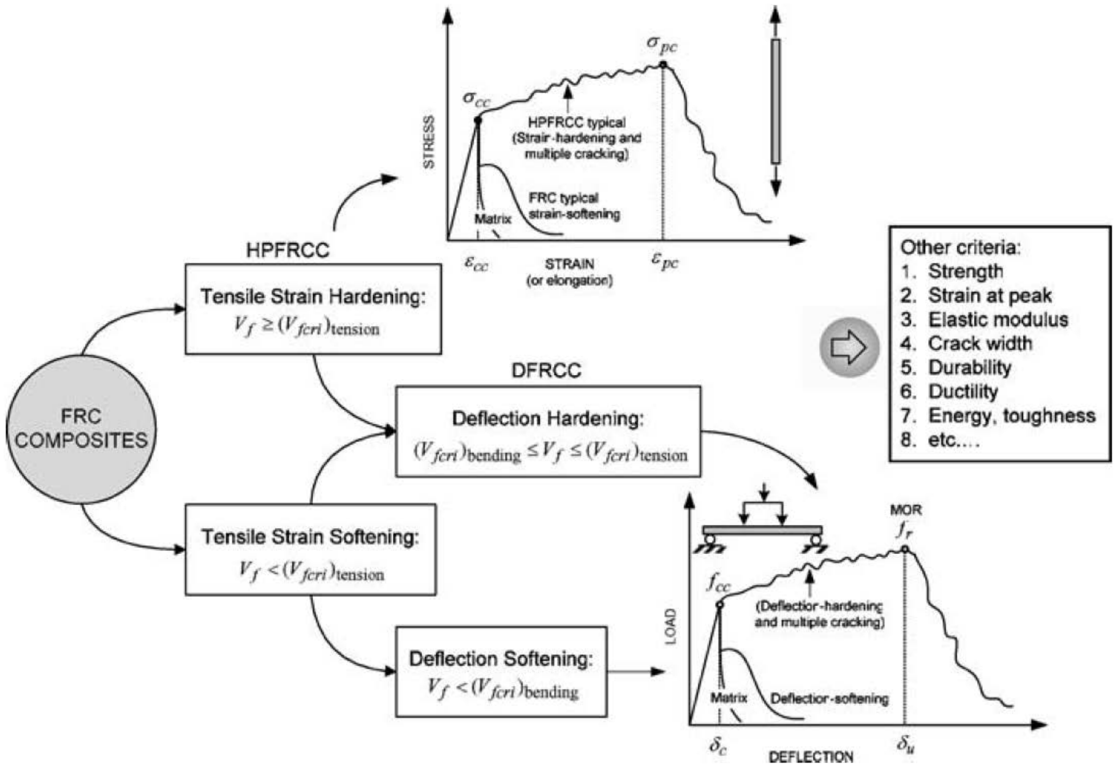

Figure 2-3. Classification of Fiber Reinforced Concrete Composites Based on the Tensile Strength Response (Naaman and Reinhardt 2006)

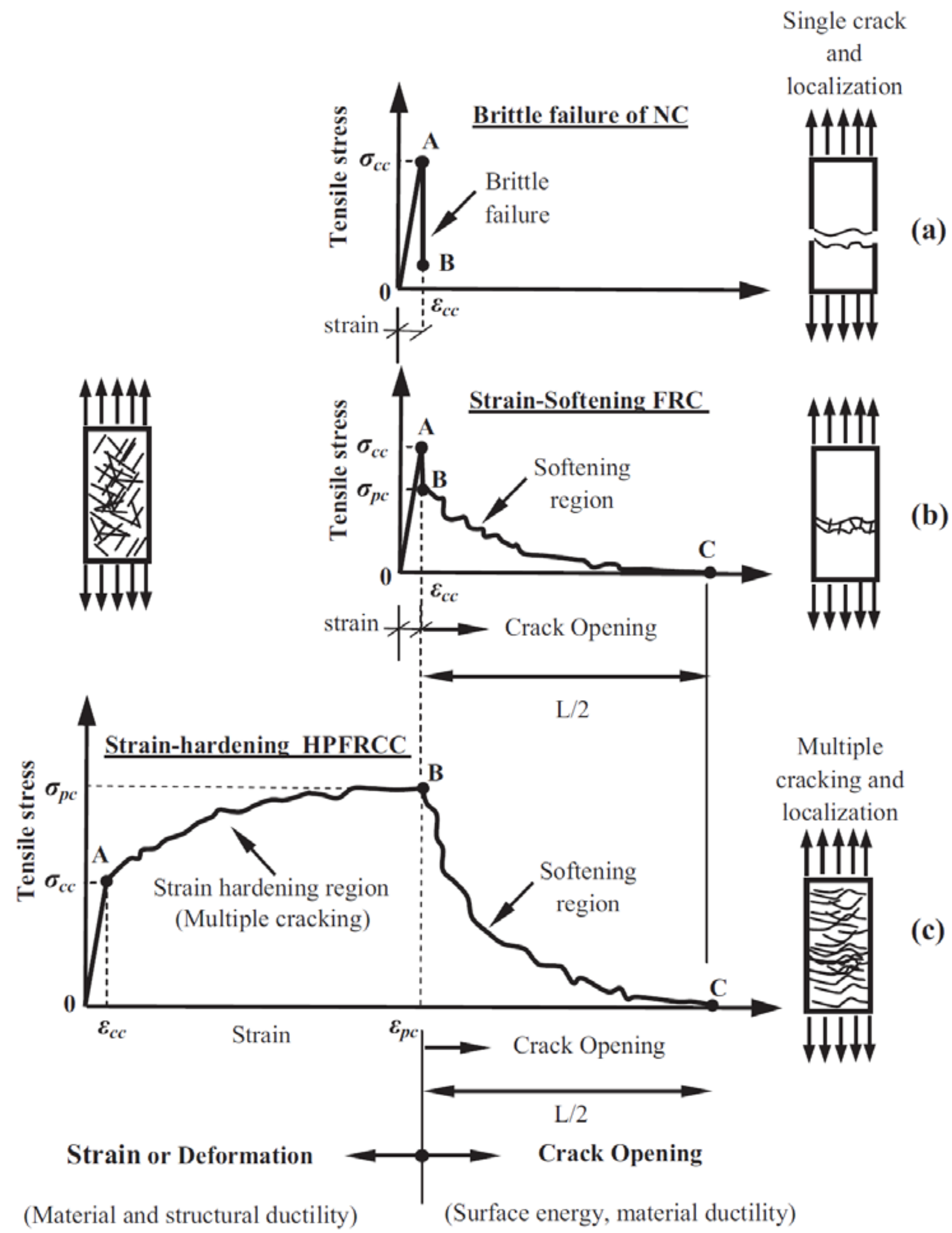

Figure 2-4. Typical tensile stress–strain or deformation relation up to failure of: (a) normal concrete (NC); (b) Fiber Reinforced Concrete (FRC); and (c) High Performance Fiber Reinforced Cementitious Composites (HPFRCC), (Fakharifar et al. 2014)

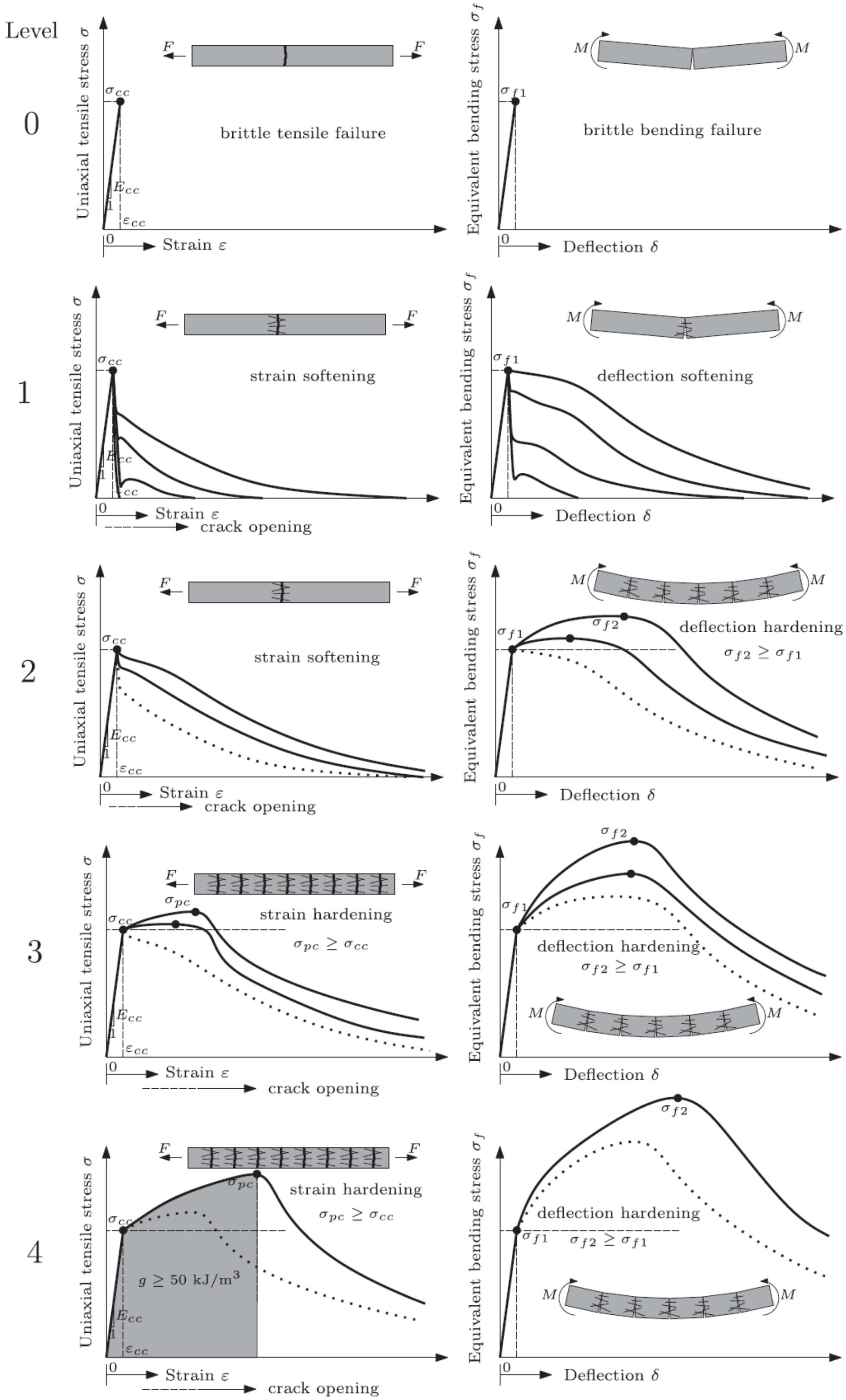

Figure 2-5. Definition of the Performance Levels of Fiber Reinforced Concrete (Wille et al. 2014)

2.2.2 Behavior of ECC

ECC is a special group of FRC that shows pseudo-strain-hardening with relatively low fiber volume fraction (2% and less) when fabricated by typical mixing and casting techniques with micromechanics approach (Li 1997). The randomly oriented discrete fibers result in an ECC which has isotropic properties, improved ductility, and shear capacity that allow it to be used for pre-cast or cast-in-place concrete without any requirement of special processing machinery (Li 1997). ECC flexibility results from the development of multiple microcracks after initial cracking. These continue to form until the maximum bridging stress is reached on one of the crack planes (Li 1993). Since this is an isotropic metal-like behavior, ECC should be well suited to multiply loaded structures such as roads, highway, and bridges.

The most important advantage of ECC is the high tensile ductility up to 5% elongation. A tensile stress-strain curve of ECC and its characteristic multiple-microcracking are shown in Figure 2-6. This metal like behavior starts from a characteristic “yield point” at the end of the elastic stage when the first microcrack appears on the specimen. Subsequent increase in load results in a strain-hardening response accompanied by the formation of multiple microcracks rather than localized crack opening normally associated with concrete. Final failure of the specimen occurs when one of the multiple cracks forms a fracture plane. The high tensile ductility is of great value in enhancing the structural ultimate limit state (ULS) in terms of structural load and deformation capacity as well as energy absorption. In this manner, ECC can offer structural safety improvements.

Table 2-1 shows the physical property ranges of typical ECC reported by Li (2008). Li (1997) compared the behavior of strain-hardening behavior of ECC (2% Spectra fiber) and strain-softening behavior FRC (1% hooked steel fiber). Figure 2-7 and 2-8 compare the stress-strain behavior under compression and tension, respectively. According to Li (1997), the crack pattern of the ECC under tension is distinctly different from plain concrete or normal FRC. The first crack started inside the mid-span at the tensile face, and multiple cracks developed from the first cracking point and spread to the outside of the mid-span. A comparison of flexural behavior of ECC and FRC is shown in Figure 2-9.

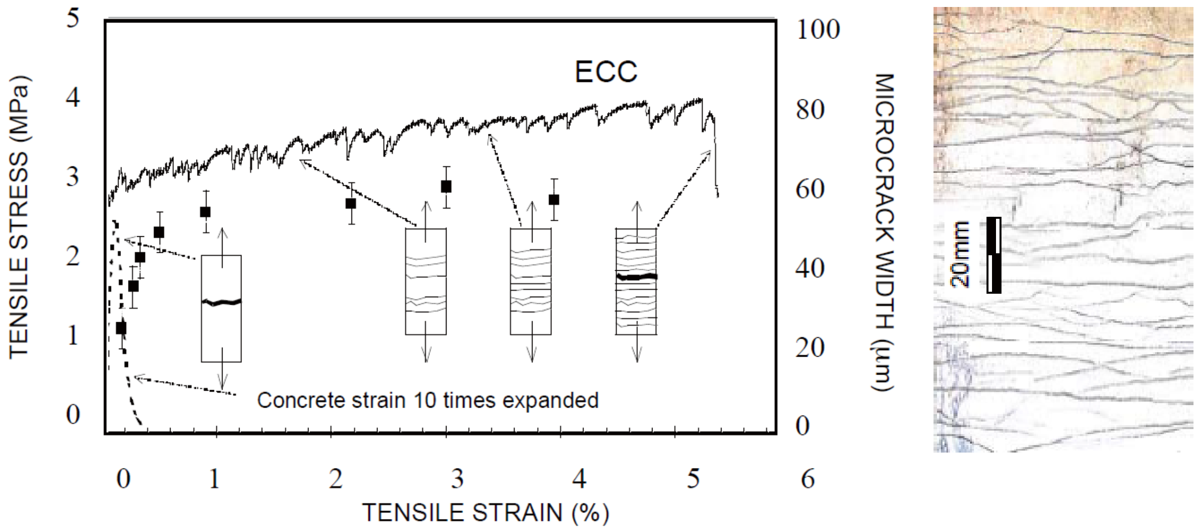

Figure 2-6. Tensile stress-strain curve of an ECC (Fisher et al. 2003; Li 2008)

Table 2-1. Typical Properties of ECC (Li 2008)

Compressive strength (MPa)	First crack strength (MPa)	Ultimate tensile strength (MPa)	Ultimate tensile strain (%)	Young's modulus (GPa)	Flexural Strength (MPa)	Density (g/cc)
20-95	3-7	4-12	1-8	18-34	10-30	0.95-2.3

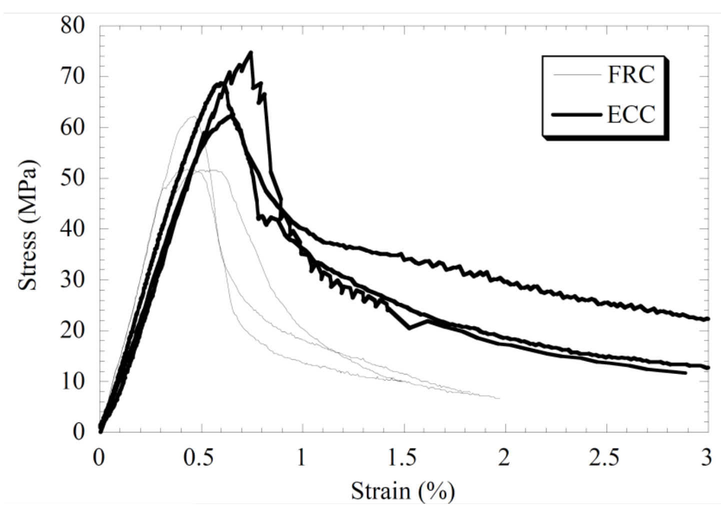

Figure 2-7. Compressive Stress-Strain Curves of ECC and FRC (Li 1997)

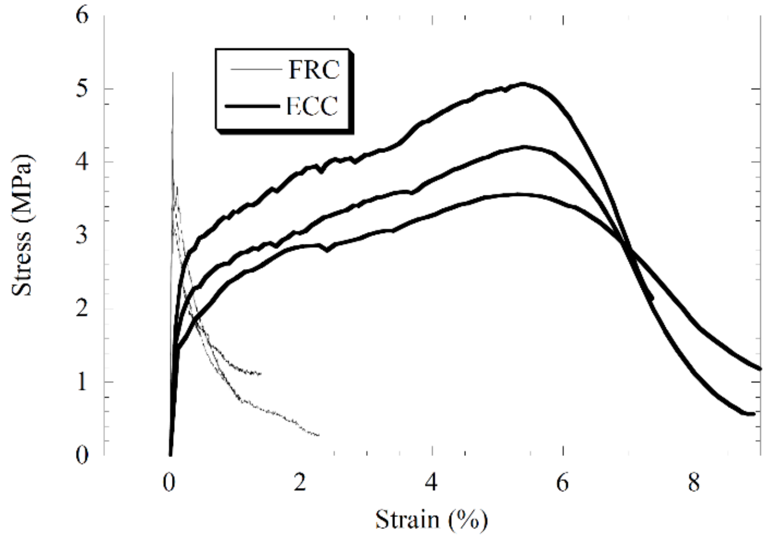

Figure 2-8. Uniaxial Tensile Stress-Strain Response of ECC and FRC. (Li 1997)

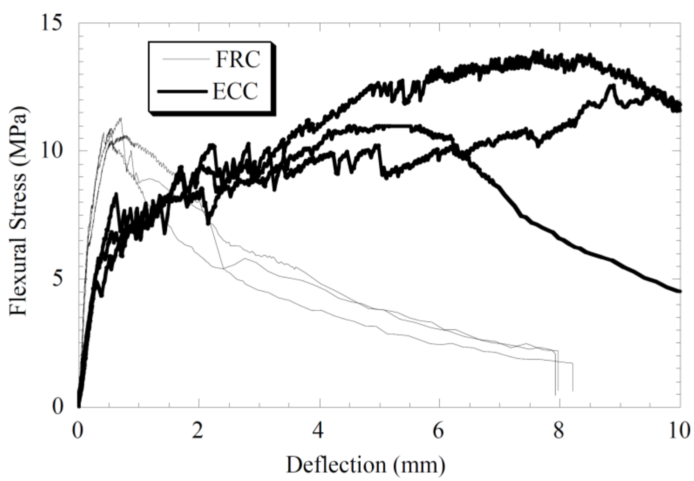

Figure 2-9. Flexural Stress-Deflection Curves of ECC and FRC. (Li 1997)

Pseudo strain-hardening of ECC was reported by Li (1993), Li et al. (1995), Lepech and Li (2005), Kanda and Li (2006), Qian et al. (2009), Yu et al. (2009), Li et al. (2009), Lee et al. (2013), Ma et al. (2015b), Pan et al. (2015), Kahn et al. (2016), Georgiou and Pantazopoulou (2017), Qui and Yang (2017), Keskinates and Felekoglu (2018), Yu et al. (2018a), Yang et al. (2019), and Ma et al. (2019b). Deflection-hardening behavior of ECC under flexural tests can be found in Kim et al. (2008), Qian et al. (2009), Said et al. (2015), and Pakravan et al. (2018).

Many papers on mechanical behavior of ECC have been published. The mechanical behavior can be measured in three representative test methods: uniaxial compression test, uniaxial tension test, and flexural (bending) test.

Compression testing of cylindrical specimens is the most common material test for concrete. Compressive strength of concrete (f_c') is used for predicting other mechanical properties, such as elastic modulus (E) and modulus of rupture (MOR). The standard test methods for compressive properties of concrete are:

- ASTM C39/C39M: Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens (ASTM International 2014a)
- ASTM C469/C469M: Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression (ASTM International 2014b)

Uniaxial compressive behavior of ECC can be found in Zhou et al. (2014), Zhu et al. (2014), Pan et al. (2015), Kai et al. (2017), Pourfalah (2018), Al Gemeel and Zhuge (2019), and Yang et al. (2019).

The uniaxial tension test is a fundamental test method for evaluating tensile properties of materials, but ASTM International has not adopted a direct tension test method for concrete. Instead, alternative test methods simulating the expected conditions of use are recommended. Those are the splitting tensile test and the beam bending test. In the splitting tensile test, diametral compression is applied to a standard cylindrical specimen through two narrow bearing strips along the two opposite sides of the cylinder. ASTM C496/C496M-17 describes the standard splitting tensile test method. The splitting tensile test simulates the splitting tension failure of concrete subjected to a compressive loading. While splitting tensile strength values are often assumed to be 30-40 percent lower than MOR values and 5-12 percent higher than direct tensile strength values, there is no simple relationships between these values (Mindess et al. 2003).

The most important benefit of fiber reinforcement is the improvement in tensile strength. Therefore, it is important to evaluate the uniaxial tensile strength of ECC for modeling and design purpose. While there is no currently available standard for concrete uniaxial tension test, AASHTO provides a standard test method for cement mortars:

- AASHTO T 132-87: Standard Method of Test for Tensile Strength of Hydraulic Cement Mortars (AASHTO 2013)

Some foreign institutes provide recommendations for uniaxial tension tests on FRCs that are used for research purpose as follows:

- RILEM TC TDF-162: Test and design methods for steel fiber reinforced concrete. Recommendations for uniaxial tension test. (RILEM TC TDF-162 2001).
- AFGC-SETRA: Ultra high performance fibre-reinforced concretes, Interim recommendations. (AFGC-SETRA 2002).

- JSCE: Recommendations for design and construction of high performance fiber reinforced cement composites with multiple fine cracks (HPFRCC) (JSCE 2008).

In addition, Wille et al. (2014) summarizes SFRC specimens for direct tension tests that have been conducted by various researchers.

Uniaxial tensile behavior of ECC that were published recently can be found in Kanda et al. (2003; 2006), Kim et al. (2007), Sahmaran et al. (2009), Yang et al. (2009; 2019), Zhou et al. (2010; 2012), Zhang et al. (2011), Tran and Kim (2013), Bhat et al. (2014), Tosun et al. (2014), Pan et al. (2015), Lu and Leung (2017), Krishnaraja and Kadasamy (2018), Pourfalah (2018), Yu et al. (2015; 2018b), Khlef et al. (2019), and Sridhar and Prasad (2019).

The beam bending tests simulating loading conditions of flexural members measure another indirect tensile strength, which is called MOR. Since the flexural loading condition is common in concrete members, MOR values are considered to be more useful than uniaxial tensile strength. The standard test methods for measuring flexural strength are:

- ASTM C293/C293M: Standard Test Method for Flexural Strength of Concrete (Using Simple Beam With Center-Point Loading) (ASTM International 2010a)
- ASTM C78/C78M: Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading) (ASTM International 2010b)

There exist several standard bending beam test methods tailored for FRCs as follows:

- ASTM C1399/C1399M: Test Method for Obtaining Average Residual-Strength of Fiber-Reinforced Concrete (ASTM International 2010c)
- ASTM C1609/C1609M: Test Method for Flexural Performance of Fiber-Reinforced Concrete (ASTM International 2012)
- RILEM TC TDF-162: Test and design methods for steel fiber reinforced concrete. Bending test. (RILEM TC TDF-162 2002).
- BS EN 14651 (British Standards): Test method for metallic fibre concrete. Measuring the flexural tensile strength (limit of proportionality (LOP), residual) (BS 2007)

The loading configurations of ASTM C1399/C1399M and ASTM C1609/C1609M are third-point loading (four-point bending), which is same as ASTM C78/C78M. While ASTM C78/C78M measures MOR of unnotched specimens, ASTM C1609/C1609M measures first peak loads and residual loads at specific deflections. The specimen toughness and flexural strength ratio are calculated from the residual loads. ASTM C1399/1399M uses a notched specimen. ASTM C1399/1399M describes a method of introducing a pre-crack, and average residual strength (ARS) is calculated from the residual strength at four specified deflections. ARS represents the average stress carrying ability of the cracked fiber reinforced concrete beam, and is suggested by Banthia and Dubey (1999; 2000). The test method recommended by RILEM TC TDF-162 uses the center-point loading (three-point bending) configuration with a pre-cracked specimen. In the RILEM TC TDF-162 bending test, the deformation of the cracked beam can be described either deflection or crack mouth opening displacement (CMOD).

The flexural behavior of ECC can be found in Wang et al. (1998), Kim et al. (2008), Sahmaran et al. (2009), Atahan et al. (2012), Jinlong et al. (2012), Sahmaran et al. (2014), Zhang et al. (2014a), Felekoglu et al. (2017), Georgiou and Pantazopoulou (2017), Meng et al. (2017a; 2017b), Krishnaraja and Kadasamy (2018), Pakravan et al. (2018), Poufalah (2018), Zheng et al. (2018), Soares et al. (2019), and Sridhar and Prasad (2019).

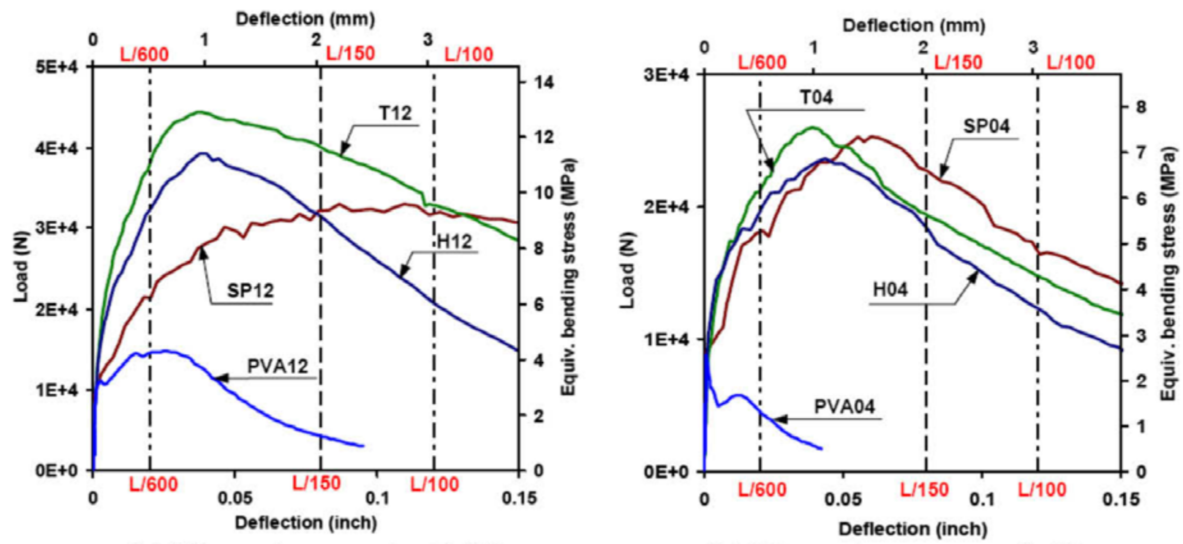

Figure 2-10. Effects of Various Fibers (Kim et al. 2008)

Kim et al. (2008) carried out an interesting comparative study. As shown in Figure 2-10, four different fiber types that have known to be effective enough to impart strain-hardening behavior were compared through flexural tests. Those were PVA fiber, spectra fiber (SP), hooked steel fiber (H), and torex (twisted steel) fiber (T).

The effects of various fiber types can be found in Wang et al. (1988), Kim et al. (2008), Lee et al. (2013), Said and Razak (2015), Zhang and Li (2015), Ali and Nehdi (2017), Ali et al. (2017), Felekoglu et al. (2017), Wu and Li (2017), Keskinates and Felokoglu (2018), Pourfalah (2018), Yu et al. (2018a), Alberti et al. (2019), Aslani and Wang (2019), Hosseini and Gencturk (2019), Kim and Yoo (2019), Nehdi and Ali (2019), and Zhang et al. (2019b).

The combinations of multiple fiber types were investigated by Maalej et al. (2012), Soe et al. (2013a; 2013b), Ali and Nehdi (2017), Wu and Li (2017), Pourfalah (2018), Khlef et al. (2019), and Sridhar and Prasad (2019).

Li and Lepech, (2004) used a ring test instead of a tension test to study ECC. The restrained shrinkage behavior of ECC was observed and ECC showed a high shrinking deformation, which can be used for repair. Reflective cracking of ECC is eliminated because of its microcracking deformation mechanism, which provides excellent performance in the fatigue environment of transportation applications. It also expected to eliminate overlay delamination and spalling when applied to pavements. This was shown in a fatigue test and overlay bond characteristics. ECC was shown to be preferable as a repair material for different transportation applications, including bridge deck patching and link slabs.

Suthiwarapirak et al. (2004) investigated the flexural fatigue characteristic of ECC composites with PVA and PE fibers. The study showed that the PVA-ECC has a high fiber/matrix bond strength and PE-ECC has higher tensile strength. These two parameters are considered very important to achieve a pseudo strain hardening behavior. When a low fatigue stress level is applied, the ECC behaves like a single cracking FRC. Also, under fatigue loading, the ECCs lose their multiple crack characteristics. The fiber rupture and pull out governs the multiple cracking and fatigue performance of the ECC and therefore must be taken into account to extend fatigue life and performance. *Fatigue resistance of ECC* was also investigated by Qui and Yang (2017), Hou et al. (2018), Qui et al. (2018), and Zhang et al. (2019b).

Tosun et al. (2014) investigated the correlation between the tensile strength and ductility of ECC by considering the effects of different processing parameters: largest flaw size, fiber dispersion, and fiber orientation. Uniaxial Tensile Tests were performed in accordance with ASTM C109. A correlation was observed between the first crack strength (the first peak stress at where strain hardening begins) and inverse square root of largest flaw size in ECC, but there is no correlation between the ultimate tensile strength (the second peak stress at where strain hardening ends) and the largest flaw size. A more cohesive matrix is beneficial for more consistent mechanical properties due to narrower fiber orientation distribution. The ductility of ECC was also discussed in Kanda et al. (2003), Li and Li (2006), Sahmaran et al. (2009), Li and Li (2011), Yao et al. (2012), Yuan (2013), Li (2014), Zhu et al. (2014), Lu et al. (2017), Zhang and Zhang (2018), Yu et al. (2018a), Kan et al. (2019), Li et al. (2019), and Zhang et al. (2019a; 2019c).

ECC can also withstand or absorb more *impact energy* compared to reinforced concrete and FRC before failure. Zhang et al. (2007) studied a hybrid fiber ECC of steel and polyethylene fibers to achieve a balanced ultimate strength and strain capacity for impact and blast resistant structures. These results provide strong support for using ECC materials for protective structures. (Zollo 1997; Zhang et al. 2007; Atahan et al. 2012; Maalej et al. 2012; Soe et al. 2013a; 2013b; Ali et al. 2017; Kai et al. 2017; Nehdi and Ali 2019).

Li and Li (2011) studied the long-term durability and self-healing robustness of ECC exposed to a high chloride concentration environment. Even under severe marine environment conditions, the ECC retains a robust tensile ductility preventing the normal failure mechanisms in concrete. *The* *durability of ECC* were discussed in Kamada and Li (2000), Li (2004), Lepech and Li (2005), Li and Li (2006), Li (2008), Sahmaran and Li (2009), Li and Li (2011), Lin et al. (2013), Li (2014), Zhang and Li (2015), Kewalramani et al. (2017), Lui et al. (2017) and Yu et al. (2018b).

2.3 Micromechanics

ECC are micromechanically designed materials and their composite performance is generally affected by flaw size distribution, number of fibers (or volume fraction), dispersion and orientation of fibers. The elastic stress field is dependent on the fiber length (embedded segment of fiber) and the ratio between fiber modulus (E) and the fiber cross-sectional area. If the fiber is short, it can be completely pulled out, and if the fiber is long, fiber rupture occurs. When ECC is loaded in tension, the matrix initially cracks in its weakest cross-section. The fibers crossing the crack will take the tensile load. ECC has a tight crack width self-control to 60 µm without the presence of steel reinforcement (Wang et al 1988). These effects are the motivation for multiple studies on the fiber properties, including investigation of hybrid fibers. The micromechanics of ECC were investigated by Li (1993), Li (1997), Sahmaran et al. (2011; 2012), and Qiu and Yang (2017).

2.3.1 Tailoring Fiber-Matrix Interface Properties

The interface bond and interaction between the fiber and the matrix is one of the key parameters in the micromechanics of ECC. Single fiber pull-out tests are often used to study the fiber-matrix bond behavior in FRCs. In the analysis of fiber pull-out tests, the elastic bond strength and frictional bond strength are assumed to be constant during the pull-out process. The frictional bond strength in general varies with the slippage distance between the fiber and the matrix during the pull-out process (Wang et al. 1988). The high chemical bonding of the PVA fiber with the matrix causes fiber rupture before pulling-out and limits tensile strain capacity. Strong slip-hardening can also cause shear delamination failure of the fiber. Slip hardening causes more damage on the fiber/matrix bonding than the frictional bond strength. In order to control the bond strength and frictional resistance at the fiber-matrix interface of ECC, an oiling agent is often used. the oiling agent helps the fibers to slip out, resulting in pseudo strain hardening, instead of fiber rupture.

Li et al. (2002) studied the effect of different percentages of oiling agent in ECC. The results show that as the oil quantity increases, the interfacial bond decreases. By increasing the oiling agent within the range of the experimental investigation, the tensile strain capacity increased with a larger crack width and reduced crack spacing. Oiling also allows the fibers to slip out with less damage, enhancing the fiber bridging properties and composite tensile strain capacity. To achieve optimal composite performance, adjustment to the other phases is necessary when one phase is changed. It is also expected that oil content will need to be altered based on the manufacturing and processing applied to a given system. Ismail et al. (2019) shows that by lowering the chemical debonding energy, the PVA-ECC exhibits a high energy absorption, which is very desirable. Reducing the slip hardening effect is desirable to avoid fiber rupture. To achieve these goals of reducing the chemical debonding energy and the slip hardening effect, oil coating was applied to the surface of the PVA fibers.

Zhou et al. (2010) showed that as the fiber slips out of the matrix, the frictional bond between the fiber and the matrix increases. They also found that ECC shows a lower water permeability and better durability compared with conventional concrete.

Redon et al. (2001) investigated the slip hardening effect resisting a complete fiber pull-out. Both chemical and frictional bonding are strong in PVA fibers. By lowering the chemical debonding energy, the PVA-ECC exhibits a high energy absorption. As mentioned before, oil coating is applied to the surface of the fiber, to achieve the reducing of chemical debonding energy and the slip hardening effect.

The effects of interfacial bonding between fiber and matrix can be found in Wang et al. (1988), Li and Li (2006), Said and Razak (2016), Bandelt et al. (2017), Sui et al. (2018), Qui et al. (2018), and Soares et al. (2019). *The data from single fiber pull-out tests* are given in Wang et al. (1988), Ma et al. (2015b), Kim and Yoo (2019), and Ranjbarian et al. (2019).

2.3.2 Matrix Property

While fine aggregates improve the elastic modulus in all cases, the excessive use of fine aggregates can lead to a suppression of desirable pseudo-strain hardening behavior and material ductility in tension. The higher matrix tougness from fine aggregates leads to a higher critical fiber volume fraction, decreasing the water to cement ratio gives a similar effect. Research to find and design a new class of ECC that can incorporate suitable aggregates that will result in higher elastic modulus without compromising the desirable features of strain hardening was needed. Li et al. (1995) emphasizes the effect of matrix parameters and the interfacial bond strength on composite pseudo-strain-hardening behavior. As long as the matrix toughness is controlled properly and the interface bond tailored properly, using fine aggregates and high elastic modulus on ECC will not change the ductility achieved through pseudo strain hardening (Li et al. 1995; Kim et al. 2003; Keskinates and Felekoglu 2018; Zhang et al. 2019c).

2.3.3 Fracture Mechanics

Lim and Li (1997) used interfacial fracture mechanics as an analytical tool to predict whether an interface crack will propagate along the interface or whether it will kink-out from the interface. An ECC overlay system with its trapping mechanism can prevent common failures in infrastructures such as delamination and spalling. The interface crack is trapped inside the interface due to effective toughening. The ECC trapping mechanism leads to high durability as a repair/rehabilitation system for aged infrastructures.

Kamada and Li (2000) investigated the micromechanical parameters associated with fiber, matrix, and interface which work together to produce two mechanisms: the first is the first crack stress, the second is steady state cracking to achieve strain hardening behavior. This paper also investigates the influence of surface preparation on the kick-crack trapping phenomenon. There is not much difference between the surfaces tested: smooth and rough surface for concrete overlay system and the SFRC overlay system. The kink-crack trapping mechanism experiment reconfirmed the excellent performance of the ECC overlay system.

2.3.4 Fiber Dispersion

The dispersion of fibers in the matrix is another important factor that influences the quality of ECC. The dispersion of fibers were investigated by Kim et al. (2007), Lee et al. (2009), Zhou et al (2012), Tosun et al. (2014), Felekoglu et al. (2017), Lu and Leung (2017). Yang et al. (2009), Zhou et al. (2012) and Tosun et al. (2014) reported that a higher viscosity of fresh ECC is beneficial for a better fiber dispersion. Zhou et al. (2012) suggested two adjusted mixing sequences to improve fiber dispersion for ECC without sand and ECC with high volume sand. The adjusted mixing sequence is to add less water during mixing until fiber is added, then to add the rest of water. The suggested sequences improve the fiber dispersion, but do not have significant effects on the ECC properties such as first cracking stress. The fiber orientation has significant impacts on the strength and ductility of ECC. Lu and Leung (2017) showed that the fiber orientation is influenced by the thickness of specimens. A thinner specimen can have a better fiber alignment, hence, the specimen thickness increased from laboratory scale (10-15 mm) to over 100 mm, the strength decreases by 20% and ductility decreases by half. Felekoglu et al. (2017) reported that adding F type fly ash improves homogeneity of fiber dispersion.

2.4 Raw Materials

Typical ECC mixtures use polyvinyl alcohol (PVA) fibers but other fiber types such as steel fibers and PE (polyethylene) fibers have been used to achieve the desired properties for specific applications. PVA fibers are hydrophilic, making the fibers have a strong chemical bond with the matrix. If the chemical bond is too strong it can lead to premature fiber rupture, so several studies have examined ways to prevent this by optimizing the fiber/cement bond.

Besides the regular ingredient of ECC such as water, cement, sand, and fibers, investigators have used other materials for various purposes. The other raw ingredient that replaces sand or cement by part include blast furnace slag (Kim et al. 2007; Qian et al. 2019; Zhou et al. 2010; Huang et al. 2014), limestone power (Qian et al. 2009; Zhou et al. 2010), fly-ash (Wang and Li 200; Yang et al. 2007; Sahmaran and Li 2009; Sahmaran et al. 2011; 2012; Zhu et al. 2014; Zhang et al. 2014b; Yu et al. 2015; Zhu et al. 2016b; Felekoglu et al. 2017; Kan et al. 2019; Noorvand et al. 2019).

Qian et al. (2009) investigated the use of calcium carbonate as the main cause of cementitious composites self-healing, this helps reduce water permeability. Özbay et al. (2013) studied the ECC mixtures using slag since adding slag reduces the environmental burden. Increasing amounts of slag in ECC led to an increase in ductility and decrease in residual crack width

Yang et al. (2007) substituted a large amount of cement with Class F fly ash resulting in high volume fly ash ECC (HVFA-ECC). This was expected to promote infrastructure sustainability through simultaneous enhancement of material greenness and infrastructure durability through tight crack width control. According to Yang et al. (2007), the increase in fly ash reduces the compressive strength of ECC and fly ash addition can be used to adjust compressive strength for different application. High fly ash content reduces the crack width in ECC. At the same time high interfacial friction restrains the slippage of fiber and is responsible for the tight crack width. This promotes self-healing in ECC and benefits durability.

The effects of high volumes of fly ash were further investigated by Wang and Li (2007). ECC mixtures with high volume of ash needed Hydroxypropyl methyl cellulous (HPMC) and high-range water-reducing admixture (HRWRA) to achieve adequate workability. A lower matrix toughness came from the increased fly ash content which is favorable in strain hardening.

Due to absence of coarse aggregates and higher cement content, the ECC mixture had the highest shrinkage strain value of the three materials tested by Li and Li (2006): concrete, steel fiber reinforced concrete (SFRC) and ECC. The concrete and SFRC were used as controls because they are widely used as repair materials.

Another additive material investigated is super absorbent polymer. Yao et al. (2012) studied ECC mixtures using a water-SAP ratio of 10:1 or 30:1 to produce the rheological properties to meet the slump flow demand of the experiments. To evaluate the cracking behavior in restrained shrinkage conditions in the ECC mixture, a ring test was performed similar to ASTM C1580-04.

Studies on ECC using local materials to make it a sustainable material without compromising the durability and strain hardening behavior. Yang et al. (2007) used recycled materials to improve the crack width and tensile strain ductility of ECC. Khan et al. (2016) studied the effect of local material, white sand, on the workability if incorporated to ECC mixture. Kewalramani et al. (2017) discuss the sustainability impact of ECC in hot arid climates. Snoeck and De Belie (2012) experimented with the use of flax and cottonised flax fibers.

Khan et al. (2016) attempted to use different sizes of white sand available locally in Saudi Arabia as a local ingredient substitute in ECC. White sand was collected from the desert and were tested to reach an optimized mixture to achieve appropriate workability. Portland cement produced in Saudi Arabia was used. The aggregate size affected the fiber dispersion, therefore affecting the bonding force among the PVA fibers and the cementitious matrix resulting in frictional force. Using finer sand requires more superplasticizer to maintain a desired level of workability.

2.5 Standard Specifications Related to ECC

Since ECC is intended to replace traditional concrete either fully or in parts of structural elements, the standard specifications, and guides on concrete construction and fiber reinforced concrete were collected and reviewed. The following are the standard specifications related to ECC applications:

- Specifications on Concrete Design
    - TxDOT Standard Specifications for Construction and Maintenance of Highways, Streets and Bridges (2014)
    - TxDOT Bridge Design Manual – LRFD (2018)
    - TxDOT Pavement Manual (2018)
    - ACI 318. Building Code Requirements for Structural Concrete and Commentary (2014)
    - AASHTO LRFD Bridge Design Specifications (2014)
- ACI Specifications on fiber reinforced concrete (ACI committee 544)
    - ACI 544: Measurement of Properties of Fiber reinforced Concrete (1999)
    - ACI 544.R1: Report on Fiber Reinforced Concrete (1996)
    - ACI 544.2R: Design Considerations for Steel Fiber Reinforced Concrete (1988)
    - ACI 544.3R: Guide for Specifying, Proportioning, Mixing, Placing, and Finishing Steel Fiber Reinforced Concrete (1998)
- ASTM Specifications on fiber reinforced concrete
    - ASTM A820: Standard Specification for Steel Fibers for Fiber-Reinforced Concrete (2006)
    - ASTM Standard C1609/C1609M: Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam with Third-Point Loading) (2012)
- International Specification on fiber reinforced concrete
    - Reunion Internationale des Laboratories et Experts des Materiaux Technical Committee 162 (RILEM TC 162-TDF) – Test and Design Methods for Steel Fibre Reinforced Concrete (2002)
    - British Standards (BS) EN 14651: Test Method for Metallic Fibre Concrete. Measuring the Flexural 790 Tensile Strength (Limit of Proportionality [LOP], Residual) (2007)
    - JSCE (Japan Society of Civil Engineers). Recommendations for Design and Construction of High Performance Fiber Reinforced Cement Composite with Multiple Fine Cracks (2008)

Below are some examples of standard test methods used to investigate ECC behavior.

Table 2-2. Standard Test Methods Used for Measuring Mechanical Properties of ECC

Compressive Tests
ASTM E399 – Three-point bending test (Yang et al. 2007)
ASTM C39 - Compressive strength of cylindrical concrete specimen (Ali and Nehdi 2017)
ASTM C109 (2016) - uniaxial compression test, matrix uniaxial compression test (Yang et al 2019)
Tensile Tests
ASTM C496 - Splitting Tensile Strength of Cylindrical Concrete Specimens (Yang et al., 2019)
Flexural Tests
ASTM E399 - Three-point Bending Test Yang et al. (2007)
ASTM C1609 - Flexural Performance of Fiber-Reinforced Concrete – Using Beam with Third-Point Loading
ASTM C1018 - Flexural Toughness and First-Crack Strength of Fiber-Reinforced Concrete – Using Beam with Third- Point Loading (Ali and Nehdi 2017)
ASTM E399 (2012) - three-point bending test (Yang et al. 2019)
ASTM E 99 three-point bending test (Wang and Li, 2007)
Other Tests
ASTM C469 - Static modulus of elasticity and poisons ratio of concrete in compression (Ali and Nehdi 2017)
ASTM C666A - Freeze thaw test (Li and Lepech 2004)
ASTM C666 Procedure - Freeze-thaw durability (Sahmaran et al. 2012)
ASTM C457- To study the air void parameters (Sahmaran et al. 2012)
ASTM DE1461 - Thermal conductivity (Yang et al. 2019)

2.6 Additional Functions of ECC

2.6.1 Improved Workability

ECC materials can be cast, extruded, and sprayed. In other words, the workability of fresh ECC can be controlled over a wide viscosity range, and this enables self-compacting or sprayable ECC. The critical micromechanics parameters governing composite ductility were systematically investigated and effectively used to guide the mixture design. As long as the governing micromechanics are controlled carefully, a high material performance from ECC can be achieved.

ECC is typically able to achieve a denser structure than conventional concrete because it uses fine materials. As particles are able to fill in smaller voids that would otherwise be unfilled by larger particles, ECC is more resistant to chloride ion ingress. The sprayable ECC can be used for shotcrete and self-consolidation concrete. A typical mixture of a spray ECC is shown below from Lin et al. (2013)

Table 2-3. The Mixture Design of Sprayable ECC (Lin et al. 2013)

Materials	lb/ft^3 (kg/m^3)
Sand	40.0 (640)
Cement	49.9 (800)
Fly ash (Class F)	15.0 (240)
Water	23.3 (374)
Fiber	1.6 (26)
Additives (plasticizer and stabilizer combined)	0.5 (8)

The fresh mixture of sprayable ECC should be deformable so it can efficiently move through the hose to the nozzle. Once it is sprayed, the mixture should be viscous enough to stay adhered to the substrate and remain cohesive without composite ingredient segregation. Kim et al. (2003) developed a sprayable ECC suitable for wet-mixture shotcreting process with comparable ductility with ordinary ECC. Type I ordinary Portland cement, silica sand, fly ash, and calcium aluminate cement were used as the major ingredients in the matrix.

According to Ali and Nehdi (2017), the workability decreases as fiber contents increases from 2.0 % to 3.5 %. The decrease in workability causes fiber clustering and the increase in matrix porosity, and eventually results in the reduced tensile and flexural capacity. Ali and Nehdi (2017) used 0.012 weight ratio of polycarboxylate-based high-range water reducing admixture (HRWRA) to cement, and reported that increasing HRWRA dosage was not effective in improving workability for the ECC containing fibers more than 2.0%. On the other hand, when fiber content is fixed as 2.0 % by volume, the workability of ECC is influenced by the HRWRA. Khan et al. (2016) showed that the workability of 2.0 % PVA-ECC increases as the dosage of HRWRA increases from 0.002 to 0.006 ratio to cement weight. According to Sahmaran et al. (2009) ECC workability is affected by fiber aspect ratio, fiber contents, and size/content of aggregates.

Fischer et al. (2003), Yu and Li (2009), Lin et al. (2013), Zhang and Li (2015), Khan et al. (2016), Alberti et al. (2019), and Ismail et al. (2019) also investigated the workability of ECC for self-compacting or sprayable ECC.

2.6.2 Self-Healing ECC

The long-lasting hydration process which can span decades is a nature of cementitious composites. With the presence of moisture, micro-cracks in cementitious composites can be healed. The self-healing of cementitious composites was originally observed by the French Academy of Science in 1863 (Kan et al. 2010). In ECC, the bridging effect of fibers prevents the localization of cracks, resulting in the multiple microcracking which is a characteristic of ECC. These microcracks provide an ideal condition for self-healing cementitious composites. Self-healing is one of the actively investigated research topics in ECC technology (Qian et al. 2009; Sahmaran and Li 2009;

Yang et al. 2009; Li and Li 2011; Snoeck and Belie 2012; Wu et al. 2012; Herbert and Li 2013; Sisomphon et al. 2013; Huang et al. 2014; Zhu et al. 2016a; Ali and Nehdi 2017; Kewairamani et al. 2017; Qui et al. 2018; Suleiman et al. 2019; Ma et al. 2019a; Zhang et al. 2019a; 2019b) .

Qian et al. (2009) investigated the self- healing behavior of pre-cracked strain hardening fiber reinforced cementitious composites which used local waste materials: blast furnace slag and limestone powder. The microcracks in the specimens submerged in water confirmed that calcium carbonate is the main ingredient that healed the cracks, it grows from both faces of the crack and grows and closes in the middle. This experiment also showed that high cementitious material percentage and low water to cementitious material ratio promote self-healing behavior.

Designs of cementitious composites with inherently tight crack width is effective in enhancing self-healing. Yang et al. (2009) found that self-healing in transport and mechanical properties are achievable. In this limited study, the mechanism of self-healing in ECC is the growth of calcites inside the tight cracks. Crack width must be controlled to be below 150 μm to enable noticeable self-healing behavior.

Sisomphon et al. (2013) studied the self-healing behavior of strain hardening cementitious composites incorporating calcium sulfo-aluminate based expansive additive (CSA) and crystalline additive (CA). The study resulted in wet/dry condition showing optimum mechanical recovery. The mixture with 10% CSA along with 1.5% CA addition had the highest recovery. The formation of calcium carbonate is preferable in terms of water tightness. The major internal crack healing product is a mixture of $CaCO_3$. The formation of the calcium carbonate was found to decrease further hydration of unreacted particles. The proportion of healing minerals depends on the exposure condition and type of cementitious material used.

Kan et al. (2010) investigated whether the crack characteristics and resonant frequency can be used to identify self-healing in addition to evaluation of chemical composition of healing products. Results showed less self-healing was observed with crack widths at 50 μm. Qiu et al. (2018) studied the effects of self-healing on flexural fatigue performance of ECC. The self-healing greatly extends the fatigue life of ECC because the water/dry conditioning not only heals the matrix cracks but also recovers the fiber/matrix interfacial bonds, which leads to increased strength due to fiber bridging. This study showed that resonant frequency is directly related to the recovery of mechanical properties and can be used as a method to quantify healing.

2.6.3 Other Structural/Nonstructural Functions

Many studies have been conducted in nonstructural functions of ECC such as *fire resistance, water resistance, and self-consolidation*. The effect of freeze-thaw cycle on ECC have also been investigated.

Sahmaran et al. (2011) showed that PVA fiber is beneficial in helping ECC overcome vapor pressure build-up under high temperatures and prevents spalling by melting at 230 degrees Celsius.

Sahmaran et al. (2012) confirmed that ECC is excellent for frost protection even though there was a slight reduction in the ultimate flexural strength and ductility, the mixture is still acceptable according to ASTM C666, Procedure A.

Fire resistive ECC (FR-ECC) exhibits high strain hardening behavior in tension test. The small size of the aggregate limits the toughness of the matrix which is preferable for multiple cracking and strain hardening behavior. It also has a low water permeability which is favorable in fire-resistive materials. FR-ECC shows a compressive ductility far higher than the minimum for fireproofing material. A lightweight, low strength and superior deformability FR-ECC can be a potential substitute for fireproofing material of steel structures to address durability issues of conventional spray-applied fire-resistant material (SFRM).

Zhang and Li (2015) aimed to develop an economical version of spray applied fire resistant ECC with more accessible and lower cost materials including exfoliated vermiculite and polypropylene fiber than conventional spray-applied fire-resistive materials (SFRM). A super fine grade vermiculite was chosen as an aggregate for the spray applied fire resistive ECC(SFR-ECC). Acrylic latex bonding agent was added to improve the adhesive properties to steel. High tensile polypropylene fibers were explored for their significantly low cost. The SFR-ECC showed a reduced tensile ductility compared to the cast specimens due to lower fiber bridging capacity, but it still exhibits a higher ultimate tensile strength than conventional SFRM .

Liu et al. (2018) investigated and quantified the role of PVA fibers at high temperature and the manner in which the fiber creates a network that is much more permeable than plain matrix. This paper demonstrates the efficiency of PVA fiber in protecting the ECC from spalling. The melting temperature of PVA fibers is 240 °C, and a significant increase in ECC permeability, which can prevent explosive spalling, was observed between 150 and 200 °C. The melted products are attached on fiber channel walls and cannot diffuse into the matrix.

Another fire resistive material, a new type of fire insulation is studied by Yang et al. (2019). Disadvantages of SFRM are the deficiencies in the mechanical property during high stress conditions and earthquakes resulting in debonding and spalling thus exposing steel structures to the threat of fire. Authors in this study aimed to develop a skin like fire proofing material for steel structures that has high tensile strain capacity, acceptable cost and appropriate low elastic modulus and strength. Fire resistant ECC (FR-ECC) is expected to work completely with steel structures under various loads by incorporating air pores, fly ash cenospheres, and light aggregate. The FR-ECC developed by Yang et al. (2019) is a satisfactory thermal insulation and is a suitable fire proofing material for steel structure.

ECC also provides very low water permeability in rehabiliated infrastructures. The high tensile stress near the interface causes ECC to go into strain-hardening and accommodates the local stress with microcrack inelastic deformation.

Yu et al. (2018a) studied the use of polyethylene (PE) fiber to develop ultra-high performance ECC. This high strength concrete prevents catastrophic structural collapse by absorption of massive amounts of energy during extreme load/ displacement events such as earthquake blasts and thus improves infrastructure sustainability. This ECC is more appealing than plain concrete for buildings that have larger seismic demand and infrastructure requiring high durability. Applications are mostly for super high-rise buildings, dams, and long span bridges.

A review of the use of ECC in hot arid coastal conditions was done by Kewalramani et al. (2017). They showed the diversity and breadth of ECC in places where temperatures remain above 45 °C and humidity over 90 percent. The review showed the compressive behavior of ECC becomes more ductile under uniaxial compression. The failure mode changes from ductile shear failure to brittle splitting tension failure at high temperature. Durability performance (e.g., permeability, capillary suction, and resistance to chloride penetration) in cracked and uncracked ECC samples were found to be comparable or better than normal concrete of the same strength without cracks.

Through this literature review, properties and characteristics of ECC were discussed. This background information should help with the future work.

Chapter 3. Meta-Analysis on ECC Behavior

3.1 Introduction to Meta-Analysis

Meta-analysis is a statistical and quantitative method used to systematically assess multiple previous studies to derive conclusions not evident in the individual studies. An individual investigation may have limitations or may even be biased by poor design or other reasons. By statistically evaluating the group of datasets produced by multiple studies and various investigators, the outcomes of meta-analysis can include a more precise answer to an engineering question than can be derived from any one study.

The question addressed herein is how much performance improvements can be expected in using ECC rather than traditional concrete. Various datasets on the behavior of ECC have been published for a variety of specimen types tested under varying conditions. The variables include the use of recycled materials such as Blast Furnace Slag or Fly ash substituting cement in the mixture design, various fiber types, sizes, and combinations, and various additives.

Previously published experimental data on tension, compression, and flexural tests are collected and analyzed in this study. The results of the meta-analysis will provide useful guidelines about the expected performance improvements of using ECC in the real-world applications where performance is affected by different mixture proportioning, large volume applications, compactions, and curing conditions.

3.2 Methodology

In the literature review, 70 papers included tension test results, 56 papers included compression test results, and 52 papers included flexural test results on a variety of ECC. The list of the collected papers for each test mode is listed in the Reference section.

For the meta-analysis, , the tensile stress-strain behavior and compressive stress-strain behavior are simplified as shown in Figures 3-1 and 3-2, respectively. Each stress-strain curve is represented by three points.

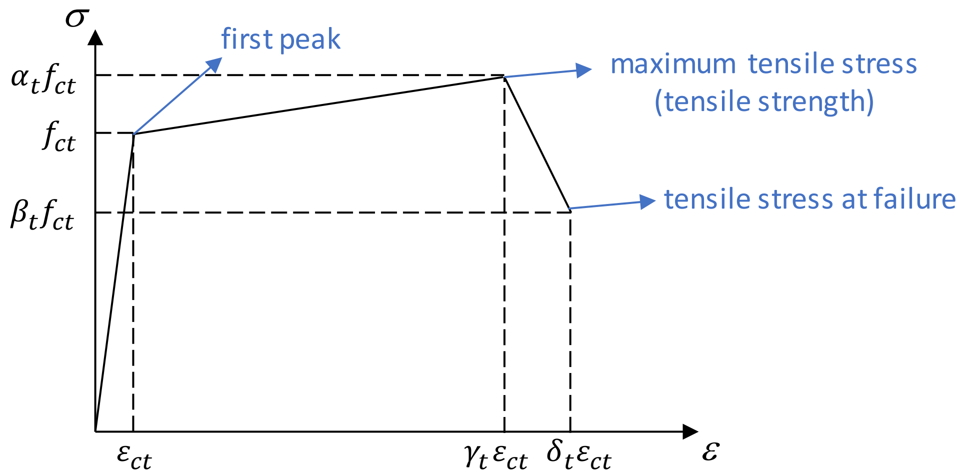

Figure 3-1. Simplified Constitutive Model for Tensile Behavior of ECC (Shi et al. 2020)

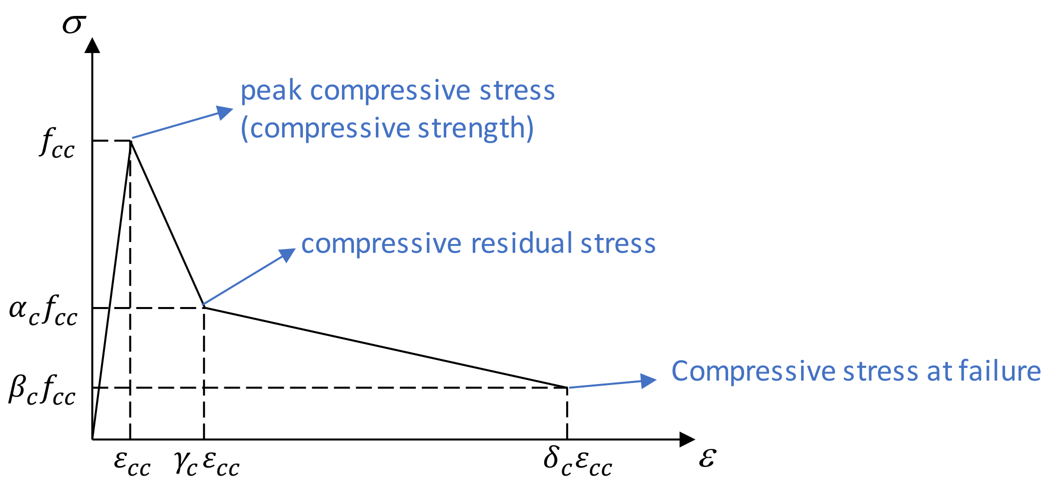

Figure 3-2. Simplified Constitutive Model for Compressive Behavior of ECC (Shi et al. 2020)

In case of a strain hardening tensile stress strain curve, the first peak is the point of first major crack development, but stress of ECC increases up to the maximum tensile stress due to the fiber bridging and multiple cracking. The last point of the data is considered as failure, and the strain at failure is an important indicator of the ductility. Since an unreinforced specimen would fail at f_{ct}, the parameter α_t, the ratio between the maximum tensile strength and the first peak stress, f_{ct}, represents the strength improvement due to fibers and the parameter δ_t, the ratio between the maximum tensile strain and the strain at the first peak, ε_{ct}, is an indicator of the ductility improvement. Considering the definition of ECC, fiber reinforced cementitious composites (FRCC) with $\alpha_t > 1.0$ can be considered to be ECC or HPFRCC (high-performance fiber reinforced cementitious composites).

Typically, ECC does not show strain hardening behavior under compression. The improvement in compressive strength in FRCC is negligible (Shi et al. 2020). In the compressive stress-strain model, the parameter α_c indicates the residual stress, and the key improvement is the ductility represented by δ_c.

Previous investigations found that the properties of FRCC are dependent on fiber volume content and the aspect ratio of the fiber. To combine the effect of both fiber content and fiber size (i.e., aspect ratio), the reinforcing index (RI) is defined as a fiber reinforcing parameter. The RI has been used to model FRCC behaviour by various research groups (Bencardino et al. 2008; Ezeldin and Balaguru 1992; Hsu and Hsu 1994; Mansur et al. 1999; Nataraja et al. 1999; Ou et al. 2011). However, since most investigations focused on one steel fiber type or didn't draw comparison between straight fibers and hooked fibers directly, the existing RI definition did not consider different fiber types. Shi et al. (2020) suggested a modified reinforcing index by including the shape factor for different fiber type. The equation to calculate the modified reinforcing index is shown in Eq. (3-1):

$$RI = \xi \frac{l}{d} V_f \tag{3-1}$$

RI= reinforcing index
ξ= shape factor
l= fiber length
d=fiber diameter
V_f= fiber volume contention

According to Shi et al. (2020), the shape factor of straight fibers is 0.733 in tension and 0.705 in compression. The shape factor of steel hooked fibers is defined to be 1.0.

3.3 Meta-Analysis Results

The collected stress-strain curves were digitized using and the values of the parameters in Figures 3-1 and 3-2 were obtained from the digitized data. Table 3-1 shows the part of the spreadsheet containing the collected data.

In general, the compressive strength of cementitious materials is controlled by water-cement ratio, i.e., the composites with low water-cement ratio have high compressive strength. On the other hand, the tensile strength of ECC can be controlled by various factors such as tensile strength of matrix, chemical/frictional bonding at fiber-matrix interface, fiber strength, and fiber contents. In case of ECC, the fiber volume content and fiber type are almost fixed, it would be interesting to see the relation between compressive strength and tensile strength of ECC. Figure 3-3 shows the correlation between the compressive strength (f_{cc} in Figure 3-2) and tensile strength ($\alpha_t f_{ct}$ in

Figure 3-1) of ECC as obtained by various investigators. A weak correlation between these two properties is observed, and the scattering of the data is wide. Figure 3-4 – 3-13 shows the variations of the parameters with respect to the RI.

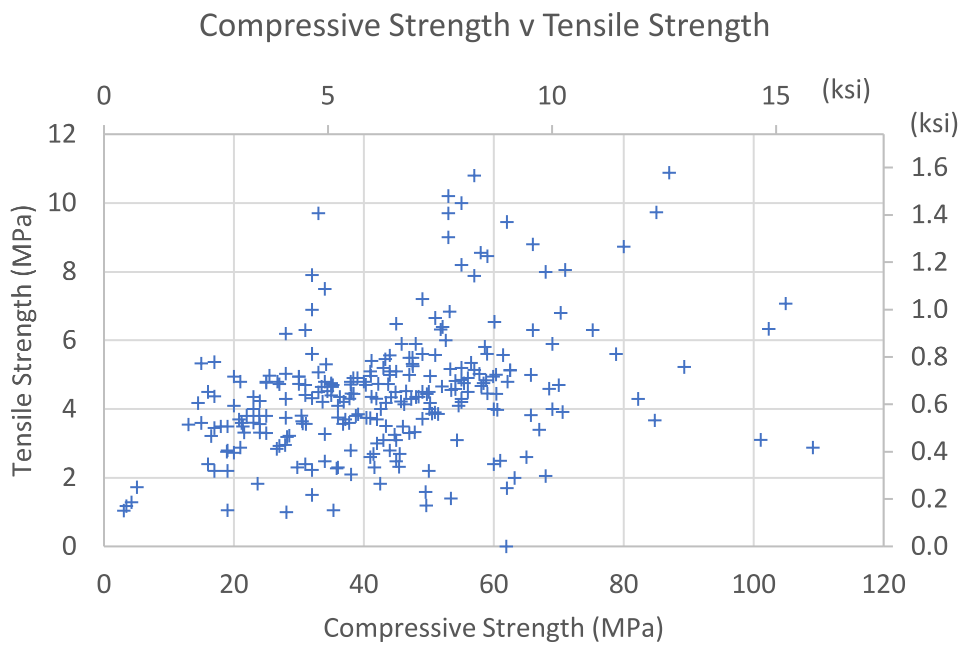

Figure 3-3 Correlation between Compressive Strength and Tensile Strength of ECC

Table 3-1. Collected Stress-Strain Data (a part of the collected data)

					Fiber Properties														RI	RI	Specimen				Stress						Strain				Normalized parameters			
Paper - Author	Type of Testing	Mixture		Specimen	Fiber Volume	Type of Fiber	Shape Factor	Length		Diameter		E		fc		ft		Elongation	L/D	RI	Fc		Ft		irst pea	Unit	cond pe	Unit	failure	Unit	First peak	Second peak	failure	Notes	α_t	β_t	γ_t	δ_t
2009 - Li et al	Uniaxial Tension Test	Mix I	Line 1	Plate (28 days)	2%	PVA Fiber	0.733	12	mm	40	μm	40 Gpa	GPa	1600	MPa			6%	300	4.4					3.6578	MPa	4.313	MPa	3.217	MPa	0.0017	0.0135	0.0140		1.18	0.88	8.19	8.48
			Line 2		2%		0.733	12		40				1600	MPa				300	4.4					4.22	MPa	4.6079	MPa	2.537	MPa	0.0027	0.0070	0.0097		1.09	0.60	2.60	3.59
			Line 3		2%		0.733	12		40				1600	MPa				300	4.4					3.96	MPa	4.587	MPa	3.271	MPa	0.0007	0.0067	0.0095		1.16	0.83	9.99	14.21
		Mix II	Line 1	Plate (28 days)	2%	PVA Fiber	0.733	12		40				1600	MPa				300	4.4					3.48	MPa	4.59	MPa	0	MPa	0.0056	0.0484	0.0572		1.32	0.00	8.70	10.27
			Line 2		2%		0.733	12		40				1600	MPa				300	4.4					3.67	MPa	4.47	MPa	3.61	MPa	0.0009	0.0380	0.0403		1.22	0.98	43.62	46.32
			Line 3		2%		0.733	12		40				1600	MPa				300	4.4					3.4	MPa	5.163	MPa	0.018	MPa	0.0007	0.0477	0.0564		1.52	0.01	64.63	76.42
2009 - Sahmaran and Li	Direct Uniaxial Tension Test for the ECC mixtures under different exposure conditions	ECC 1 pre-loading to 1.5 % tensile strain	Loading up to failure	Coupon	2%	PVA Fiber	0.733	8	mm	39	μm	42.8 GPa				1620	MPa	6%	205.1	3.01					4.388	MPa	5.3627	MPa	4.491	MPa	0.0016	0.0237	0.0396		1.22	1.02	15.03	25.10
			Pre-loading 1.5% at 28 days		2%		0.733												205.1	3.01					4.7	MPa	5.097	MPa	4.718	MPa	0.0019	0.0133	0.0143		1.08	1.00	6.87	7.40
			Reloading after preloading 1.5% at 28 days		2%		0.733												205.1	3.01					4.0291	Mpa	4.029	MPA	3.2887	Mpa	0.0077	0.0077	0.0199		1.00	0.82	1.00	2.59
			Reloading after 30 days in NaCl Solution		2%		0.733												205.1	3.01					3.6739	MPa	4.75	MPa	3.009	MPa	0.0040	0.0357	0.0394		1.29	0.82	8.90	9.83
			Reloading after 90 days in NaCl Solution		2%		0.733												205.1	3.01					3.9	MPA	4.809	MPa	3.7035	Mpa	0.0051	0.0282	0.0357		1.23	0.95	5.49	6.94
			Reloading after 180 days in NaCl Solution		2%		0.733												205.1	3.01					3.901	Mpa	4.8	MPA	3.68	Mpa	0.0036	0.0193	0.0244		1.23	0.94	5.41	6.86
		ECC 2 pre-loading to 2.5% tensile strain	Loading up to failure		2%		0.733												205.1	3.01					4.4358	MPa	4.6342	MPa	4.22568	MPa	0.0035	0.0369	0.0403		1.04	0.95	10.44	11.40
			Pre-loading 2.5% at 28 days		2%		0.733												205.1	3.01					4.167	MPa	4.4125	MPa	4.36576	MPa	0.0052	0.0195	0.0252		1.06	1.05	3.74	4.82
			Reloading after preloading 2.5% at 28 days		2%		0.733												205.1	3.01					3.571	MPA	4.0739	Mpa	3.73	MPa	0.0153	0.0351	0.0392		1.14	1.04	2.30	2.57
			Reloading after 30 days in NaCl Solution		2%		0.733												205.1	3.01					3.572	MPa	4.07	MPa	3.73541	Mpa	0.0153	0.0351	0.0392		1.14	1.05	2.30	2.57
			Reloading after 90 days in NaCl Solution		2%		0.733												205.1	3.01					3.9455	MPa	4.1556	MPa	3.23346	Mpa	0.0170	0.0272	0.0378		1.05	0.82	1.60	2.23
			Reloading after 180 days in NaCl Solution		2%		0.733												205.1	3.01					3.3269	Mpa	4.0623	MPa	2.17121	MPa	0.0088	0.0268	0.0355		1.22	0.65	3.06	4.05
		ECC 1 (M45) preloading to 2% tensile strain	Loading after (28+30 days in air)		2%		0.733												205.1	3.01					4.35	Mpa	4.83	Mpa	3.78	Mpa	0.0036	0.0287	0.0370		1.11	0.87	8.01	10.33
			Loading after (28+90 days in air)		2%		0.733												205.1	3.01					4.47	MPa	4.69	Mpa	3.417	MPa	0.0038	0.0279	0.0347		1.05	0.76	7.38	9.18
			eloading after (28 days in air + 30 days in NaOH		2%		0.733												205.1	3.01					4.11	MPa	4.44	MPa	1.978	MPa	0.0108	0.0180	0.0301		1.08	0.48	1.67	2.79
			eloading after (28 days in air + 90 days in NaOH		2%		0.733												205.1	3.01					3.73	MPa	4.35	Mpa	3.18519	MPa	0.0084	0.0234	0.0288		1.17	0.85	2.80	3.45
		ECC 1 (M45)	Preloading 1.0% at 28 days		2%		0.733							7d - 38.1	Mpa				205.1	3.01					4.07	MPa	4.27	MPa	4.27%	MPa	0.0031	0.0107	0.0107		1.05	0.01	3.49	3.49
			Preloading 2.0% at 28 days		2%		0.733							28d - 50.2	Mpa				205.1	3.01					4.26	MPa	4.571	MPa	4.55	MPA	0.0031	0.0146	0.0201		1.07	1.07	4.76	6.55
			Loading up to failure at 28 days		2%		0.733							90d - 54.4	Mpa				205.1	3.01					4.736	Mpa	5.03	Mpa	4.31	Mpa	0.0032	0.0250	0.0326		1.06	0.91	7.82	10.22
			Reloading after preloading 1%		2%		0.733												205.1	3.01					4.57	Mpa	4.6	Mpa	2.48	MPA	0.0119	0.0156	0.0262		1.01	0.54	1.31	2.21
			Reloading after preloading 2%		2%		0.733												205.1	3.01					4.34	MPA	4.34	MPa	3.63	MPA	0.0105	0.0105	0.0171		1.00	0.84	1.00	1.63
		ECC2 (M45)	Preloading 1.0% at 28 days		2%		0.733							7d - 21.6	Mpa				205.1	3.01					3.9	MPa	4.03	MPA	4.03	MPa	0.0054	0.0100	0.0100		1.03	1.03	1.84	1.84
			Preloading 2.0% at 28 days		2%		0.733							28d - 36.3	Mpa				205.1	3.01					3.9953	Mpa	3.995	Mpa	3.81	Mpa	0.0041	0.0041	0.0201		1.00	0.95	1.00	4.90
			Loading up to failure at 28 days		2%		0.733							90d - 41.9	Mpa				205.1	3.01					3.927	Mpa	4.81	MPa	4.16	Mpa	0.0043	0.0367	0.0395		1.22	1.06	8.60	9.26
			Reloading after preloading 1%		2%		0.733												205.1	3.01					4.11	MPA	4.11	Mpa	3.18	Mpa	0.0153	0.0153	0.0366		1.00	0.77	1.00	2.39
			Reloading after preloading 2%		2%		0.733												205.1	3.01					3.76	Mpa	4.07	MPA	3.08438	MPa	0.0054	0.0232	0.0273		1.08	0.82	4.28	5.04
2009 - Yang et al	Uniaxial Tension Test	Preloading and reloading after 10CR1 (water/air) Specimen with preloading to above 1%	Preloading 3%	Mortar Coupon	2%	REC-15 PVA fibers	0.733	12	mm	40									300	4.4					3.6809	MPa	4.27	MPa	4.18202	Mpa	0.0012	0.0232	0.0305		1.16	1.14	18.71	24.56
			Reloading after preloading 3%		2%		0.733			40									300	4.4					2.2	MPA	3.905	MPa	2.601	MPa	0.0012	0.0167	0.0224		1.78	1.18	14.51	19.47
			Preloading 2%		2%		0.733			40									300	4.4					4.31	Mpa	4.4	Mpa	4.4	MPa	0.0012	0.0203	0.0203		1.02	1.02	16.67	16.67
			Reloading after preloading 2%		2%		0.733			40									300	4.4					3.972	Mpa	4.4694	Mpa	3.5	Mpa	0.0073	0.0299	0.0296		1.13	0.88	4.08	4.04
		Preloading and reloading after 10CR1 (water/air)Specimens with preloading with to 1% or below	Preloading 1%		2%		0.733			40									300	4.4					3.4274	Mpa	4.0369	MPa	3.45371	Mpa	0.0007	0.0090	0.0095		1.18	1.01	12.98	13.67
			Reloading after preloading 1%		2%		0.733			40									300	4.4					3.3145	MPa	4.0895	Mpa	3.1076	Mpa	0.0052	0.0187	0.0284		1.23	0.94	3.58	5.42
			Preloading 0.5%		2%		0.733			40									300	4.4					3.5929	MPa	4.2363	MPa	4.23627	Mpa	0.0007	0.0052	0.0052		1.18	1.18	7.42	7.42
			Reloading after preloading 0.5%		2%		0.733			40									300	4.4					3.1565	Mpa	4.1573	Mpa	2.82543	Mpa	0.0025	0.0299	0.0336		1.32	0.90	12.13	13.65
		preloading and reloading after 10 CR2 (water/hot air)Specimen with preloading to above 1%	Preloading 3%		2%		0.733			40									300	4.4					3.6313	Mpa	3.9761	MPA	3.97612	MPa	0.0011	0.0311	0.0311		1.09	1.09	28.13	28.13
			Reloading after preloading 3%		2%		0.733			40									300	4.4					2.6821	MPa	5.1179	Mpa	1.75522	Mpa	0.0013	0.0211	0.0216		1.91	0.65	16.61	16.94
			Preloading 2%		2%		0.733			40									300	4.4					3.6985	MPa	4.1015	Mpa	4.08358	Mpa	0.0015	0.0102	0.0203		1.11	1.10	6.96	13.89
			Reloading after preloading 2%		2%		0.733			40									300	4.4					2.9687	MPA	5.297	MPa	1.99701	MPa	0.0025	0.0136	0.0182		1.78	0.67	5.45	7.29
		preloading and reloading after 10 CR2 (water/hot air) Specimen with preloading to 1% or below	Preloading 1%		2%		0.733			40									300	4.4					4.7295	MPa	4.729	Mpa	4.19	Mpa	0.0020	0.0020	0.0210		1.00	0.89	0.99	10.36
			Reloading after preloading 1%		2%		0.733			40									300	4.4					4.1653	Mpa	4.4096	MPa	2.53693	MPa	0.0082	0.0133	0.0302		1.06	0.61	1.63	3.69
			Preloading 0.5%		2%		0.733			40									300	4.4					3.8381	MPa	4.4421	MPa	4.2758	Mpa	0.0020	0.0111	0.0115		1.16	1.11	5.56	5.77
			Reloading after preloading 0.5%		2%		0.733			40									300	4.4					4.6457	Mpa	4.8114	Mpa	3.21653	MPa	0.0079	0.0135	0.0248		1.04	0.69	1.70	3.13
		Self-healing Tensile stress strain curve of ECC	Pre-loading		2%		0.733			40									300	4.4					3.7522	Mpa	4.3628	Mpa	4.30088	MPa	0.0010	0.0288	0.0299		1.16	1.15	28.40	29.55
			Reloading		2%		0.733			40									300	4.4					3.9646	MPa	4.92	Mpa	4.46903	Mpa	0.0139	0.0378	0.0382		1.24	1.13	2.71	2.74
2009 - Yu and Li	Direct Tension Test		Line 1		2%	igh Modulus PVA Fibe	0.733	12	mm	40									300	4.4					4.2903	Mpa	5.2437	MPa	2.75986	Mpa	0.0018	0.0118	0.0327		1.22	0.64	6.57	18.29
			Line 2		2%		0.733	12		40									300	4.4					4.5914	Mpa	4.5914	Mpa	2.9355	Mpa	0.0010	0.0010	0.0217		1.00	0.64	1.00	21.25
			Line 3		2%		0.733	12		40									300	4.4					5.2437	Mpa	6.147	MPa	2.6595	Mpa	0.0020	0.0542	0.0567		1.17	0.51	26.50	27.75
2010 - Zhou et al	Uniaxial Tension Test		Line 1	Prism	2%	PVA Fiber	0.733	8	mm	40	μm					1600	Mpa		200	2.93					3.0865	MPa	4.2077	Mpa	3.45592	Mpa	0.0005	0.0304	0.0345		1.36	1.12	62.31	70.85
			Line 2		2%		0.733	8		40									200	2.93					2.81	Mpa	3.7188	Mpa	2.6296	Mpa	0.0004	0.0248	0.0353		1.32	0.94	55.08	78.42
			Line 3		2%		0.733	8		40									200	2.93					3.283	Mpa	3.7396	Mpa	2.68293	Mpa	0.0016	0.0280	0.0370		1.14	0.82	17.38	22.96
			Line 4		2%		0.733	8		40									200	2.93					2.81	Mpa	3.7576	Mpa	3.08709	Mpa	0.0006	0.0276	0.0370		1.34	1.10	43.81	58.73
			Line 5		2%		0.733	8		40									200	2.93					3.2329	Mpa	3.698	Mpa	2.9878	Mpa	0.0014	0.0205	0.0322		1.14	0.92	14.41	22.63
2011 - Li and Li	Uniaxial Tension Test	Not Preloaded	Not Preloaded 28 days		2%	PVA Fiber	0.733	8	mm	39	μm	42.8	GPa					6%	205.1	3.01					4.5632	Mpa	5.396	Mpa	4.539	Mpa	0.0018	0.0239	0.0394		1.18	0.99	13.50	22.29
			Loaded after 30 days in NaCl Solution		2%		0.733	8		39									205.1	3.01					3.2	MPa	4.38	Mpa	2.1014	Mpa	0.0006	0.0290	0.0345		1.37	0.66	52.04	61.82
			Loaded after 60 days in NaCl Solution		2%		0.733	8		39									205.1	3.01					3.6786	Mpa	4.6896	MPa	3.75351	Mpa	0.0024	0.0297	0.0340		1.27	1.02	12.46	14.24
			Loaded after 90 days in NaCl Solution		2%		0.733	8		39									205.1	3.01					3.3417	Mpa	4.8	Mpa	4.48362	Mpa	0.0012	0.0319	0.0334		1.44	1.34	27.03	28.27
		Preloaded to 0.5% tensile strain	Not Preloaded 28 days		2%		0.733	8		39									205.1	3.01					4.553	MPa	5.342	Mpa	4.478	MPa	0.0014	0.0240	0.0396		1.17	0.98	16.95	27.95
			Preloaded 0.5% 28 days		2%		0.733	8		39									205.1	3.01					3.71	MPa	4.7	Mpa	4.529	MPa	0.0015	0.0052	0.0060		1.27	1.22	3.45	3.92
			Reloaded after 30 days in NaCl Solution		2%		0.733	8		39									205.1	3.01					3.366	Mpa	4.94	Mpa	4.21	MPa	0.0018	0.0370	0.0412		1.47	1.25	20.50	22.85
			Reloaded after 60 days in NaCl Solution		2%		0.733	8		39									205.1	3.01					3.1542	Mpa	4.4549	MPa	1.85197	Mpa	0.0019	0.0253	0.0341		1.41	0.59	13.23	17.84
			Reloaded after 90 days in NaCl Solution		2%		0.733	8		39									205.1	3.01					3.67	Mpa	4.73	Mpa	2.032	Mpa	0.0019	0.0255	0.0336		1.29	0.55	13.81	18.15
			Reloaded 1 day after preloading		2%		0.733	8		39									205.1	3.01					3.808	Mpa	4.039	Mpa	3.26	Mpa	0.0063	0.0085	0.0198		1.06	0.86	1.34	3.13
		Preloaded to 1.0% tensile strain	Not Preloaded 28 days		2%		0.733	8		39									205.1	3.01					4.557	Mpa	5.335	MPa	4.5	MPa	0.0014	0.0240	0.0393		1.17	0.99	16.94	27.76
			Preloaded 1.0% 28 days		2%		0.733	8		39									205.1	3.01					3.7603	Mpa	4.51	Mpa	4.46107	Mpa	0.0008	0.0067	0.0106		1.20	1.19	8.44	13.21
			Reloaded after 30 days in NaCl Solution		2%		0.733	8		39									205.1	3.01					2.48	MPa	3.94	Mpa	2.74809	Mpa	0.0009	0.0191	0.0373		1.59	1.11	21.89	42.73
			Reloaded after 60 days in NaCl Solution		2%		0.733	8		39									205.1	3.01					3.33	Mpa	4.447	Mpa	3.43053	MPa	0.0028	0.0351	0.0410		1.34	1.03	12.49	14.60
			Reloaded after 90 days in NaCl Solution		2%		0.733	8		39									205.1	3.01					3.5542	Mpa	3.885	Mpa	2.38	Mpa	0.0050	0.0252	0.0306		1.09	0.67	5.07	6.17
			Reloaded 1 day after preloading		2%		0.733	8		39									205.1	3.01					3.7557	Mpa	4.0122	Mppa	3.274	Mpa	0.0061	0.0083	0.0197		1.07	0.87	1.36	3.23
		Preloaded to 1.5% tensile strain	Not Preloaded 28 days		2%		0.733	8		39									205.1	3.01					4.53	Mpa	5.34	Mpa	4.48	Mpa	0.0014	0.0241	0.0395		1.18	0.99	16.67	27.34
			Preloaded 1.5% 28 days		2%		0.733	8		39									205.1	3.01					4.367	Mpa	5.0766	Mpa	4.7165	Mpa	0.0014	0.0132	0.0142		1.16	1.08	9.56	10.26
			Reloaded after 30 days in NaCl Solution		2%		0.733	8		39									205.1	3.01					3.25	Mpa	4.726	Mpa	2.988	Mpa	0.0023	0.0356	0.0393		1.45	0.92	15.70	17.32
			Reloaded after 60 days in NaCl Solution		2%		0.733	8		39									205.1	3.01					3.974	MPa	4.87	Mpa	1.59	Mpa	0.0050	0.0272	0.0345		1.23	0.40	5.49	6.97
			Reloaded after 90 days in NaCl Solution		2%		0.733	8		39									205.1	3.01					3.915	MPa	4.77	Mpa	3.685	Mpa	0.0049	0.0282	0.0356		1.22	0.94	5.77	7.30
			Reloaded 1 day after preloading		2%		0.733	8		39									205.1	3.01					3.8787	Mpa	4.019	Mpa	3.297	Mpa	0.0068	0.0086	0.0199		1.04	0.85	1.26	2.91
2011 - Sahmaran et al		ECC 1 (M45)	With PVA	200 X 75 X 13 mm coupon	2%	PVA Fiber	0.733	12	mm	39	μm	42.8	GPa			1600	MPa		307.7	4.51	63	Mpa			3.9645	Mpa	5.4671	Mpa	3.58	Mpa	0.0006	0.0211	0.0260		1.38	0.90	33.50	41.28
			Without PVA		2%		0.733	12		39									307.7	4.51	60	MPa			4.29	Mpa	5.5	Mpa	3.76	Mpa	0.0022	0.0159	0.0249		1.28	0.88	7.36	11.53
		ECC 2 (M45)	With PVA		2%		0.733	12		39									307.7	4.51	54	MPa			3.68	Mpa	4.767	Mpa	3.997	Mpa	0.1705	0.0313	0.0323		1.30	1.09	0.18	0.19
			Without PVA		2%		0.733	12		39									307.7	4.51	52	MPa			4.166	Mpa	4.75	Mpa	2.57	Mpa	0.0016	0.0275	0.0330		1.14	0.62	16.86	20.23
2012 - Yao et al	Direct Tension Test	ECC with 50% FA	ECC1-0	Dog bone coupon	2%	PVA Fiber	0.733	8	mm	40		42	GPa			1600	Mpa	7%	200	2.93					4.95	Mpa	5.476	Mpa	4.62	Mpa	0.0014	0.0082	0.0239		1.11	0.93	5.91	17.16
			ECC1-0.2		2%		0.733	8		40									200	2.93					4.83	Mpa	5.14	Mpa	4.722	Mpa	0.0015	0.0249	0.0310		1.06	0.98	16.81	20.93
			ECC1-0.4		2%		0.733	8		40									200	2.93					4.429	Mpa	4.71	Mpa	4.359	Mpa	0.0023	0.0139	0.0323		1.06	0.98	5.92	13.75
		ECC wiith 70% FA	ECC1-0		2%		0.733	8		40									200	2.93					3.439	Mpa	4.96	Mpa	4.07	Mpa	0.0013	0.0249	0.0278		1.44	1.18	19.89	22.24
			ECC1-0.2		2%		0.733	8		40									200	2.93					3.228	Mpa	4.69	Mpa	3.963	Mpa	0.0017	0.0310	0.0345		1.45	1.23	18.34	20.41
			ECC1-0.4		2%		0.733	8		40									200	2.93					2.974	Mpa	4.11	Mpa	3.49	Mpa	0.0026	0.0295	0.0394		1.38	1.17	11.42	15.27
2012 - Zhou et al	Uniaxial Tension Test	M mixes at 28 days	M1		2%	PVA Fiber	0.733	8		39						1600	Mpa		205.1	3.01					2.491	Mpa	3.46	Mpa	1.199	Mpa	0.0010	0.0126	0.0242		1.39	0.48	13.19	25.34
			M2		2%		0.733	8		39									205.1	3.01					2.614	MPa	2.614	Mpa	1.565	Mpa	0.0003	0.0003	0.0212		1.00	0.60	0.96	67.73
			M1A		2%		0.733	8		39									205.1	3.01					2.621	Mpa	3.813	Mpa	2.549	Mpa	0.0005	0.0224	0.0332		1.45	0.97	43.90	65.02
			M2A		2%		0.733	8		39									205.1	3.01					2.01	Mpa	2.98	Mpa	1.852	Mpa	0.0005	0.0121	0.0313		1.48	0.92	23.40	60.52
		S mixes at 28 days	S1		2%		0.733	8		39									205.1	3.01					3.452	Mpa	4.5	Mpa	3.794	Mpa	0.0009	0.0304	0.0416		1.30	1.10	34.98	47.81
			S2		2%		0.733	8		39									205.1	3.01					2.82	Mpa	3.102	Mpa	0.811	Mpa	0.0007	0.0039	0.0135		1.10	0.29	5.71	19.73
			S2A		2%		0.733	8		39									205.1	3.01					3.08	Mpa	3.668	Mpa	2.32	Mpa	0.0009	0.0204	0.0292		1.19	0.75	23.39	33.49

Figures 3-4 – 3-13 show the variations of the parameters defined in Figure 3-1 with RI. As shown on Equation 3-1, RI is the function of shape factor, fiber volume fraction, and aspect ratio of fibers (l/d). It should be noted that the shape and volume fraction of fibers vary only slightly in ECC (straight fibers with ~2% V_f), the x-axis in Figures 3-4 – 3-13 represents the influence of the aspect ratio.

Because of the almost constant fiber shape and volume fraction in the collected dataset, the analysis using RI only provides insight into the effects of fiber aspect ratio. On the other hand, numerous mixture designs of ECC were evaluated in the literature so the effects of mix design on ECC performance can be investigated. The mixture designs can be broadly classified into the mixes without fly ash and mixes containing pozzolanic fly ash (typically class F fly ash). Figures 3-14 through 3-19 show the variations of the parameters (defined in Figure 3-1) for ECC without fly ash, and Figure 3-20 through 3-37 show the variations of parameters for ECC containing class F fly ash.

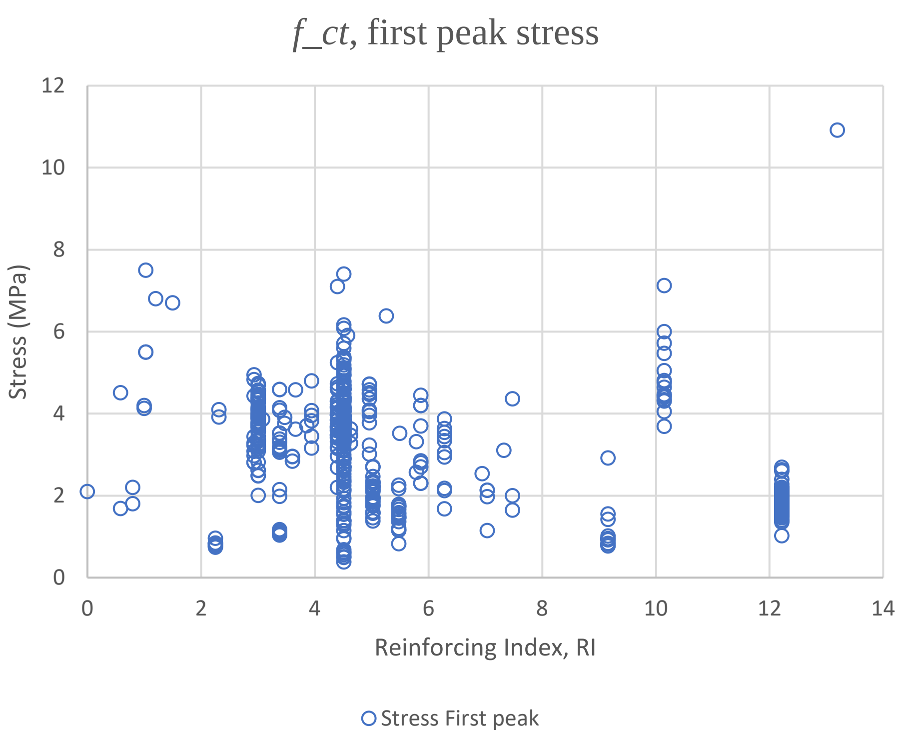

Figure 3-4 The First Peak Stress of ECC in Tension

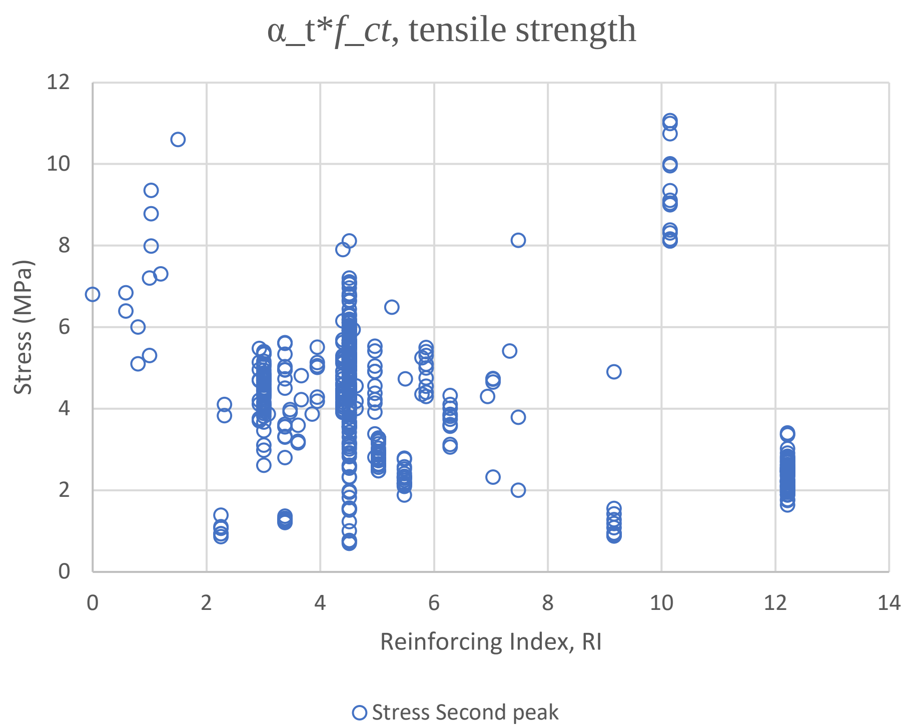

Figure 3-5 Tensile Strength of ECC in Tension

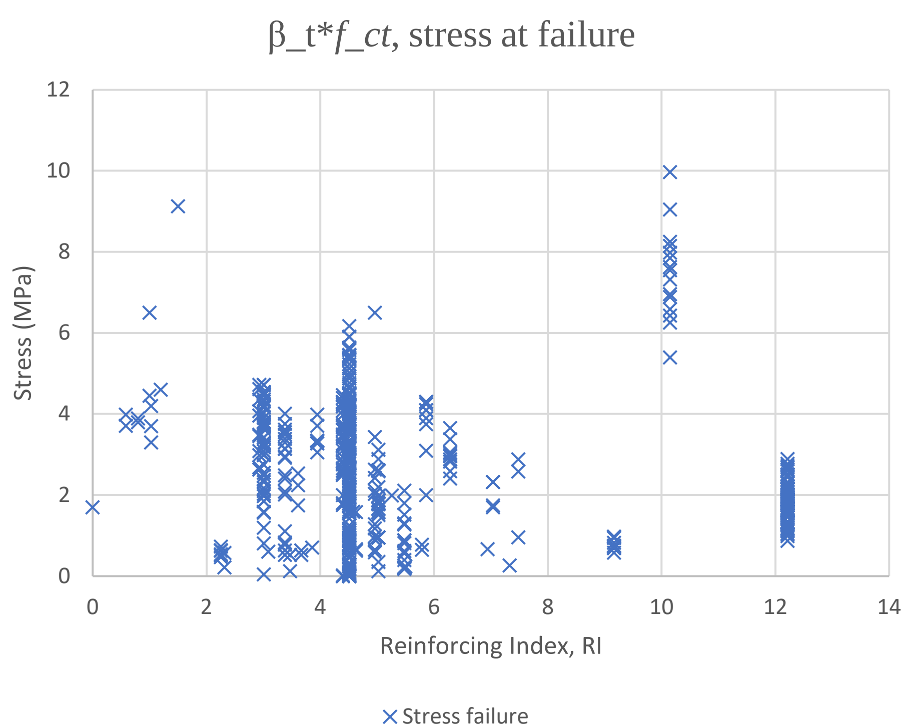

Figure 3-6 The Tensile Failure Stress of ECC

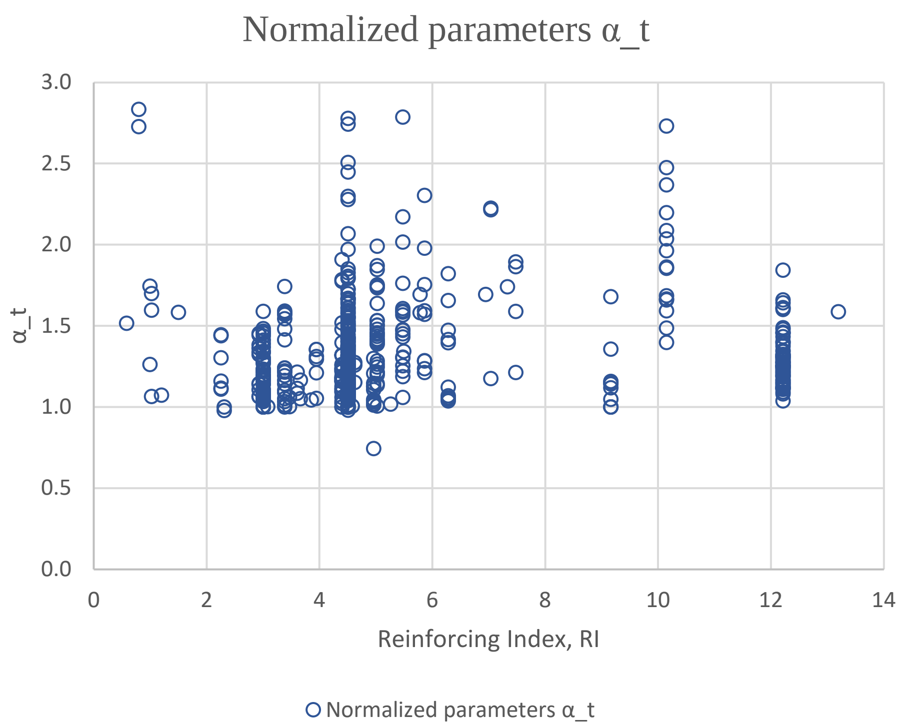

Figure 3-7 The Normalized Parameter α_t of ECC in Tension

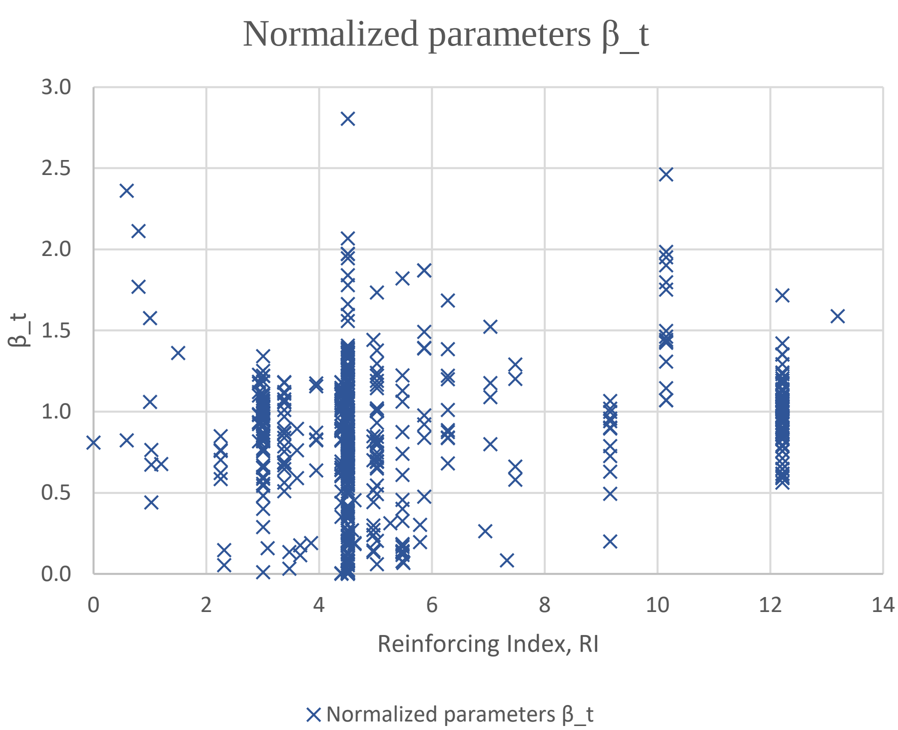

Figure 3-8 The Normalized Parameter β_t of ECC in Tension

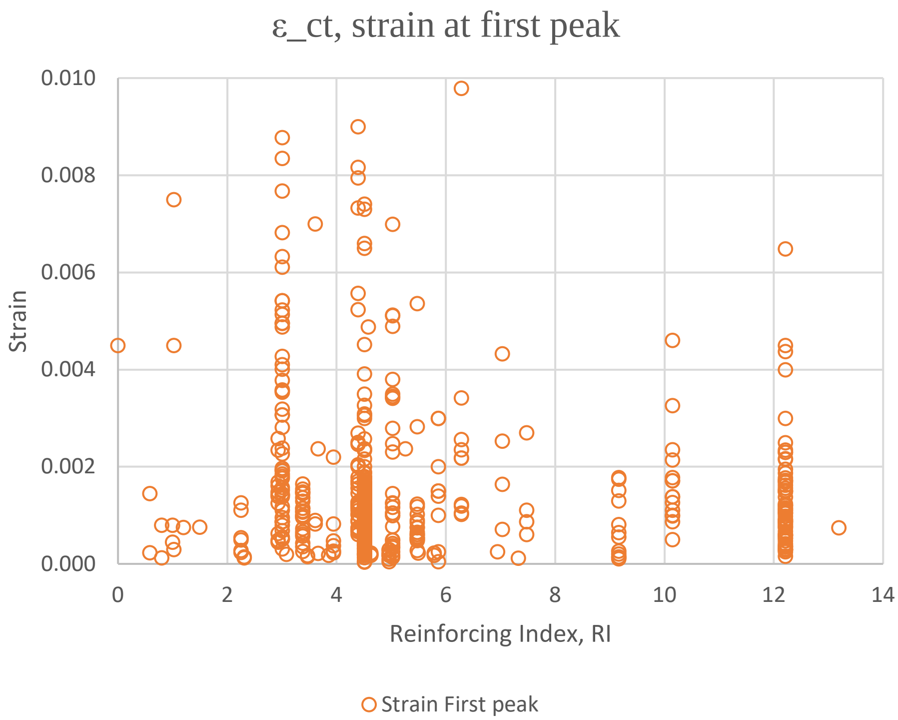

Figure 3-9 The Strain at First Peak Stress of ECC in Tension

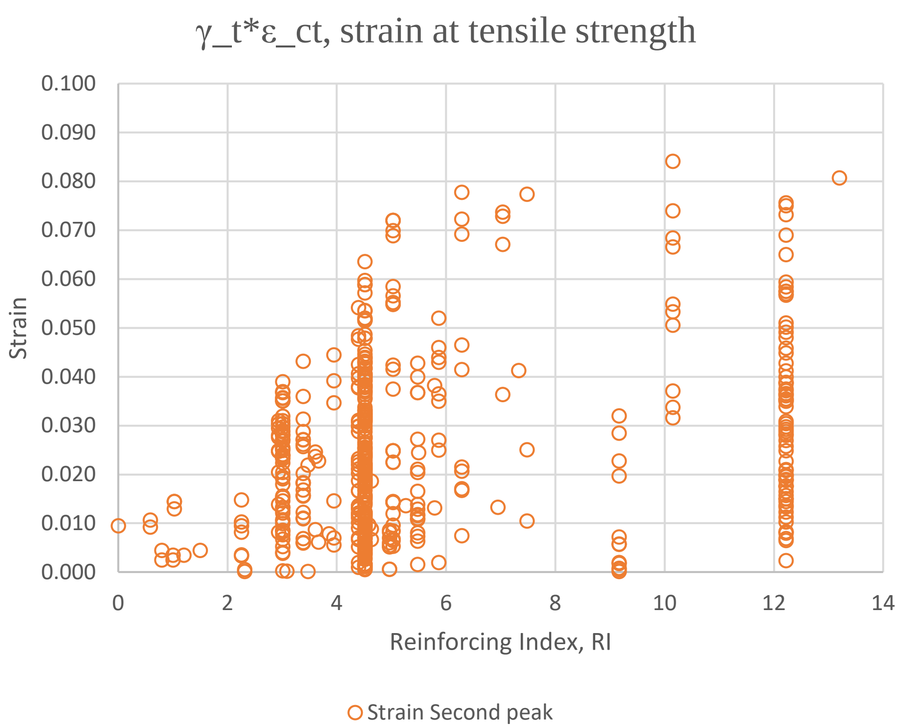

Figure 3-10 The Strain at Tensile Strength of ECC

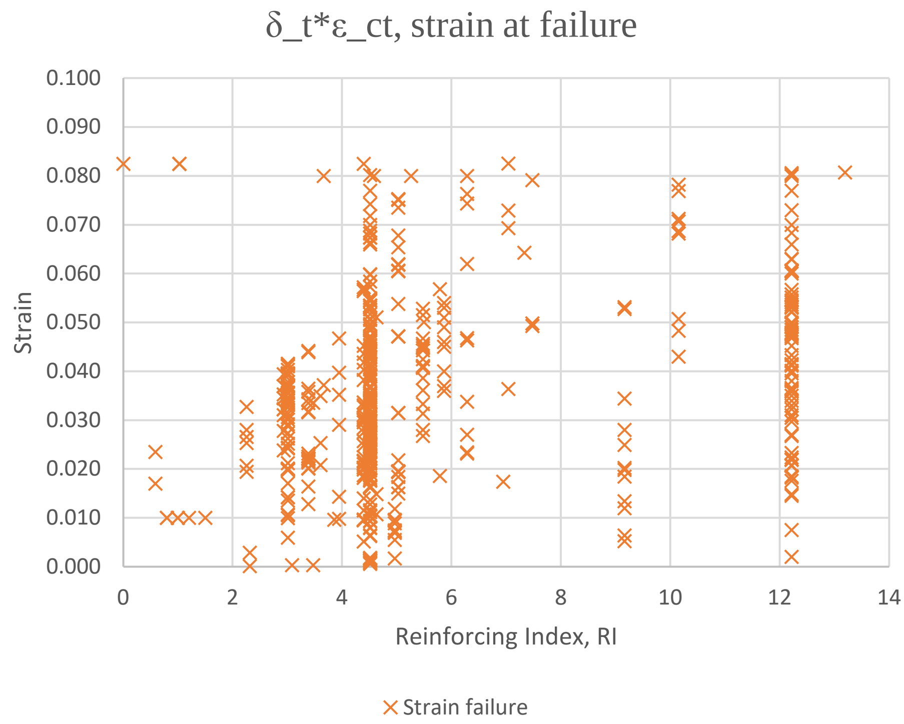

Figure 3-11 The Strain at Failure in Tension

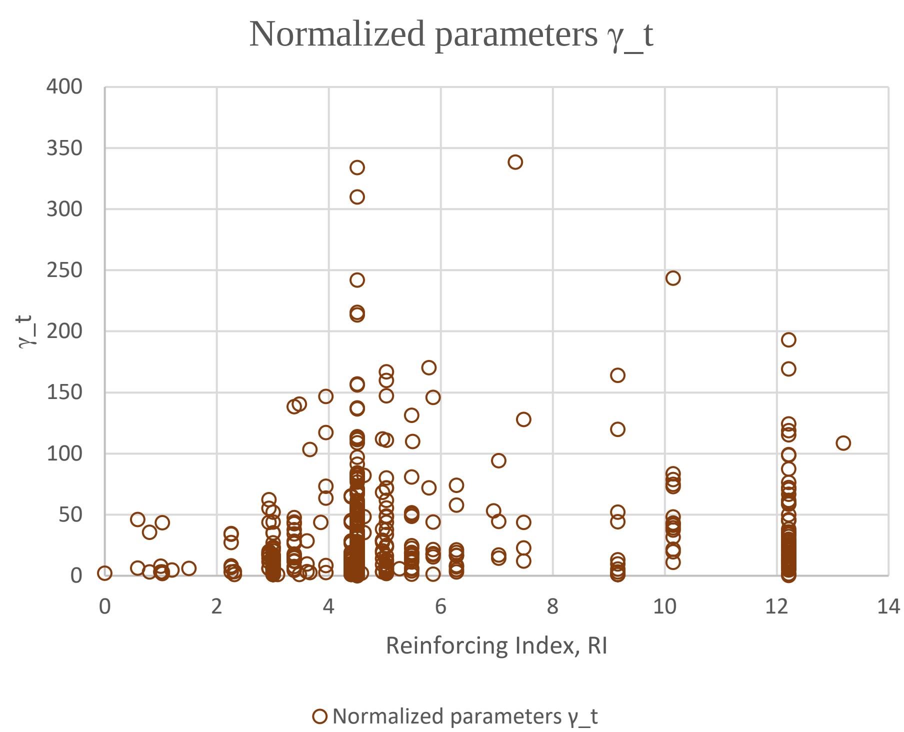

Figure 3-12 The Normalized Parameter γ_t of ECC in Tension

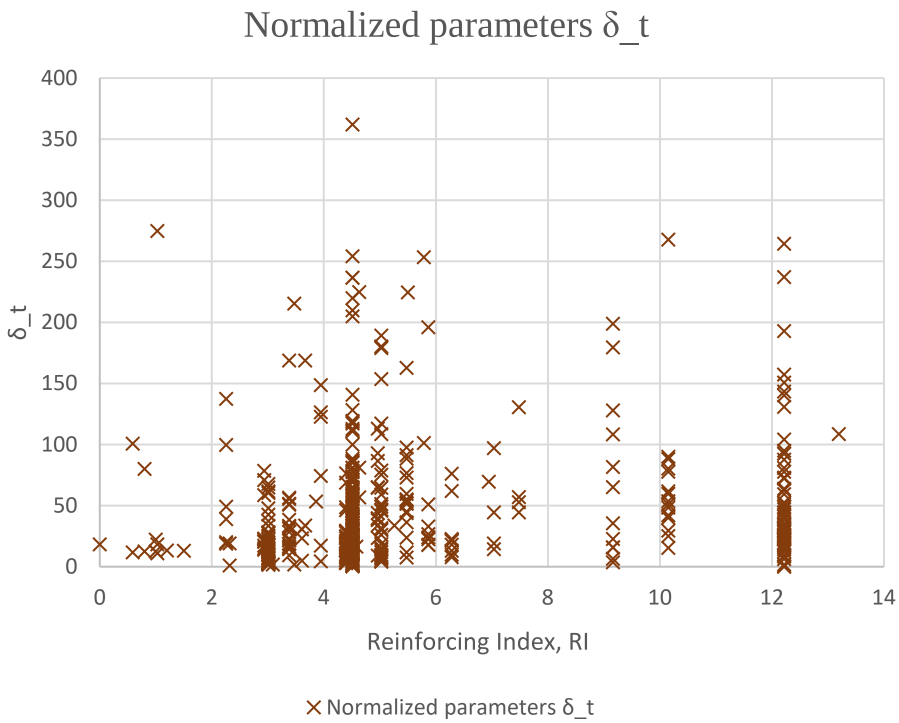

Figure 3-13 The Normalized Parameter δ_t of ECC in Tension

The ingredients of ECC without fly ash are cement, sand, water, and water reducing agent. In general, the strength of cementitious composites decreases with the increase of water cement ratio, W/C (W = weight of water and C = weight of cement). Figures 3-14 – 3-19 show the variations of the six parameters (f_{ct}, $\alpha_t f_{ct}$, $\beta_t f_{ct}$, ε_{ct}, $\gamma_t \varepsilon_{ct}$, and $\delta_t \varepsilon_{ct}$) of ECC without fly ash with varying water-cement ratios, and Figures 3-20 – 3-25 show the variations of the six parameters of ECC containing fly ash with varying water-cement ratios.

The ECC without fly ash was investigated in the earlier development stage of ECC, and hence, there is not much data on this type of ECC. Fly ash was added to reduce the volume of cement in ECC. Previous investigators recognized that adding fly ash improves ductility and fly ash became one of the basic ingredients in the current ECC mixture design.

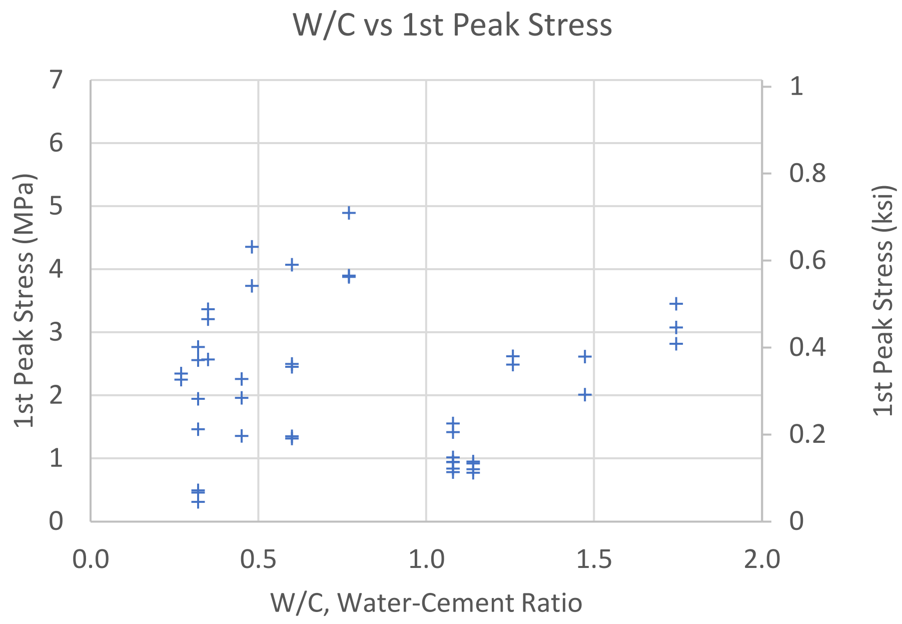

Figure 3-14 Variation of the 1st Peak Stress (f_{ct}) with Water Cement Ratio of ECC without Fly Ash

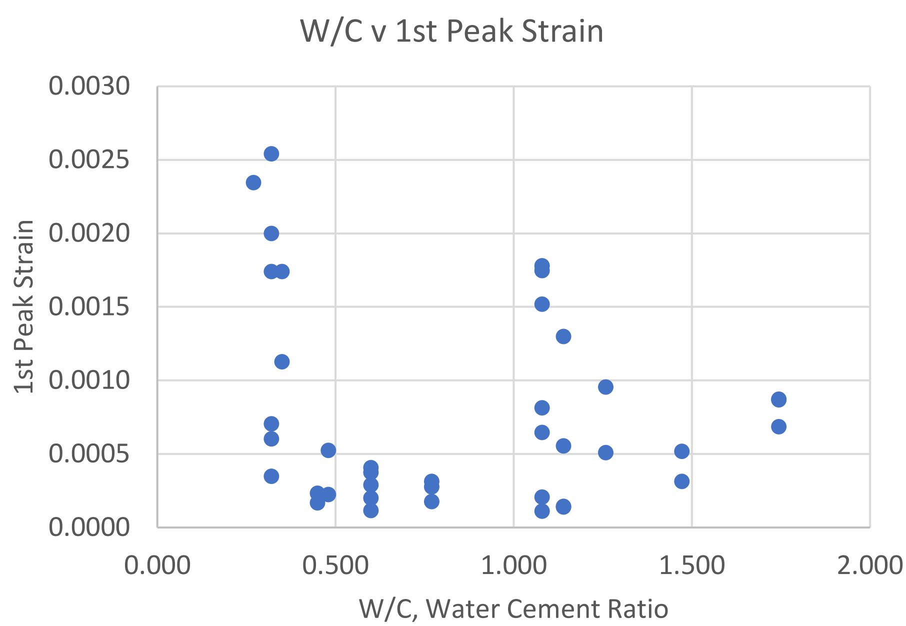

Figure 3-15 Variation of the 1st Peak Strain (ε_{ct}) with Water Cement Ratio of ECC without Fly Ash

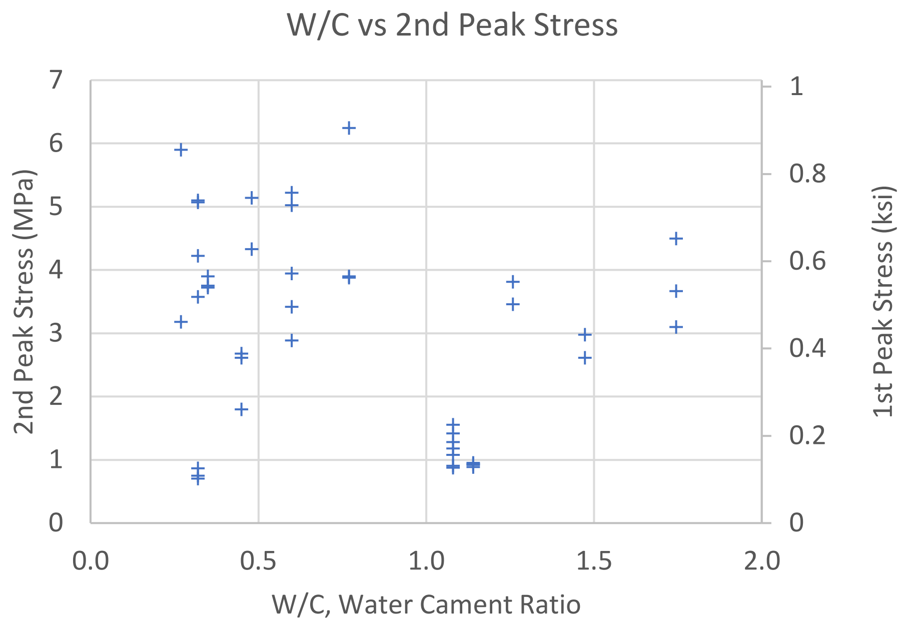

Figure 3-16 Variation of the 2nd Peak Stress ($\alpha_t f_{ct}$) with Water Cement Ratio of ECC without Fly Ash

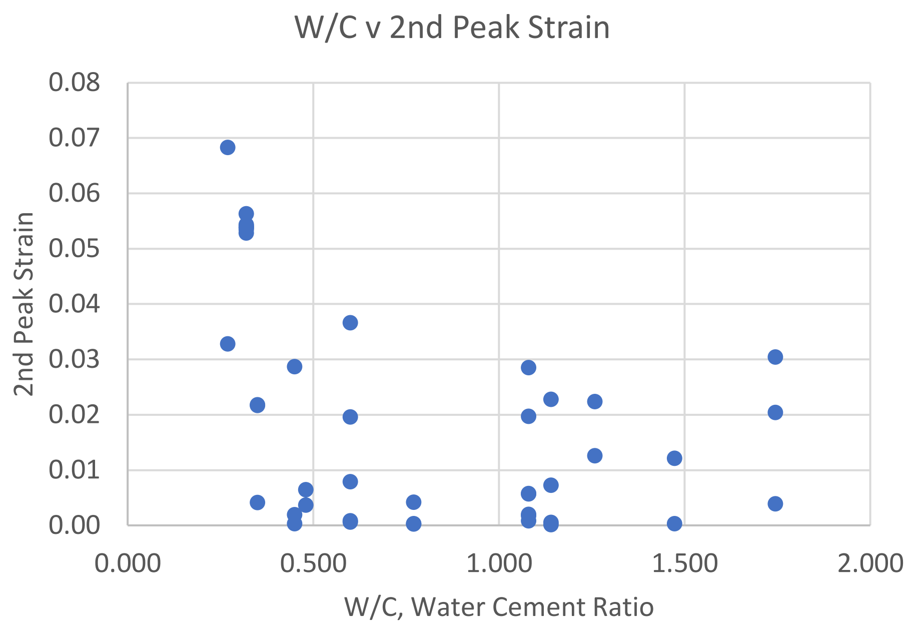

Figure 3-17 Variation of the 2nd Peak Strain ($\gamma_t \varepsilon_{ct}$) with Water Cement Ratio of ECC without Fly Ash

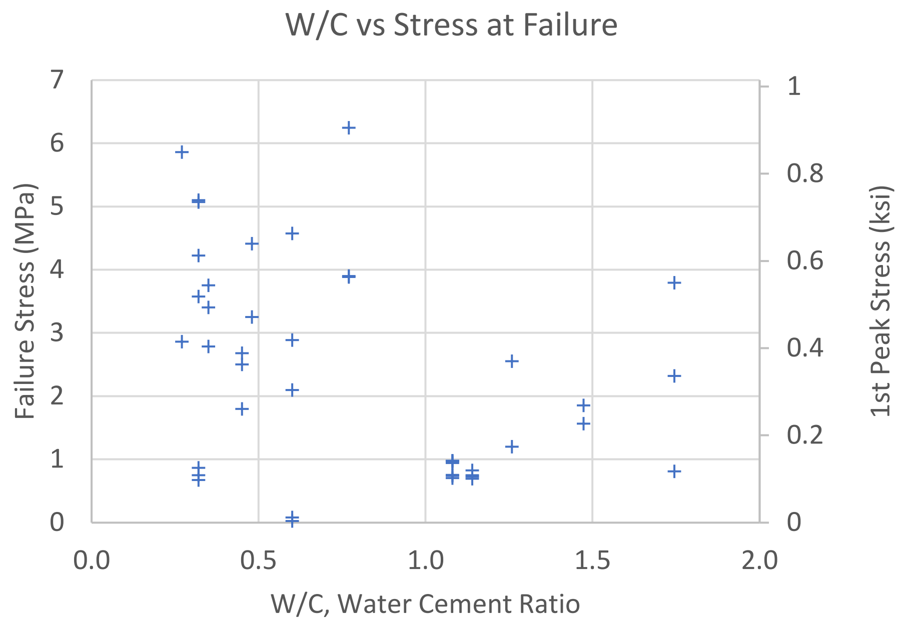

Figure 3-18 Variation of Failure Stress ($\beta_t f_{ct}$) with Water Cement Ratio of ECC without Fly Ash

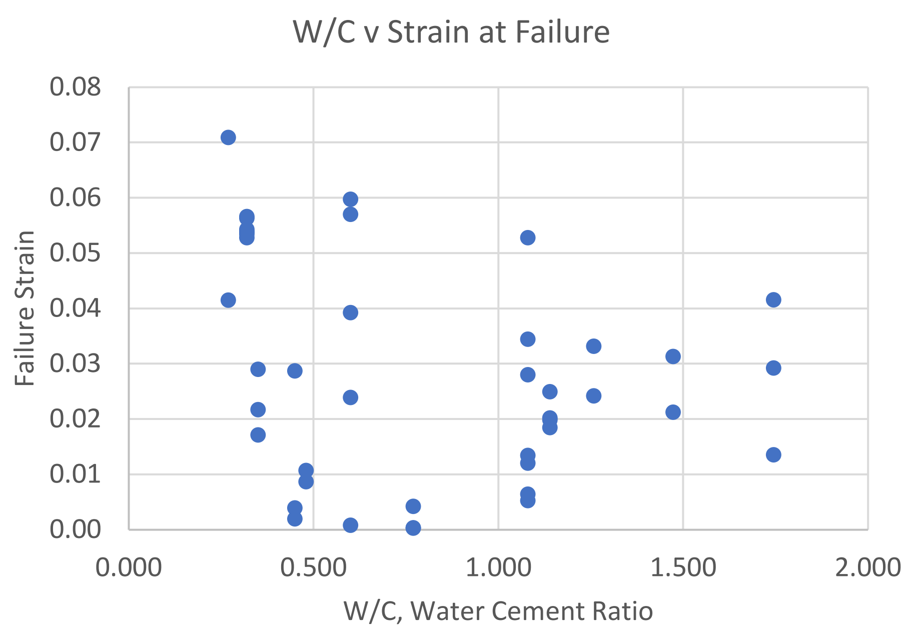

Figure 3-19 Variation of Failure Strain ($\delta_t \varepsilon_{ct}$) with Water Cement Ratio of ECC without Fly Ash

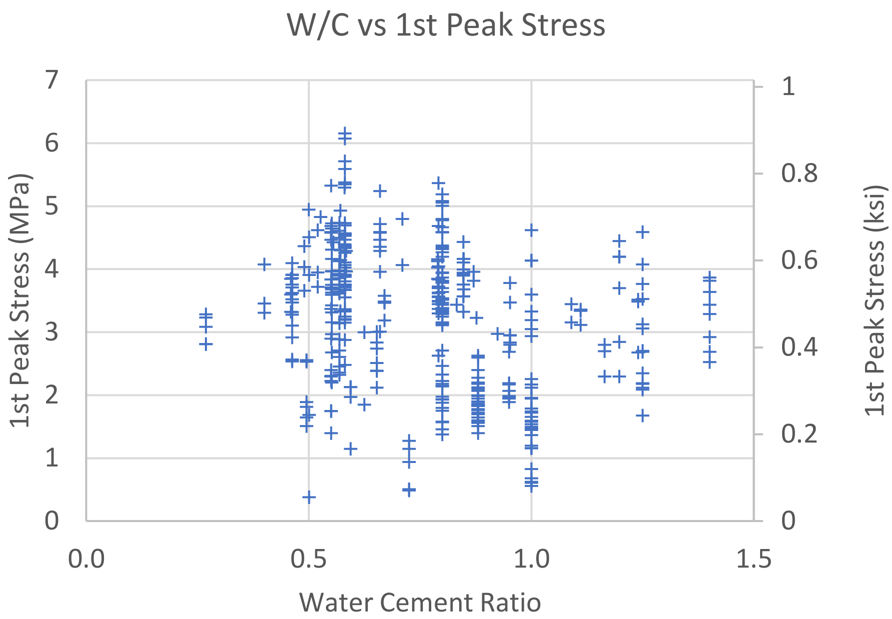

Figure 3-20 Variation of the 1st Peak Stress (f_{ct}) with Water Cement Ratio of ECC Containing Fly Ash

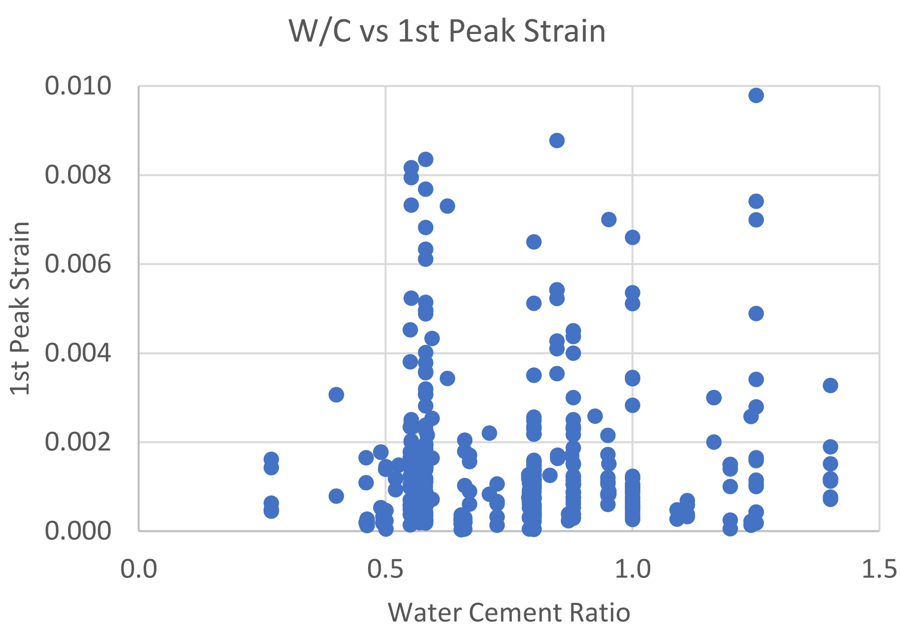

Figure 3-21 Variation of the 1st Peak Strain (ε_{ct}) with Water Cement Ratio of ECC Containing Fly Ash

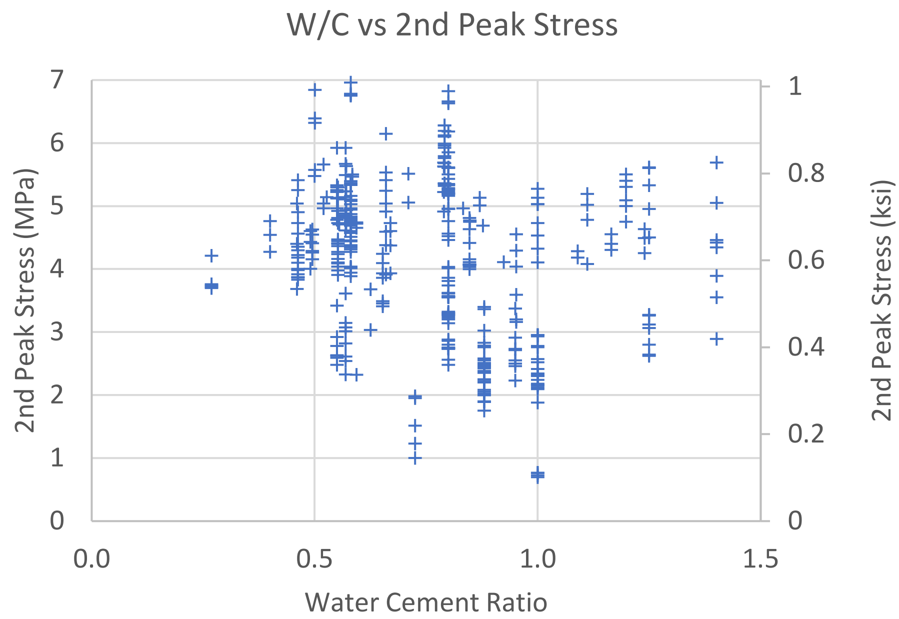

Figure 3-22 Variation of the 2nd Peak Stress ($\alpha_t f_{ct}$) with Water Cement Ratio of ECC Containing Fly Ash

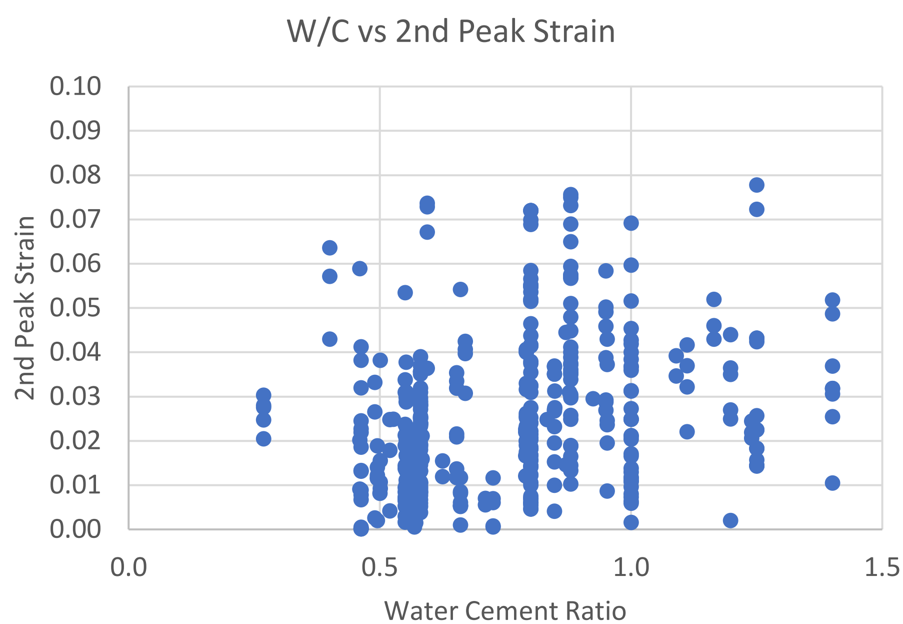

Figure 3-23 Variation of the 2nd Peak Strain ($\gamma_t \varepsilon_{ct}$) with Water Cement Ratio of ECC Containing Fly Ash

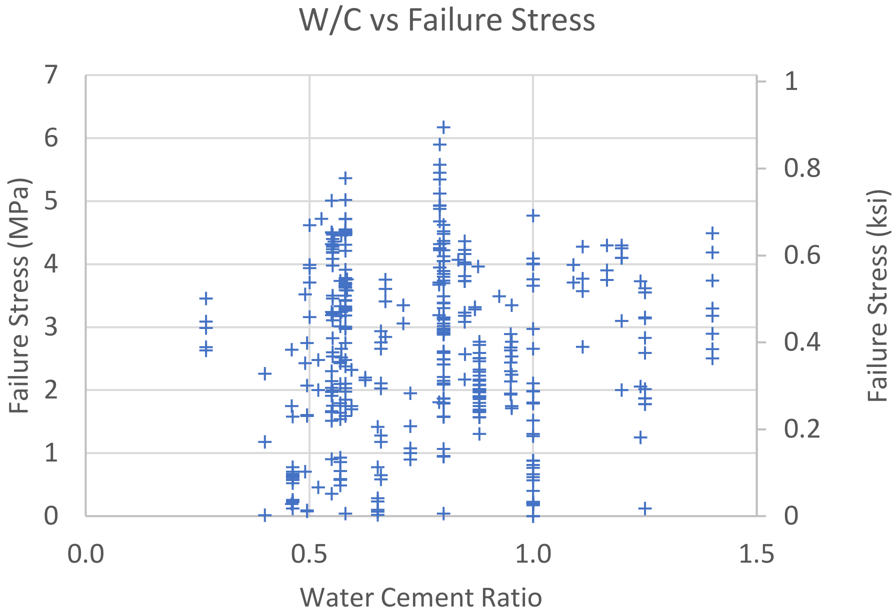

Figure 3-24 Variation of Failure Stress ($\beta_t f_{ct}$) with Water Cement Ratio of ECC Containing Fly Ash

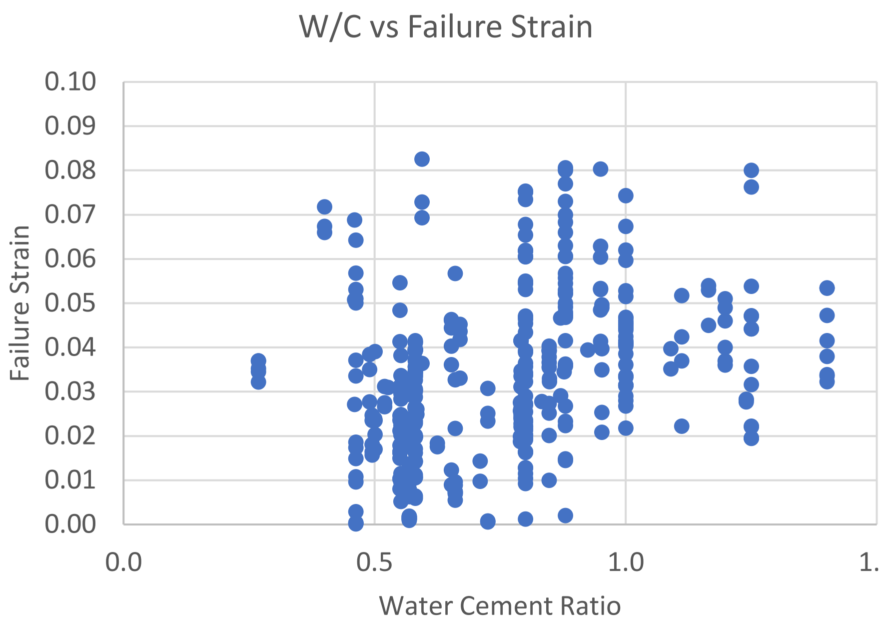

Figure 3-25 Variation of Failure Strain ($\delta_t \varepsilon_{ct}$) with Water Cement Ratio of ECC Containing Fly Ash

Fly ash has the pozzolanic reaction and is considered as a binder along with cement. When fly ash is added, water-binder ratio (W/(C+F), C = weight of cement, F = weight of fly ash, and C+F = weight of binder) is more important than water-cement ratio. Most of the previous investigators kept the water binder ratio constant while the water cement ratio varied with the amount of fly ash. The variations of the six parameters with water-binder ratio are shown in Figures 3-26 – 3-31. The most frequently used mixture design in known as M45 mixture (Table 4-3) suggested by Wang and Li (2007). It contains 55% of fly ash and its water-binder ratio is 0.24 (corresponding water-cement ratio is 0.53). With the exception of a few extreme cases, the typical water-binder ratio has been in the range of 0.24 – 0.30, and most of the data are concentrated within this range in Figures 3-26 – 3-31.

The effects of fly ash on the tensile properties is revealed by plotting the six parameters against the fly ash content. Figures 3-32 – 3-37 show the variations of the six parameters with fly ash-binder ratio (F/(C+F), F = weight of fly ash, C = weight of cement).

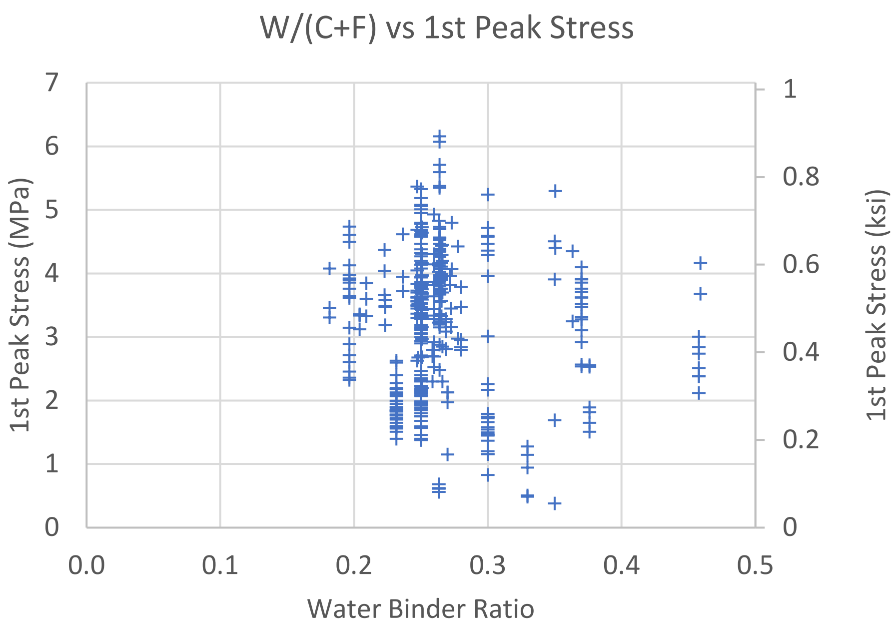

Figure 3-26 Variation of the 1st Peak Stress (f_{ct}) with Water Binder (Cement + Fly Ash) Ratio of ECC Containing Fly Ash

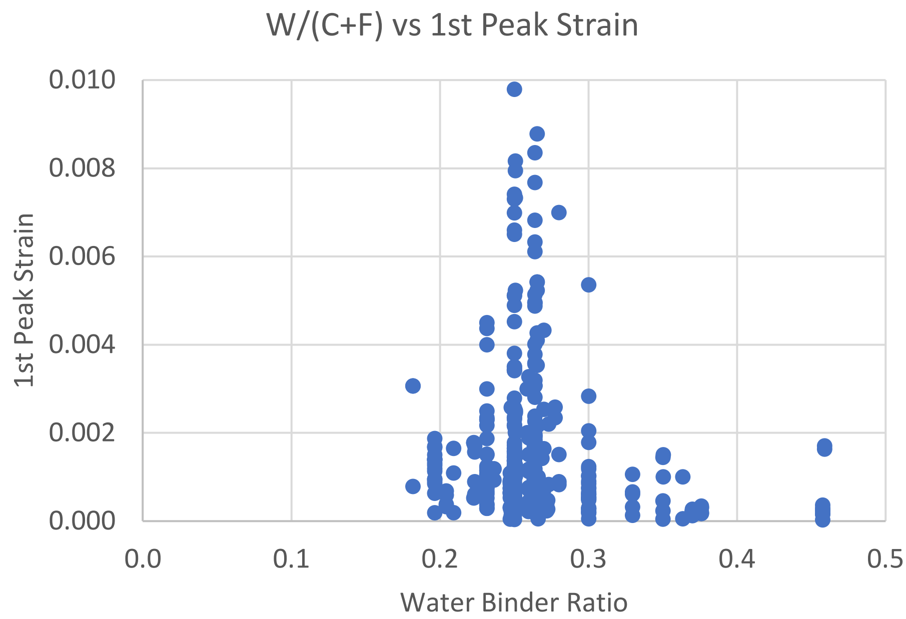

Figure 3-27 Variation of the 1st Peak Strain (ε_{ct}) with Water Binder (Cement + Fly Ash) Ratio of ECC Containing Fly Ash

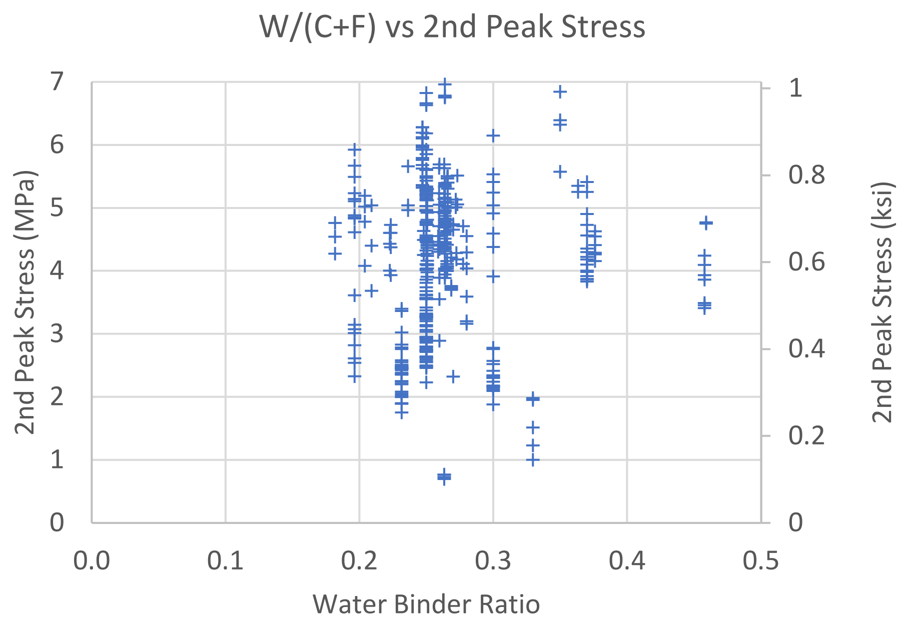

Figure 3-28 Variation of the 2nd Peak Stress ($\alpha_t f_{ct}$) with Water Binder (Cement + Fly Ash) Ratio of ECC Containing Fly Ash

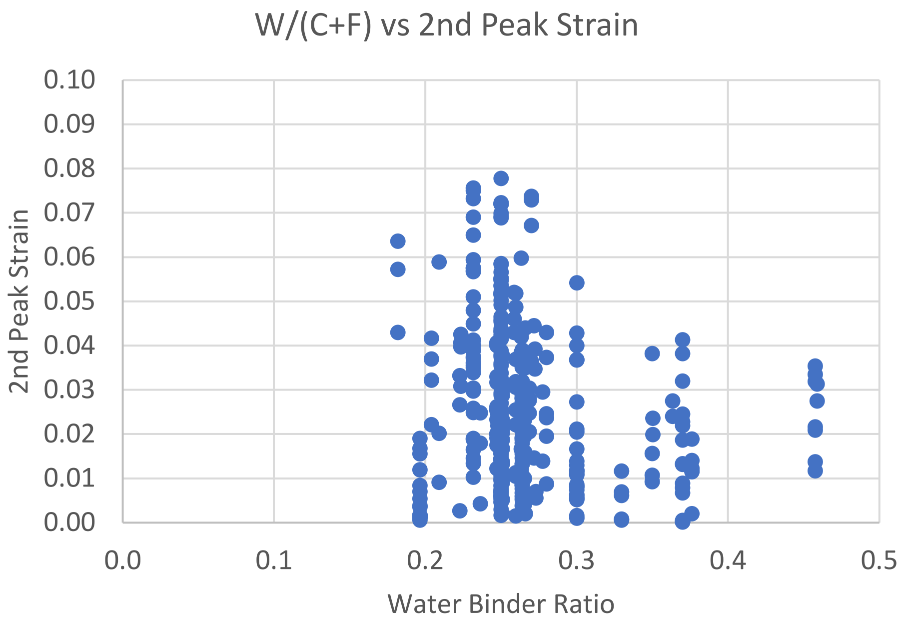

Figure 3-29 Variation of the 2nd Peak Strain ($\gamma_t \varepsilon_{ct}$) with Water Binder (Cement + Fly Ash) Ratio of ECC Containing Fly Ash

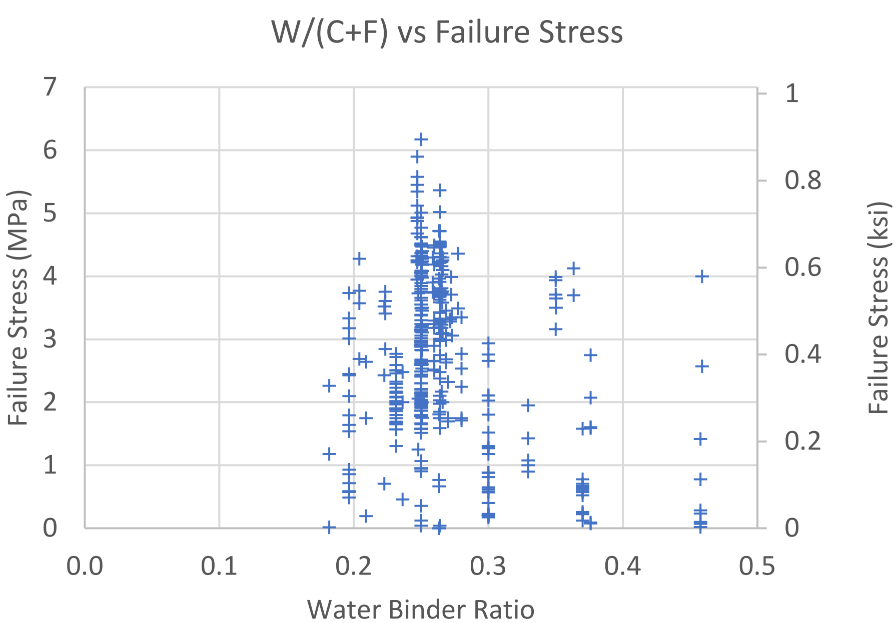

Figure 3-30 Variation of Failure Stress ($\beta_t f_{ct}$) with Water Binder (Cement + Fly Ash) Ratio of ECC Containing Fly Ash

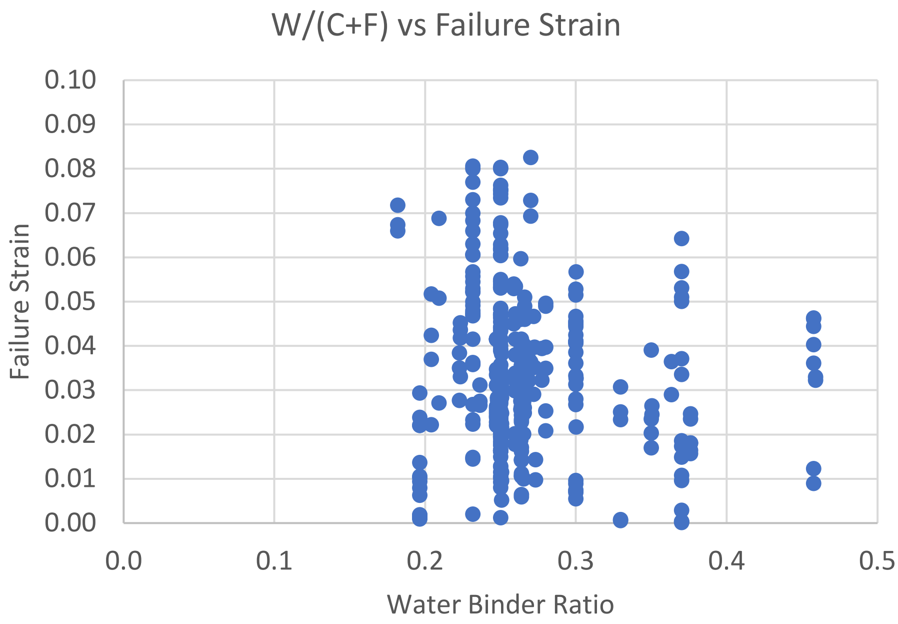

Figure 3-31 Variation of Failure Strain ($\delta_t \varepsilon_{ct}$) with Water Binder (Cement + Fly Ash) Ratio of ECC Containing Fly Ash

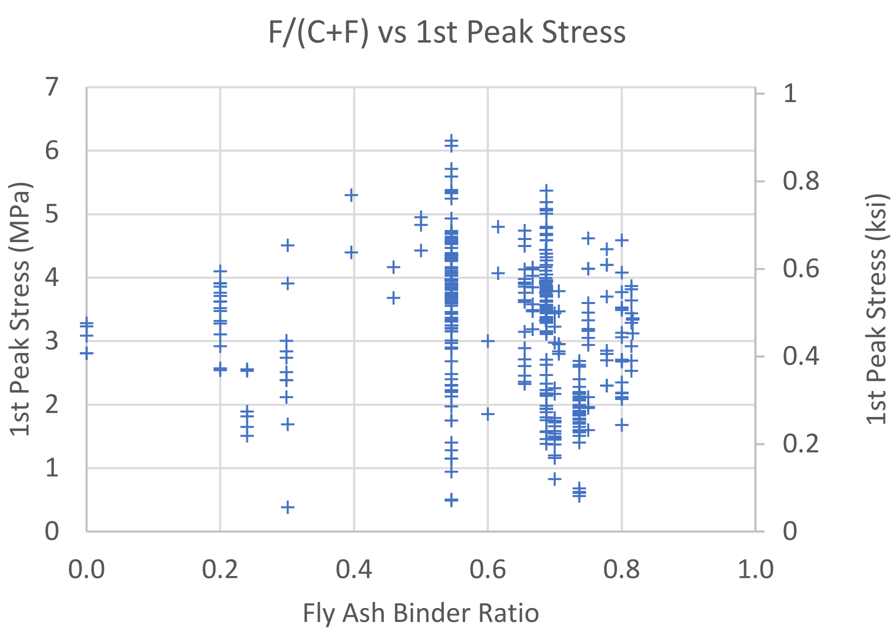

Figure 3-32 Variation of the 1st Peak Stress (f_{ct}) with Fly Ash to Binder (Cement + Fly Ash) Ratio of ECC Containing Fly Ash

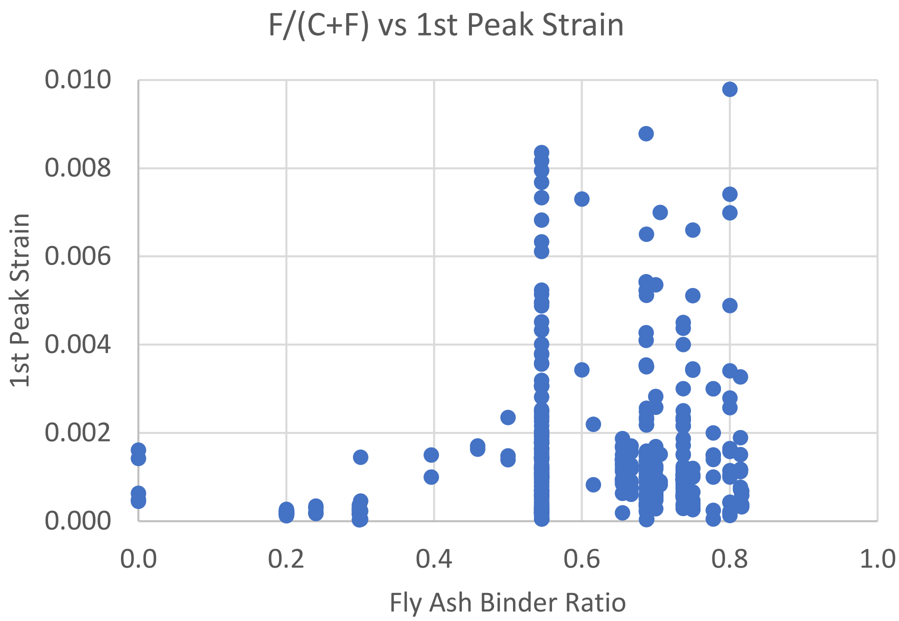

Figure 3-33 Variation of the 1st Peak Strain (ε_{ct}) with Fly Ash to Binder (Cement + Fly Ash) Ratio of ECC Containing Fly Ash

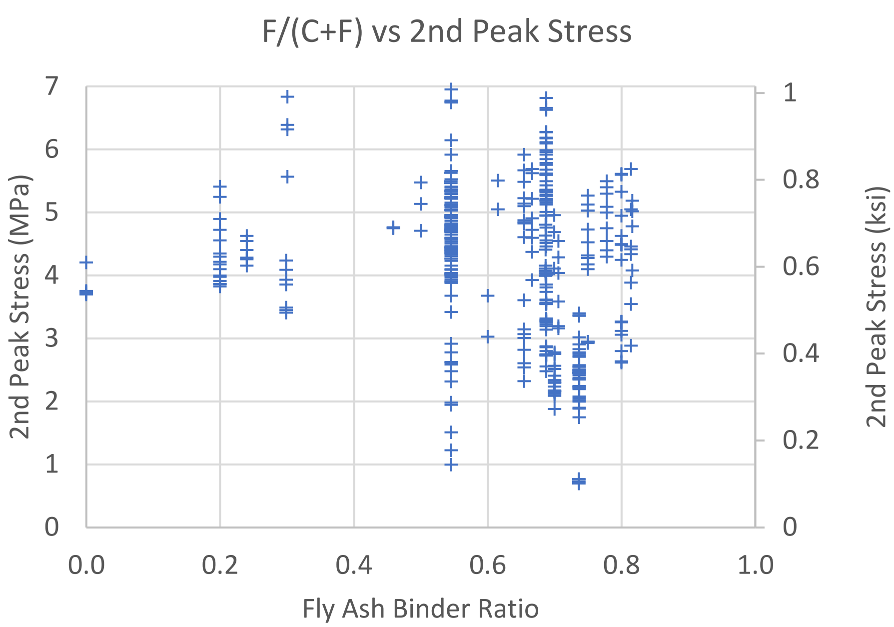

Figure 3-34 Variation of the 2nd Peak Stress ($\alpha_t f_{ct}$) with Fly Ash to Binder (Cement + Fly Ash) Ratio of ECC Containing Fly Ash

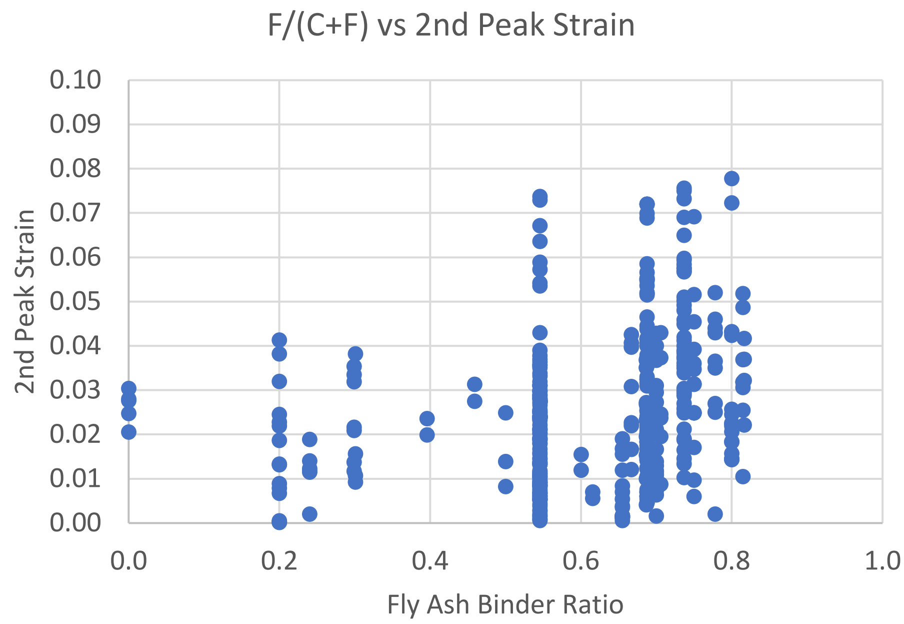

Figure 3-35 Variation of the 2nd Peak Strain ($\gamma_t \varepsilon_{ct}$) with Fly Ash to Binder (Cement + Fly Ash) Ratio of ECC Containing Fly Ash

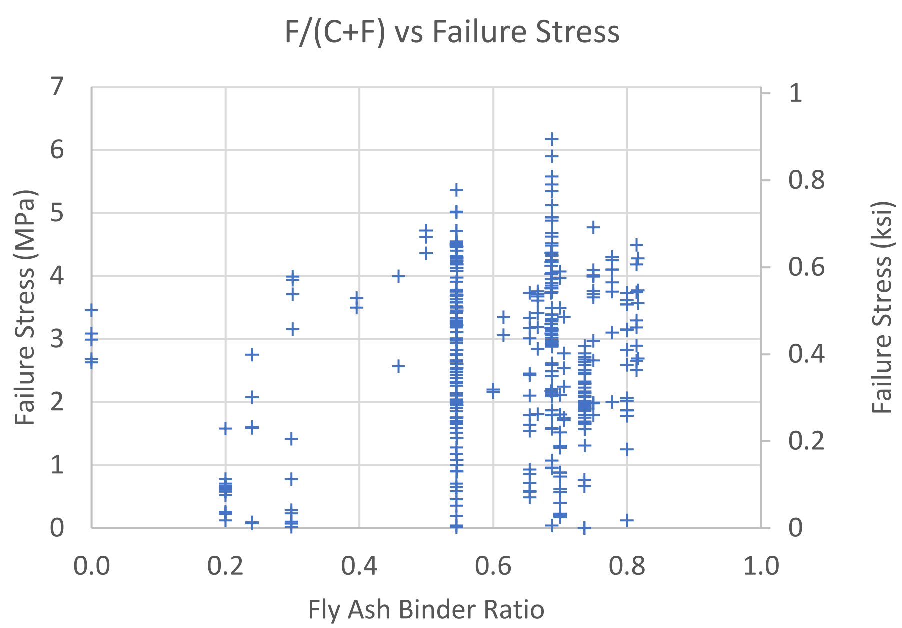

Figure 3-36 Variation of Failure Stress ($\beta_t f_{ct}$) with Fly Ash to Binder (Cement + Fly Ash) Ratio of ECC Containing Fly Ash

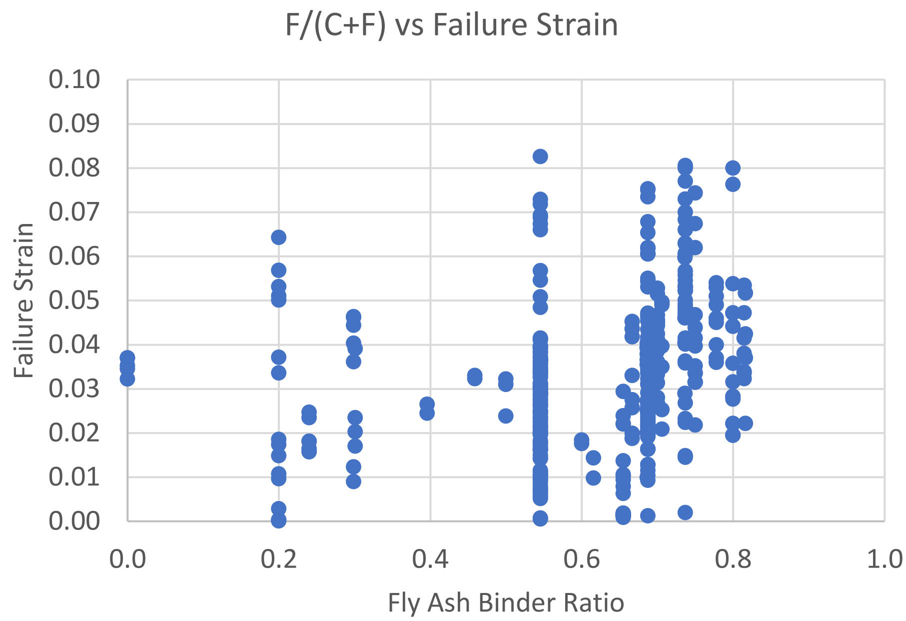

Figure 3-37 Variation of Failure Strain ($\delta_t \varepsilon_{ct}$) with Fly Ash to Binder (Cement + Fly Ash) Ratio of ECC Containing Fly Ash

The observations from the meta-analysis can be summarized as follows:

- The length of PVA fibers used in ECC ranges from 6 mm to 12 mm, and the diameter is 0.039 mm. Corresponding aspect ratio ranges from 154 – 308.
- The most frequently used mixture, known as M45 mixture has 55 % fly ash in the binder, 24 % water-binder ratio, and 53 % water-cement ratio. Tensile strength of the M45 mixture is close to the peak average strength (when fly ash-binder ratio = 0.4).
- Overall, the data collected from the literature show wide scattering ranges. Such large scattering of the data indicates that the quality of ECC can vary with the mixing process or factors other than the mixture proportioning. This also implies that the quality control of ECC through materials tests is a critical factor in the successful application of ECC. A standard experimental protocol to assess the tensile properties of ECC has to be developed to enable reliable application of ECC.

Chapter 4. ECC Mixture Design and Construction

4.1 Components of ECC Mixtures

Traditional concrete mixtures are composed of cement, water, fine/coarse aggregates, and chemical/mineral admixtures. Among them, cement and water form cement paste and serve as a binder (matrix phase), and fine/coarse aggregates are dispersed phase. Based on the mechanical, workability, and environmental demands, various admixtures can be added.

Fibers are added as a reinforcement for improving tensile behavior. According to the definition by Li (1993), ECC is a sub-group of fiber reinforced cementitious composites that has the attributes of pseudo-strain-hardening (with microcracking) and high ductility (3-5% of strain). This definition does not specify the fiber type, and the earlier research on ECC tested fibers made of various materials including poly-vinyl-alcohol (PVA, Takashima et al. 1973; Li et al. 2001; Fisher et al. 2003), polyester (Wang et al. 1987, polyethylene (Maleej and Li 1994; Li et al. 1995b; Li 1997; Kamada and Li 2000; Kanda and Li 2006), arcryl (Wang et al. 1987), spectra (Li 1993; Lim and Li 1997), polypropylene (Takashima et al. 2003), and steel (Maleej and Li 1994; Lim and Li 1997; Li and Li 2006). However, since 2001, the majority of the research on ECC has used PVA fibers, and as a result, the term ECC usually indicates PVA-ECC.

Another important difference between traditional concrete and ECC is the lack of coarse aggregates in the ECC mixtures. Typical mixtures contain cement, water, fine aggregates, and admixtures, and some ECC do not even contain fine aggregate (Kanda and Li 2006; Felekoglu et al. 2017; Keskinates and Felekoglu 2018). The lack of coarse aggregate increases the volume fraction of cement and is one of the main reasons for the high material cost of ECC. Such high-volume contents of cement cause negative impacts on environment because the production of Portland cement generates large amounts of greenhouse gas (GHG). Typical selection of cement for ECC was type I Portland cement. In case of fine aggregate, fine silica sand (maximum grain size = 250μm and mean size = 100-150μm) was used in most cases. The gradation chart of the fine silica sand can be found in Fischer et al. (2003). The use of river sand (maximum grain size 4.8mm) was reported by Soares et al. (2019).

In order to reduce the volume fraction of cement in ECC, mineral admixtures having pozzolanic reactions are added. Fischer et al. (2003) tried to use fly ash (class F 50% and class C 30% by weight of cement) in ECC for the first time, and fly ash became one of the basic components in most of the recent studies (Wang and Li 2007; Yang et al. 2007; Sahmaran and Li 2009; Sahmaran et al. 2011; 2012; Zhu et al. 2014; Zhang et al. 2014b; Yu et al. 2015; Zhu et al. 2016b; Felekoglu et al. 2017; Kan et al. 2019; Noorvand et al. 2019). In addition to class F and class C fly ash, the use of bottom ash and raw ash were also investigated by Wang and Li (2007) and Felekoglu et al. (2017). Most of the reported investigations after Wang and Li (2007) use class F fly ash because of its abundance and lower energy-intensity (requiring less post processing, Yang et al. 2007). The effects of class F and class C fly ash on workability, mechanical performance, and costs were compared by Felekoglu et al. (2017), and they concluded that class F fly ash is more advantageous than class C fly ash. The use of fly ash is environmentally friendly because it is a biproduct of coal combustion. Fly ash has pozzolanic reaction and is considered as a part of binder. Adding fly ash decreases water-binder (cement+fly ash) ratio and improves ductility. The other mineral admixtures tested in ECC are blast furnace slag (Kim et al. 2007; Qian et al. 2019; Zhou et al. 2010; Huang et al. 2014), limestone powder (Qian et al. 2009; Zhou et al. 2010), and silica fume.

The mixing of fiber reinforced cementitious composites becomes challenging when the volume fraction of fibers exceeds 1.5%. To ensure the uniform distribution of fibers, high workability is needed in fresh ECC mixtures. The most common choice to improve workability is adding small amounts of chemical admixtures such as HRWR (high-range water reducer) or superplasticizers. The types of water reducing agents used for ECC are listed below:

- Melamine formaldehyde sulfonate-based high-range water-reducing admixture (HRWRA; Wang and Li 2007; Yang et al. 2007)
- Viscosity agent hydroxypropyl methylcellulose (HPMC; Wang and Li 2007)
- Polycarboxylate-based high range water reducing admixture (HRWRA; Yang et al. 2008; Felekoglu et al. 2017; Soares et al. 2019)

4.2 Fibers: Materials, Dimensions, Contents, and Tailoring

In the earlier research on ECC, polyethylene (PE) fiber was considered as a most promising reinforcement because of the superior mechanical performance. However, the high cost of PE fibers hindered broad applications of PE-ECC. As an alternative of PE fiber, polyvinyl alcohol (PVA) fiber was selected because of the low cost (1/8 of PE fiber) and high tensile strength (ranged from 1600 to 2500 MPa). Other low-cost fibers, such as Nylon, low-density polyethylene fiber, and polypropylene fiber, are less suitable due to low tensile strength and low modulus of elasticity (Li et al. 2001).

PVA fibers are hydrophilic, which makes the fibers have a strong chemical bond with the cement paste. The strong chemical bond of PVA may cause the rupture of fibers instead of fiber pull-out. Since pulling out of fibers from matrix is preferred to maintain fiber bridging effects on the crack surface, coating fiber with oiling agent is recommended to reduce the chemical bonding strength (Li et al. 2002; Li 2012; Ma et al. 2015b; Zhang and Zhang 2018; Ma et al. 2019b).

The dimensions of PVA fibers used for ECC are: length 6-12 mm and diameter 0.014 – 0.039 mm. The most common fiber diameter studied was 0.039 mm, and common fiber lengths were 6, 8, and 12 mm. The corresponding aspect ratios (length/diameter) were 158, 205, and 308, respectively. Table 4-1 shows a part of the collected data on the type, dimension, and mechanical properties of fibers used in ECC mixtures. The full data are in the supplied Excel file (0-7030 TM 4 Raw Data).

Table 4-1. Fibers Used for ECC (a part of the collected data)

Authors	Year	Fiber ID	L (mm)	D (mm)	Specific Gravity	Tensile Strength (MPa)	Bond Strength (MPa)	Young's Modulus (MPa)	Elongation (%)
Takashima et al.	1973	PVA	6	0.0379	1.3	1650		43700	
Wang et al.	1987	Acrylic		0.0192	1.1	500		5500	12.6%
		Polyester		0.0231				10200	24.4%
		Aramid		0.0119	1.4	3000		10000	4.1%
		Nylon		0.0272	1.1	1000		73100	15.8%
Li	1993	Spectra	12.7	0.038	0.97			120000	
Maleej and Li	1994	Steel	6	0.15	7.8	2500		200000	
		Polyethylene	12.7	0.038	0.98	2700		120000	
Li et al.	1995b	Polyethylene	12.7	0.038	0.97			117000	
Li	1997	Polyethylene	12.7	0.038	0.98	2700		120000	
Lim and Li	1997	Steel	30	0.5	1.2				
		Spectra	12.7	0.028	0.97				
Kamada and Li	2000	PE	19	0.038	0.98	2700		120000	
		Steel	30		1.2				
Li et al.	2001	REC PVA	12	0.039	1.3				
		RMU PVA	6	0.014	1.3				
Li et al.	2001	REC PVA	12	0.039	1.3				
		RMU PVA	6	0.014	1.3				
Kim et al.	2003	PVA	8.12	0.039	1.3	1620		42800	6.0%
Takashima et al.	2003	PP - A	10	0.018	0.91	295		3700	
		PP - B	6	0.018	0.91	295		3700	
		PP - C	10	0.043	0.91	295		3700	
Fischer et al.	2003	PVA			1.3				
Kanda et al.	2003	PVA	12	0.04	1.3	1690		40600	

4.3 Mixture Proportions

As discussed previously, the components of ECC can be summarized as follows:

- Portland cement (C)
- Water (W)
- Fine aggregate (typically Silica sand, S)
- Fly Ash (mineral admixture)
- Fiber
- Chemical admixtures
    - High-range water reducer (HRWR)
    - Superplasticizer
    - Others
- Other mineral admixtures
    - Silica fume
    - Glass bubbles, Expanded perlite (Wang and Li 2003)
    - Slag (Atahan et al. 2012; Ozbay et al. 2013; Sahmaran et al. 2014)

Comprehensive data on the mixture proportioning of ECC were collected and tabularized in a spreadsheet. The full data are provided as a sheet in the 'Raw Data' Excel file. The weight fraction and volume fraction of each component, fiber type and dimension, cement-binder ratio, water-cement ratio, and water-binder ratio are summarized as shown in Table 4-2.

Table 4-2. The Sample Data of the Mixture Proportioning of ECC

Publication		Mixture ID	C	W	S	Fly Ash	Coarse Aggregates	Fiber	Additive 1	Additive 2	Additive 3	Additive 4	C	W	S	Fly Ash	Coarse Aggregates	Fiber	Additive 1	Additive 2	Additive 3	Additive 4	Material	L (mm)	d (mm)	L/d	Oiling Agent (%)			C/Binder	W/C	W/(C+FA)
Takashima et al.	1973	1	432.9	259.7	259.7			13.0	0.0	8.7	4.3	21.6	43.3%	26.0%	26.0%	-	-	1.3%	0.0%	0.9%	0.4%	2.2%	PVA	6	0.0379	158.311		1: Perlite 2: Laubholz Bleached Kraft Pulp 3: HPMC Mineral Fiber 4: Magnesium Silicate 2.775		1.00	0.600	0.600
		2	423.7	254.2	254.2			12.7	21.2	8.5	4.2	21.2	42.4%	25.4%	25.4%	-	-	1.3%	2.1%	0.8%	0.4%	2.1%	PVA	6	0.0379	158.311				1.00	0.600	0.600
		3	414.9	249.0	249.0			12.4	41.5	8.3	4.1	20.7	41.5%	24.9%	24.9%	-	-	1.2%	4.1%	0.8%	0.4%	2.1%	PVA	6	0.0379	158.311				1.00	0.600	0.600
		4	398.4	239.0	239.0			12.0	79.7	8.0	4.0	19.9	39.8%	23.9%	23.9%	-	-	1.2%	8.0%	0.8%	0.4%	2.0%	PVA	6	0.0379	158.311				1.00	0.600	0.600
		5	398.4	318.7	239.0			12.0	0.0	8.0	4.0	19.9	39.8%	31.9%	23.9%	-	-	1.2%	0.0%	0.8%	0.4%	2.0%	PVA	6	0.0379	158.311				1.00	0.800	0.800
		6	390.6	312.5	234.4			11.7	19.5	7.8	3.9	19.5	39.1%	31.3%	23.4%	-	-	1.2%	2.0%	0.8%	0.4%	2.0%	PVA	6	0.0379	158.311				1.00	0.800	0.800
		7	383.1	306.5	229.9			11.5	38.3	7.7	3.8	19.2	38.3%	30.7%	23.0%	-	-	1.1%	3.8%	0.8%	0.4%	1.9%	PVA	6	0.0379	158.311	-			1.00	0.800	0.800
		8	369.0	295.2	221.4			11.1	73.8	7.4	3.7	18.5	36.9%	29.5%	22.1%	-	-	1.1%	7.4%	0.7%	0.4%	1.8%	PVA	6	0.0379	158.311	-			1.00	0.800	0.800
Wang et al	1987	A1	811.9	406.0	811.9			26.4					25.8%	40.6%	31.2%		-	2.4%	-	-	-	-	Acrylic	25.4	0.0136	1867.65	-			1.00	0.500	0.500
		A2	811.9	406.0	811.9			26.4					25.8%	40.6%	31.2%		-	2.4%	-	-	-	-	Acrylic	38.1	0.0136	2801.47	-			1.00	0.500	0.500
		K1	811.9	406.0	811.9			26.6					25.8%	40.6%	31.2%		-	1.9%	-	-	-	-	Aramid	25.4	0.0119	2134.45	-			1.00	0.500	0.500
		A3	811.9	406.0	811.9			71.5					25.8%	40.6%	31.2%		-	6.5%	-	-	-	-	Acrylic	6.4	0.0192	333.333	-			1.00	0.500	0.500
		A4	811.9	406.0	811.9			22					25.8%	40.6%	31.2%		-	2.0%	-	-	-	-	Acrylic	6.4	0.0192	333.333	-			1.00	0.500	0.500
		A5	811.9	406.0	811.9			44					25.8%	40.6%	31.2%		-	4.0%	-	-	-	-	Acrylic	6.4	0.0192	333.333	-			1.00	0.500	0.500
		A6	811.9	406.0	811.9			22					25.8%	40.6%	31.2%		-	2.0%	-	-	-	-	Acrylic	12.7	0.0136	933.824	-			1.00	0.500	0.500
		A7	811.9	406.0	811.9			22					25.8%	40.6%	31.2%		-	2.0%	-	-	-	-	Acrylic	19.1	0.0192	994.792	-			1.00	0.500	0.500
		A8	811.9	406.0	811.9			49.5					25.8%	40.6%	31.2%		-	4.5%	-	-	-	-	Acrylic	Tow	0.0192		-			1.00	0.500	0.500
		N1	811.9	406.0	811.9			22					25.8%	40.6%	31.2%		-	2.0%	-	-	-	-	Nylon	38.1	0.0176	2164.77	-			1.00	0.500	0.500
		N2	811.9	406.0	811.9			26.4					25.8%	40.6%	31.2%		-	2.4%	-	-	-	-	Nylon	38.1	0.0176	2164.77	-			1.00	0.500	0.500
		N3	811.9	406.0	811.9			33					25.8%	40.6%	31.2%		-	3.0%	-	-	-	-	Nylon	190	0.052	3653.85	-			1.00	0.500	0.500
Lim and Li	1997	Concrete	423.3	211.7	986.8		764.9						13.4%	21.2%	37.0%	-	28.5%	0.0%	0.0%	0.0%	-	-	-	-	-	-	-		River Sand 2.68, Crushed	1.00	0.500	0.500
		SFRC	419.1	209.6	977.0		757.2	78					13.3%	21.0%	36.6%	-	28.3%	1.0%	0.0%	0.0%	-	-	Steel	30	0.5	60			Limestone 2.67	1.00	0.500	0.500
		ECC	1080.8	378.3	550.8		0.0	26	108.1	10.8			34.3%	37.8%	20.8%	-	0.0%	2.0%	4.1%	1.0%	-	-	Spectra	12.7	0.028	453.571			silica sand 2.65	1.00	0.350	0.350
Kamada and Li	2000	Concrete	423.3	211.7	979.5		764.9	0	0.0	0.0			13.4%	21.2%	37.0%	-	28.5%	0.0%	0.0%	0.0%	-	-	-	-	-	-	-	1: Superplasticizer 2: HPMC		1.00	0.500	0.500
		SFRC	419.1	209.6	969.7		757.2	13	0.0	0.0			13.3%	21.0%	36.6%	-	28.3%	1.0%	0.0%	0.0%	-	-	Steel	30						1.00	0.500	0.500
		ECC	1204.1	337.2	613.7		0.0	19.5	36.1	0.6			38.2%	33.7%	23.2%	-	0.0%	1.5%	1.4%	0.1%	-	-	PE 968.79	19	0.038	500				1.00	0.280	0.280
		ECC	875.2	525.1	446.0		0.0	19.5	8.8	6.1			27.8%	52.5%	16.8%	-	0.0%	1.5%	0.3%	0.6%	-	-	PE 968.80	19	0.038	500				1.00	0.600	0.600
Li et al.	2001	1	1019.4	458.7	519.5			26	2.0	0.0			32.4%	45.9%	19.6%	-		2.0%	0.2%	0.0%	-	-	REC - PVA	12	0.039	307.692	0.3	1: HPMC 2:HRWR	HPMC 1.28	1.00	0.450	0.450
		2	964.1	433.9	589.6			26	1.9	19.3			30.6%	43.4%	22.2%	-		2.0%	0.2%	1.6%	-	-	REC - PVA	12	0.039	307.692	0.3		HRWR 1.20	1.00	0.450	0.450
		3	889.8	400.4	725.6			26	1.3	26.7			28.2%	40.0%	27.4%	-		2.0%	0.1%	2.2%	-	-	REC - PVA	12	0.039	307.692	0.3			1.00	0.450	0.450
		4	831.7	374.3	847.7			26	1.2	25.0			26.4%	37.4%	32.0%	-		2.0%	0.1%	2.1%	-	-	REC - PVA	12	0.039	307.692	0.3			1.00	0.450	0.450
		5	964.5	434.0	589.8			26	1.4	19.3			30.6%	43.4%	22.3%	-		2.0%	0.1%	1.6%	-	-	REC - PVA	12	0.039	307.692	0.5			1.00	0.450	0.450
		6	889.8	400.4	725.6			26	1.3	26.7			28.2%	40.0%	27.4%	-		2.0%	0.1%	2.2%	-	-	REC - PVA	12	0.039	307.692	0.5			1.00	0.450	0.450
		7	831.7	374.3	847.7			26	1.2	25.0			26.4%	37.4%	32.0%	-		2.0%	0.1%	2.1%	-	-	REC - PVA	12	0.039	307.692	0.5			1.00	0.450	0.450
		8	780.8	351.3	954.9			26	1.2	23.4			24.8%	35.1%	36.0%	-		2.0%	0.1%	2.0%	-	-	REC - PVA	12	0.039	307.692	0.5			1.00	0.450	0.450
		9	964.5	434.0	589.8			26	1.4	19.3			30.6%	43.4%	22.3%	-		2.0%	0.1%	1.6%	-	-	REC - PVA	12	0.039	307.692	0.8			1.00	0.450	0.450
		10	831.7	374.3	847.7			26	1.2	25.0			26.4%	37.4%	32.0%	-		2.0%	0.1%	2.1%	-	-	REC - PVA	12	0.039	307.692	0.8			1.00	0.450	0.450
		11	780.8	351.3	954.9			26	1.2	23.4			24.8%	35.1%	36.0%	-		2.0%	0.1%	2.0%	-	-	REC - PVA	12	0.039	307.692	0.8			1.00	0.450	0.450
		12	780.8	351.3	954.9			26	1.2	23.4			24.8%	35.1%	36.0%	-		2.0%	0.1%	2.0%	-	-	REC - PVA	12	0.039	307.692	0.8			1.00	0.450	0.450
		PVA-FRC RMU	956.7	430.5	585.0			26	1.4	28.7			30.4%	43.0%	22.1%	-		2.0%	0.1%	2.4%	-	-	RMU - PVA	6	0.014	428.571	-			1.00	0.450	0.450
Fischer et al.	2003	M-Ref	844.2	379.9	688.4	126.6		26	16.9	1.3			26.8%	38.0%	26.0%	5.8%		2.0%	1.3%	0.1%	-	-	PVA	12	0.039	307.692		1:MFS 2:HPMC		0.87	0.450	0.391
		M-1	712.4	256.5	580.9	569.9		26	21.4				22.6%	25.6%	21.9%	26.1%		2.0%	1.7%	0.0%	-	-	PVA	12	0.039	307.692				0.56	0.360	0.200
		M-2	707.3	261.7	576.7	565.8		26	21.2				22.5%	26.2%	21.8%	26.0%		2.0%	1.7%	0.0%	-	-	PVA	12	0.039	307.692				0.56	0.370	0.206
		M-3	702.2	266.8	572.6	561.8		26	21.1				22.3%	26.7%	21.6%	25.8%		2.0%	1.6%	0.0%	-	-	PVA	12	0.039	307.692				0.56	0.380	0.211
		M-4	692.3	276.9	564.5	553.8		26	20.8				22.0%	27.7%	21.3%	25.4%		2.0%	1.6%	0.0%	-	-	PVA	12	0.039	307.692				0.56	0.400	0.222
		M-5	682.7	286.7	556.6	546.1		26	20.5				21.7%	28.7%	21.0%	25.1%		2.0%	1.6%	0.0%	-	-	PVA	12						0.56	0.420	0.233
Kanda et al.	2003	Mix - N	634.8	417.0	591.3	272.3		26	17.1				20.2%	41.7%	22.3%	12.5%		2.0%	1.3%	-	-	-	PVA	12	0.04	300		1: anti-shrinkage agent		0.70	0.657	0.460
		Mix - M	632.4	415.5	598.8	271.3		26	17.1				20.1%	41.5%	22.6%	12.4%		2.0%	1.3%	-	-	-	PVA	12	0.04	300				0.70	0.657	0.460

- *Raw Data*: the mixture proportioning of ECC and fiber types, dimensions, and mechanical performances are provided in Excel file: '0-7030 TM4 Raw Data-Mixture Design.xlsx'. The contents of data are:
  - 'Mixture' tab includes:
    - Author/Year of Publications
    - Weight fraction of each components per cubic meter of ECC
    - Volume fraction of each component (percent)
    - Type and dimensions of fibers used
    - Notes on admixtures
    - C/binder = cement-binder (cement + fly ash) ratio
    - W/C = water-cement ratio
    - W/(C+FA) = water-binder ratio
  - 'Fiber' tab includes:
    - Author/Year of Publications
    - Fiber ID
    - Fiber dimensions: L (length), D(diameter), and specific gravity
    - Mechanical properties of fibers: tensile strength, bond strength, Young's modulus, and elongation

The initial version of ECC were composed of cement, sand, water, and fibers. The water cement ratio ranged from 0.35 to 0.60, and small amount of water reducing agents were added to facilitate the fiber distribution (Takashima et al. 1973; Wang et al. 1987; Lim and Li 1997; Kamada and Li 2000; Li et al. 2001). Fly ash has been added since Ficher et al. (2003). The use of cement can be decreased by adding mineral admixtures including fly ash, and correspondingly, the cost and environmental impacts can be reduced. The weight fraction of pozzolanic admixtures has been tested close to 80% of the binder (Yang et al. 2007; Sahmaran et al. 2009; Ranade et al. 2014; Yu et al. 2015; Zhu et al. 2016b; Felekoglu et al. 2017). The research shows that the class F fly ash content increases crack width, dry shrinkage, and toughness. On the other hand, the compressive strength of ECC decreases as the fly ash content increases. The use of pozzolanic admixtures (mostly fly ash) also reduces water-binder ratio, and its typical range is 0.25 – 0.27. Most commonly selected mixture design in recent years is the mixture containing 55% of class F fly ash by weight of binder (i.e., cement-fly ash ratio = 1:1.2), which is known as M45 mixture. The mixture ID, M45 originated from Wang and Li (2007), and 45 indicates cement-binder ratio in % (i.e., the binder is composed of 45% cement and 55% of fly ash by weight). The mixture proportioning by weight in 1 m^3 and 1 yd^3 of ECC is shown in Table 4-3.

Table 4-3. Mixture proportion of M45 mixture (kg/m^3)

Unit	C	W	S	Fly Ash	Fiber	Superplasticizer
kg/m^3	567	300	462	680	26	17
lb/yd^3	955	506	779	1146	44	29

4.4 Large Volume Applications and Quality Control Issues

The large volume applications of ECC and the potential concerns in material processing were investigated by Kanda et al. (2003; 2006), Li (2003; 2008) and Yildirim et al. (2018). According to Fischer et al. (2003), the key to successful mixing of ECC in a regular drum mixer is to maintain a fluid consistency of the ECC mixture throughout the mixing process. In fresh ECC mixtures, the grinding force and blending effect due to the moving coarse aggregate do not exist, and the blending depends only on internal shear friction generated by rotating drum mixer and gravity. Therefore, the water cement ratio and the amount of superplasticizer play a critical role in mixing. Fischer et al. (2003) suggested a step-by-step mixing procedure for large volume applications. Owing to the accumulated mixing experience, there exist sufficient data on the mixture proportion to ensure a proper fluid consistency of fresh ECC.

Kanda et al. (2003) listed the potential problems in large scale mixing and investigated whether the mechanical performance achieved in the laboratory can be obtained in large volume applications. They assumed that the type of cement, ambient temperature, and uneven distribution of air content may cause low tensile/compressive strength and ductility. The experimental showed that the effects of those factors are not significant, and the mechanical performance of ECC produced by the large volume mixer equaled the laboratory scale product. Kanda et al. (2006) compared the quality of ECC produced at different plants with the same mixture design and observed that a fresh ECC produced in one of the plants showed significantly lower performance. They suggest that the low mechanical performance was caused by the quality of raw materials, and suggested test mixing and material tests prior to manufacturing large volume ECC.

Based on the full-scale production experience of ECC in Japan (Kunieda and Rokugo, 2006) and in the US (Lepech and Li 2007), Li (2008) suggested a material charging sequence into ready-mix trucks as shown in Table 4-4. Li (2003) also mentioned that it is necessary to develop standardized test methods for evaluating uniaxial tensile stress-strain curves of ECC.

Yildirim et al. (2018) described two ECC mixing sequences: one for relatively small volume mixing for the applications of ECC to structural repair and another for relatively large volume mixing using mobile and central mixers.

Table 4-4. Materials charging sequence into ready-mix trucks (Li 2008)

Activity No.	Activity	Elapsed Time (min)
1	Charge all sand	2
2	Charge approximately 90-95% of mixing water, all HRWR, all hydration stabilizer	2
3	Charge all fly ash	2
4	Charage all cement	2
5	Charge remaining mixing water to wash drum fins	4
6	Mix at high RPM for 5 minutes or until material is homogenous	5
7	Charge fibers	2
8	Mix at high RPM for 5 minutes or until material is homogenoug	5
	Total	24

As shown above, some investigators leading ECC technology mentioned the need for standard test methods to evaluate tensile properties of ECC for quality control. On the other hand, direct tension tests for ECC are expensive and difficult and not regularly performed on cementitious materials. Development of a correlation between tensile properties and the data obtained from traditional tests for concrete may be a good alternative to tensile tests for quality control of ECC.

Chapter 5. Cases of ECC Field Applications

The field applications of fiber reinforced cementitious composites (FRC) have a long history. Li (2002) summarized various field application cases from the 1990s including two cases of using PVA fibers. The cases include the applications to pavement overlay (Denmark, Canada, US, and United Kingdom), repair of pavement and bridge (Denmark, Germany, US, and Canada), floor/bridge deck slab (France, US, Denmark, and Canada), wall panels (Japan, Australia, and Denmark), tunnel lining (Norway and France), septic tank/pipes (Australia, Belgium, Denmark), and column/column slab joints (France and Denmark). ECC was used for thin sheet products for cladding (Europe, Bentur 1995) and stair treads (Japan, Yurugi et al. 1991).

Field applications of ECC have been more active in 2000s in Japan and US. However, the information about the field applications of ECC is more limited because the projects using ECC were led by engineers in practice rather than engineers in academia. This chapter collects the cases of the field applications of ECC.

5.1 ECC application to pavement overlay

The application of FRC for pavement overlay was reported by Glavind (1993), Ramboll et al. (1992), Balaguru and Shah (1992), Van Mier (1995), Ramakrishnan (1993), and Johnston (1995). However, the application of ECC for a full pavement overlay has not been tried yet. On the other hand, the feasibility and economic and environmental benefits of ECC overlay have been investigated through LCA.

Zhang and Li (2002) showed that the propagation of reflective cracking can be effectively blocked by ECC in lab scale experiments (Figure 5-1). Shamaran et al. (2014) showed that the bond strength between concrete substrate and overlay can be significantly improved by using ECC. Zhang et al. (2008) conducted life cycle assessment for pavement overlay systems and concluded that the life-cycle cost and GHG emission can be reduced by using ECC. Similar LCA results were reported by Lepech and Li (2010), Zhang et al. (2010), and Qian et al. (2012).

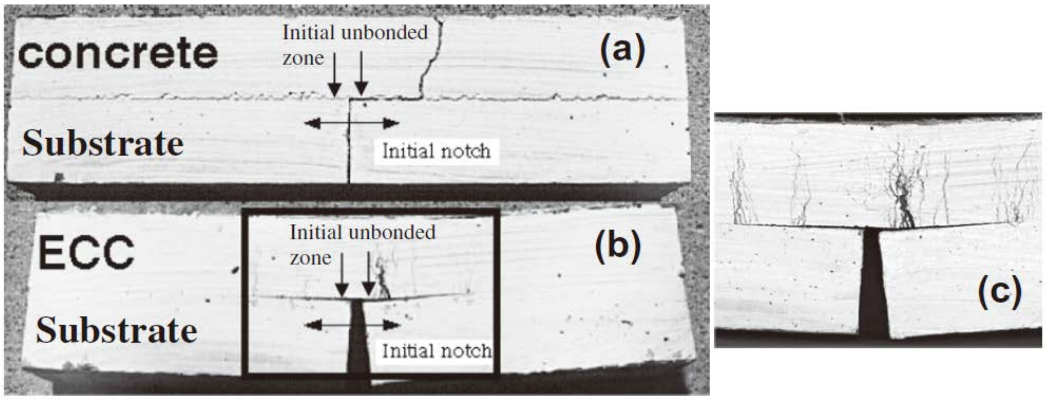

Figure 5-1 Comparison of high stress concentration effects on concrete and ECC repair materials, showing (a) brittle fracture in concrete layer, and (b) ductile strain-hardening response in ECC layer (Zhang and Li 2002)

The field application of ECC for pavement repair was reported by Li (2008). Figure 5-2 compares the ability to control cracks in ECC and concrete patches on the pavement. As shown in the left photo, the concrete patch and ECC patch are installed on the bridge surface. ECC shows a superior crack control when compared to the concrete patch.

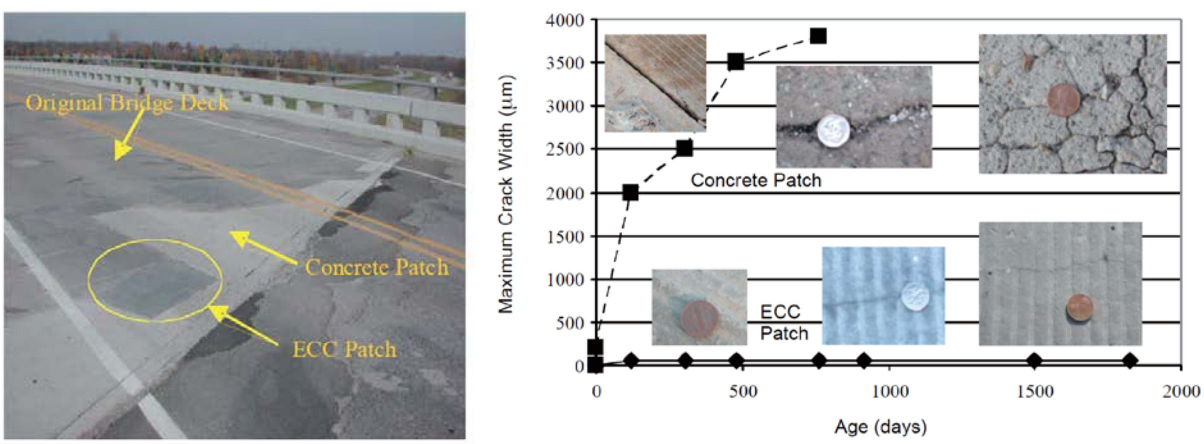

Figure 5-2 Comparison of ECC and concrete patches for pavement repair at Ann Arbor Michigan (Li 2008)

5.2 Bridge link-slab

Leaking of water at bridge expansion joints allows water and other corrosives to penetrate below the deck and corrode bridge beams. Continuous bridge decks with no expansion joints can prevent this problem, and link slabs are a suitable application for ECC (Li et al. 2003; Li and Lepech 2004). Lepech and Li (2005) designed a link slab for a demonstration project in Michigan. The ECC link slab measure 5.5m x 20.25m and is shown in Figure 5-3. The ECC link slab was constructed in 2005 (Li et al. 2005) as shown in Figure 5-4.

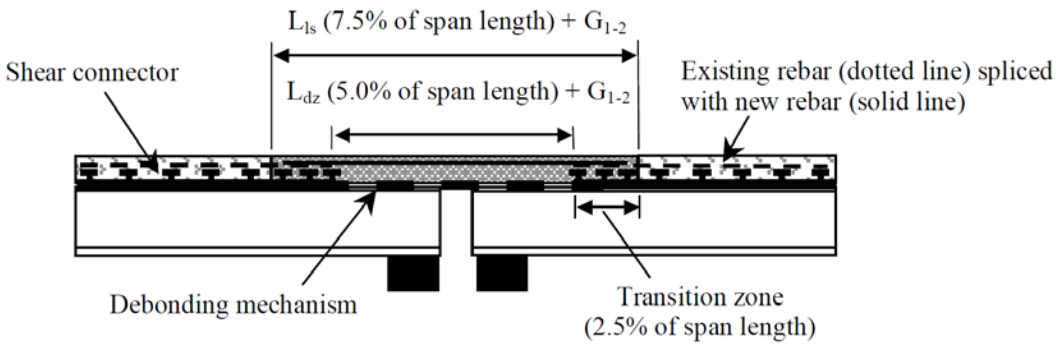

Figure 5-3 ECC link slab design (Lepech and Li 2005)

Figure 5-4 ECC Link Slab Constructed in Michigan (Li 2014)

The field demonstration of ECC link slab was conducted through three phases with the support of Michigan department of transportation from 2003 to 2007. The first phase (Li et al. 2003) provided the ECC link slab design and construction guidelines based on laboratory material tests. The link slab was constructed for the deck of Grove Street Bridge over Interstate 94 in Ypsilanti, Michigan (Li et al. 2005). The full-scale mixing sequences and construction and procedures were provided, and load tests were conducted to ensure safety of the link-slab. In the third phase, the mixture design and construction issues were addressed focusing on shrinkage control to enhance long-term performance of ECC link slab (Li et al. 2007). The observations after two years of the construction show that ECC link slab has better resistance to wear and scaling than the bridge deck made of conventional concrete. Shamaran and Li (2016) investigated the conditions of the ECC link slab after 10 years of service and reported that the ECC link slab functioned well without any maintenance.

The LCA for bridge link slab was conducted by Koeleian et al. (2005), and the results show that ECC link slab reduces the cost and GHG emission when compared to conventional concrete link slab and traditional expansion joints. Additional lab scale tests were conducted to validate the performance of ECC link slabs by Said et al. (2015) and Hou et al. (2018).

5.3 Repair of concrete structures

The high ductility, the ability to redistribute localized stresses, and self-healing capability make ECC a good repair material. According to Li (2014), bridge deck patch repair was one of the earliest ECC applications (Li and Lepech 2004; Li and Li 2008). Following are the cases of repair application of ECC.

- In 2003, Mitaka Dam in Hiroshima, Japan that is a 60 year old concrete dam with severe surface damage. ECC with high workability was sprayed on the surface of the dam with an average thickness of 20 mm over 600 m^2 of the upstream dam surface
- A patch repair using high early strength ECC was made on Ellsworth Road Bridge over US-23 in Ann Arbor Michigan (Li et al. 2006; Li 2009).
- An earth retaining wall damaged by ASR cracking was repaired using ECC and cement mortar (Rokugo et al 2005). A 50-70 mm thick layer is added on the damaged surface. The condition of the repair layer was investigated at 10 and 24 month after the repair, and the crack widths of ECC were narrower than the cement mortar (Kunieda and Rokugo 2006).

5.4 ECC Steel Composite Bridge deck

A slab of Mihara bridge in Hokkaido, Japan was constructed using ECC. Mihara bridge is a newly constructed cable stayed bridge built in 2005 that is 1,000 m long with a maximum span length of 340 m in the middle. The superstructure of the bridge is composed of steel girders and ECC slab having composite behavior. The thickness of ECC slab was 38 mm and the area of the ECC slab was 20,000 m^2. The design service life of the ECC steel composite deck is 100 years, and a significantly reduced life-cycle cost is expected (Li 2014).

Figure 5-5 Construction of ECC Steel Composite Bridge Deck at Mihara Bridge in Hokkaido, Japan

5.5 Structural Members

Kanda et al. (2011) reported a construction case of ECC beams in a high-rise building at Osaka, Japan. The ECC coupling beams connect the columns of 60-story reinforced concrete building and are key members for seismic load resistance.

Although those are not field applications, full scale laboratory tests have been conducted for various structural elements made of ECC as follows:

- Bending beams subjected to monotonic and cyclic loads were conducted by Fischer and Li (2002; 2003) and Kim et al. (2004). Shear beam (deep beam) elements made of ECC were tested by Kanda et al. (1998), Fukuyama et al. (2000), and Shimizu et al. (2006).
- The behavior of ECC beam-column connections under reversed cyclic loads were tested by Fukuyama et al. (2000), Parra-Montesinos and Wight (2000), and Yuan et al. (2013).
- The behavior of ECC wall elements subjected to reversed cyclic loads were investigated by Kanda et al. (1998), Kesner and Billington (2005) and Fukuyama et al. (2006).

Chapter 6. State-of-the-Practice Survey

6.1 Survey Questionnaire

As a part of the investigation on the state-of-the-practice of ECC, a survey was conducted for the engineers in industry and academia. The survey questionnaire is composed of five parts as follows:

- Brief introduction to ECC including the properties, mixture design, and environmental/economic considerations of ECC
- Questions on the background information of the survey respondents (Set A, six questions)
- Questions on the practical applications of ECC (Set B, three questions)
- Questions on the barriers in ECC applications (Set C, two questions)
- Question on ECC experience

The survey questions are listed below:

Question Set A: The following questions provide us information about your background:

Q1. In what sector you work?
- Government
- Industry
- Education
- Research
- Other (please specify)

Q2. Select your area of expertise and write the years of your professional experience (you can select multiple answers):
- Structural Engineering
- Construction Materials
- Construction Engineering and Management
- Transportation Engineering
- Geotechnical Engineering
- Environmental Engineering
- Water Resource Engineering
- Other (please specify):

Q3. In what state (or country) you work?

Q4. Do you have engineering license(s)? If YES, please list your engineering license(s) and when did you obtain (e.g., EIT 2015, PE 2019):

Q5. What is your level of understanding on ECC (you can select multiple answers)?
- Level 5: I have experience of using ECC for practical applications
- Level 4: I have research/lab test experience of using ECC
- Level 3: I know well about ECC, but do not have direct experience using ECC
- Level 2: I heard about ECC, but do not much about it
- Level 1: I never heard about ECC

Q6. [Optional Question] If you provide your name, affiliation, and preferred contact information, we may contact you later for more information:

Question Set B: The list below shows the practical applications of ECC reported by various investigators. Please answer the questions about the list:

(a) Pavement overlay made of ECC
(b) Repair of concrete pavement
(c) Replacing bridge deck joints with ECC known as ECC link slab)
(d) Bridge deck repair (surface & slab)
(e) Beam-column joints of critical structural members
(f) Sprayable ECC (shotcrete for repair)
(g) Fire resistant wall/panel
(h) Blast/impact resistant panel

Q7. Please select practically feasible ECC applications from the list, and rank the selected applications starting from the most suitable one (Example: if you select b, c, d, e and think that c is the most suitable one then write **c-d-b-e**)

Q8. Please explain about your rank and selections. What attributes of ECC make your selected applications suitable?

Q9. Texas climate is categorized by hot-humid (eastern Texas) and hot-dry (western Texas). Considering Texas climate, what is the best ECC application(s) in Texas?

Question Set C: Following questions ask about barriers in widespread use of ECC. The examples of possible barriers in practical applications are: lack of accumulated construction experience/data, high initial cost, lack of material quality test, and others.

Q10. What are the barriers hindering the practical applications of ECC?

Q11. What research, improvements, or supports are needed to overcome such barriers against ECC applications?

Question Set D: Your experience on ECC or fiber reinforced concrete

Q12. If you have laboratory or construction experience related to ECC or fiber reinforced concrete, please share your experience with details (strengths, weaknesses, and your suggestions for improvements)

6.2 Collected Data

6.2.1 The Background Information of the Survey Respondents

The survey questionnaire was distributed to the experts in various sectors and collected. The research team received 12 responses with respondent backgrounds including two from government, five from industry, and five from research/educational institutes. The areas of expertise of the respondents are structural (5), materials (6), construction/management (3), transportation (1), Geotechnical (2), environmental (2), and water resource (1). Some respondents have multiple areas of expertise/experience, but most of them have experience in structural/materials engineering. The years of professional experience of the respondents range from 3 years to 19 years, and the average years of experience was 13.4 years. Figure 6-1 shows the years of professional experience of the survey respondents in each area. The numbers in the chart indicate total years of experience of the respondents per each area. For example, 66 years in materials was obtained by adding the years of experience of all respondents in materials engineering.

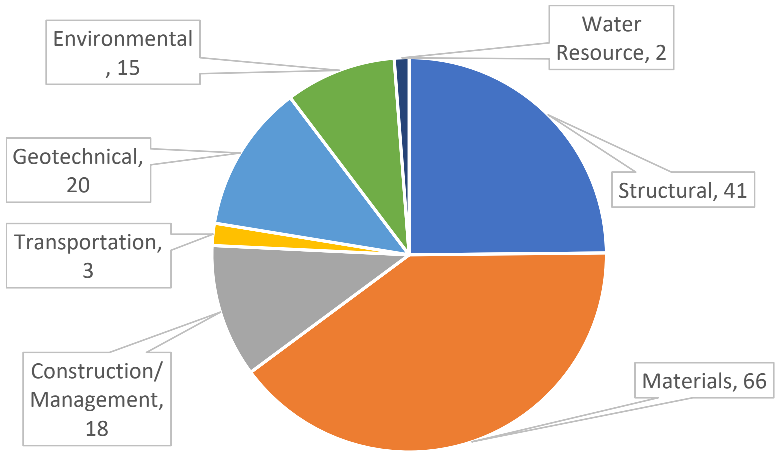

Figure 6-1 The Years of Professional Experience of the Survey Respondents in Each Area

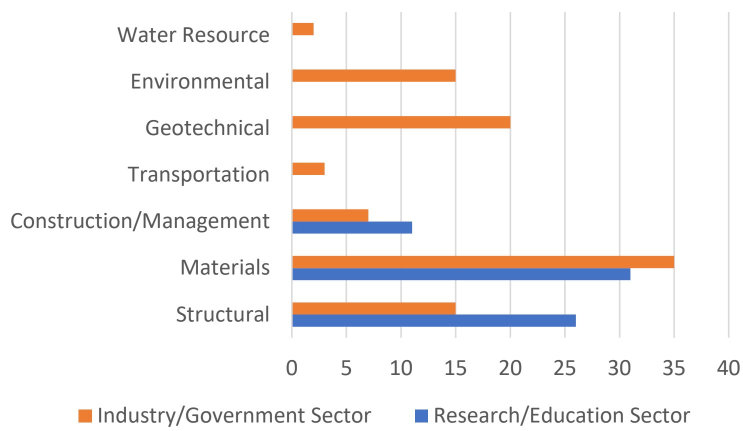

Figure 6-2 The Years of Experience in Each Area of the Experts in Industry/Government Sector and Research/Education Sector

In Figure 6-2, the respondents are broken into two groups based on their sectors: the industry/government sector and the research/education sector. Their years of experience in each area are shown for each group. The reason for this separation is that the approach and point of view on a relatively new technology such as ECC is likely to vary based on professional sector. The experts in industry/government sector have more practical experience and may consider practical aspects of new technology. The other group, the experts in research/education sector are prone to be exposed to new technologies and may be interested in their possibilities. They often lack recent practical experience with field applications. Another tendency can be found in Figure 6-2. The respondents in industry/government have various experience in all areas while the experience of the respondents in research/education is limited within Materials, structural, and construction engineering.

Most of the respondents work in Texas. The respondents out of Texas were two from Nebraska (research/education sector) and one from New York (research/education sector). 75% of the respondents have PE licenses, and all respondents from government/industry have PE licenses. 25% of the respondents who do not have a PE license work in research/education sector and have Pd.D. degree.

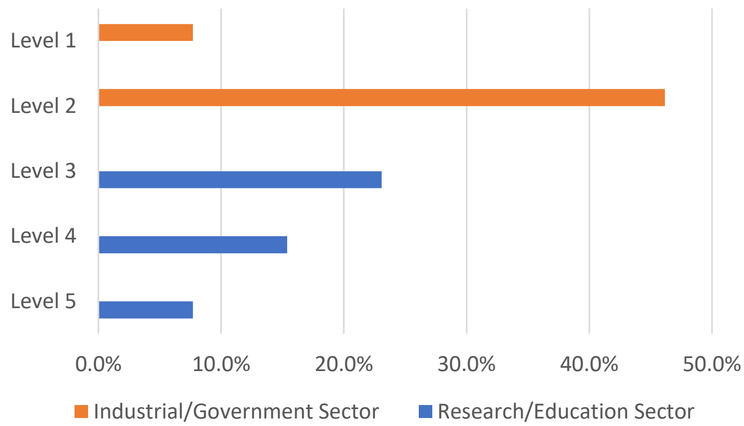

Figure 6-3 The Level of Understandings on ECC

The survey question 5 (Q5) asked about the level of understanding of ECC technology. Based on Q5, the respondents can be grouped into two: the group with good understanding about ECC (experience group, Level 3, 4, and 5) and the group with less information about ECC (no-experience group, Level 1 and 2). In case of respondents in Level 3, they have experience in fiber reinforced concrete (but not in ECC). Figure 6-3 shows the distribution of the ECC understanding levels of the experts. All respondents in the industry/government sector are included in the no-experience group (Level 1 and 2) and all respondents in the research/education sector are included in the experienced group. Considering that there have been not many practical applications of ECC worldwide, no-experience of the experts in industry/government sector is not surprising. In case of the research/education sector, it is likely that the experts who are interested in ECC would be most likely to respond to the survey of all the experts who received it.

Since the experience, perspective, and level of understandings of ECC in the two groups are different, it would be meaningful to separate the responses of these two groups in the evaluation of the survey. The following discussion of the survey results are made for all responses as well as for the responses from the separated groups.

6.2.2 Practical Applications of ECC

Respondents were asked about the feasibility of eight applications of ECC (listed below) through the survey questions 7-9 (Q7 – Q9). The list below – the reported ECC applications – was obtained from the literature review.

(a) Pavement overlay made of ECC
(b) Repair of concrete pavement
(c) Replacing bridge deck joints with ECC known as ECC link slab)
(d) Bridge deck repair (surface & slab)
(e) Beam-column joints of critical structural members
(f) Sprayable ECC (shotcrete for repair)
(g) Fire resistant wall/panel
(h) Blast/impact resistant panel

The survey question 7 (Q7) asked respondents to rank the applications starting from the most suitable among the listed applications. To determine a suitability weight, numbered scores were given to the rank from 8 to 1 with highest suitability given an 8.

In addition to the listed applications, some respondents suggested applications not in the list: concrete floor deck (floor in buildings) and tilt-up wall. The tilt-up wall is a type of a building construction technique. Tilt-up walls are formed and cured in horizontal position, often off-site, then transported to the site where they are tilted to the vertical position and attached to a foundation and each other. The tilt-up method is a fast and cost-effective construction technique.

Figure 6-4 shows the distribution of the points (in % of the total points) from all respondents on the various applications. The use of ECC for bridge deck repair earned the highest points (19 %), and repair of concrete pavement earned the second (16 %). By adding sprayable ECC (shotcrete for repair, 8 %), the total point for the repair applications of ECC was 43 %. The ECC applications to pavement overlay and bridge deck joint obtained 15 % of points respectively. The ECC applications to bridges (repair and bridge joint) earned 34 % and to pavements (overlay and concrete pavement repair) earned 31 %.

Figure 6-5 shows the ECC suitability points voted from the industry/government group (no-experience group) and research/education group (experience group) separately. The overall trend is similar in both groups – applications (a), (b), (c), (d) have higher points than others –, and there are no notable differences.

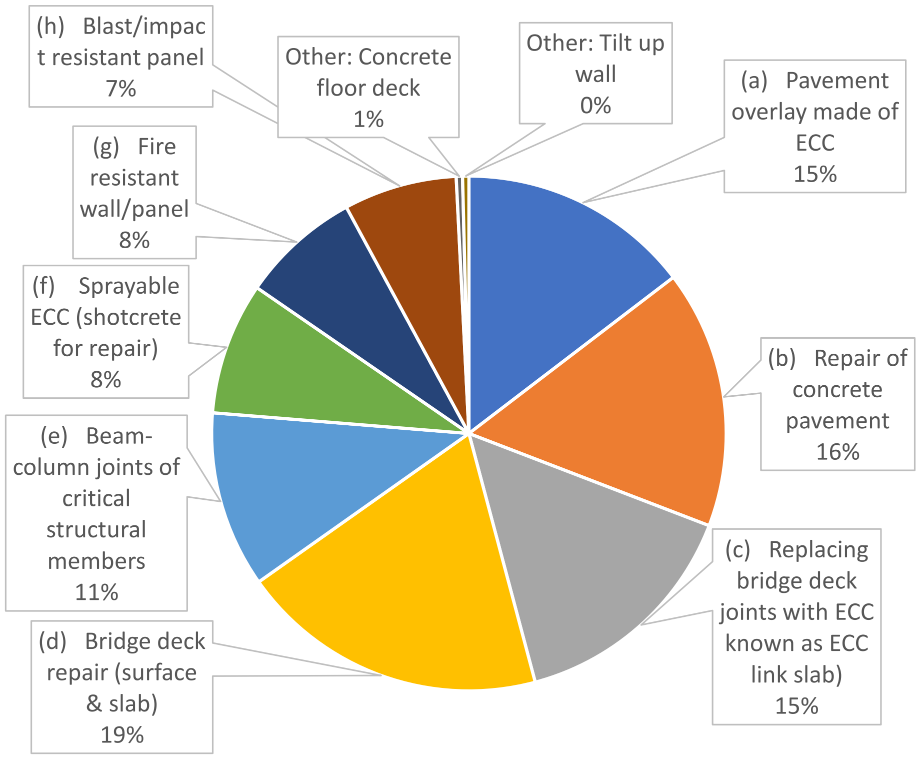

Figure 6-4 The Suitable ECC Applications Voted from the Survey

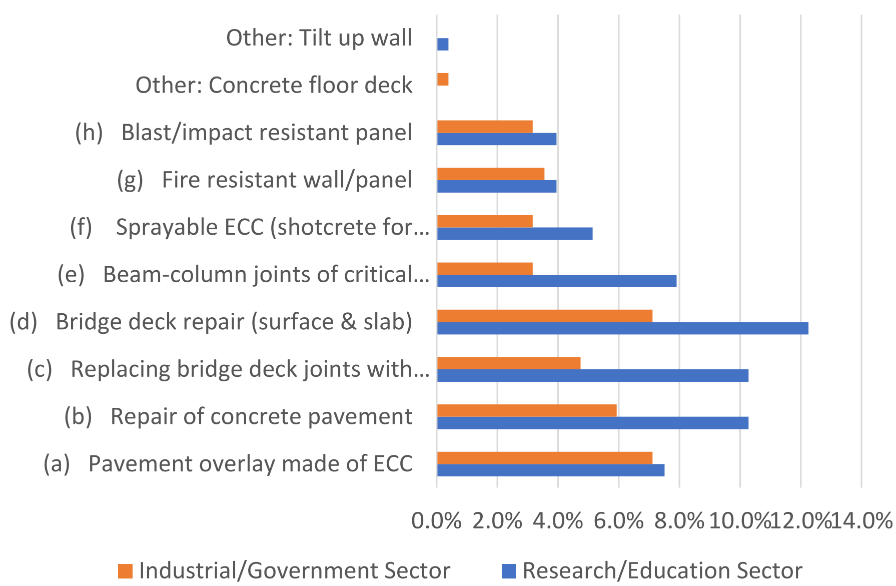

Figure 6-5 The Suitable ECC Applications Voted by Two Groups of the Experts: Industry/Government Sector and Research/Education Sector

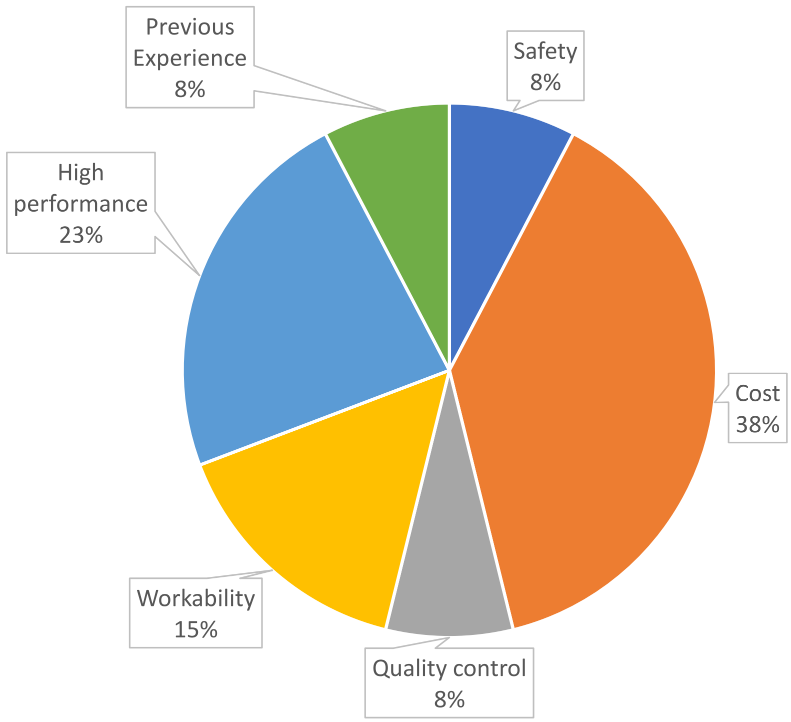

Figure 6-6 The Considerable Attributes in ECC Applications

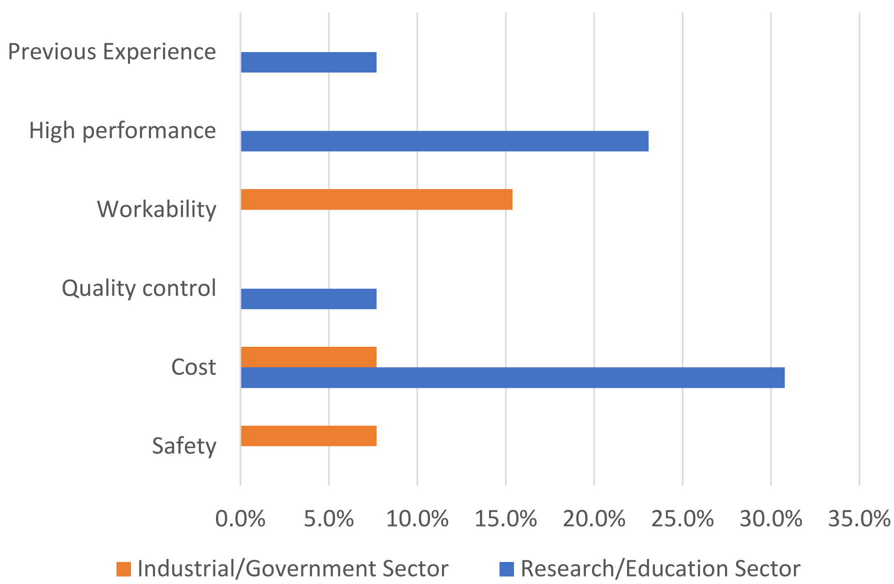

Figure 6-7 The Considerable Attributes in ECC Applications Voted by Two Groups of the Experts: Industry/Government Sector and Research/Education Sector

The survey question 8 (Q8) asked what attributes of ECC make them suitable for the respondents' selections from applications. Examples were not given, and the respondents wrote the attributes of consideration in their own words. The responses can be categorized into six factors: structural safety, cost, quality control, workability, high-performance, and previous experience. The distribution of these factors is shown in Figure 6-6. The cost was selected as the first consideration in using ECC and the high-performance of ECC follows. It should be noted that some attributes were selected for different reasons. For example, some respondents selected only repair applications because the initial cost of ECC is too high to apply ECC to whole members while some respondents made their selections because the life-cycle cost of ECC is lower than traditional concrete.

The responses on the considerable attributes of ECC were divided in the two expert groups. As shown in Figure 6-7, the experts in industry/government sector selected workability, safety, and cost while the experts in research/education sector selected cost, high-performance, previous experience, and quality control. An interesting selection was the high interest of industry/government sector on the workability of ECC.

Some responses on Q8 are listed below:

- An expert in industry sector: "*I see ECC being practical for horizontal applications such as pavements and bridge decks. For vertical repair applications, ECC would have to compete with non-shrink grout and spray applied fireproofing which is very dominant in vertical construction*."

- An expert in industry sector: "*55% fly ash and plasticizer seem to indicate proper use for most applications such as slabs, pavings, and vertical members. The lack of coarse aggregate I think makes these applications (b-d-e-g) more suitable. Tilt up wall may be another application to consider*."

- An expert in research sector: "*First of all, (a), (b), (c), (d) from the list looks most feasible ECC applications for many of our aging bridge infrastructures. With limited budget from state DOTs, it may make sense for repair/replacement projects which is the reason, I chose (b) and (d) first. Yet, if overlays could be initially made of ECC and deck joints which has a lot of problems could be eventually replaced with ECC, that would also be a feasible application. Do not have much information about sprayable ECC but this could also be a good method to repair locations of damage in structural concrete. Due to the increased ductility of concrete, structures that need to absorb energy as in blast/impact applications, (h) would also be a feasible option. In addition, (e) would also be a feasible application due to the improvements in material properties such as the increase in ductility. However, steel reinforcement will contribute more in this case than the improved ductility of concrete which is the reason I listed (h) and (e) towards the end. Regarding fire resistance, what matters most is the concrete cover thickness to the steel reinforcement that will govern the behavior of structural concrete under fire. Depending on the temperature and duration of the fire, designers may increase the thickness of concrete cover to improve the fire resistance of structural concrete and ECC could* *possibly help hold the cover for a longer time under elevated temperature until the fire reaches the steel reinforcement, but this seems to be the most least feasible application among the list provided above*."

- An expert in research sector: "*The observed characteristics (e.g., reduction or elimination of shear reinforcement, sustaining large imposed deformation, compatible deformation between ECC and reinforcement, synergistic interaction with FRP reinforcement, and high damage tolerance and reduction) of ECC structural elements can be applied to (i) structures requiring collapse resistance under severe mechanical loading and (ii) structures requiring durability even when subjected to harsh environmental loading*."

- An expert in education sector: "*d and c are strategic applications of ECC that have been demonstrated. e (or a similar application – coupling beams) has been utilized in Japan for seismic resistance. a has also been demonstrated; however, it could be cost-prohibitive. g has been demonstrated in the lab, but I am not aware of field testing – however, other polymer fiber-reinforced concretes (not ECC) have been tested for use in tunnel lining for fire protection. Other applications are either cost-prohibitive or less effective (blast/impact resistance).*"

- An expert in education sector: "*ECC is a material with unique mechanical behavior, but likely too expensive for normal applications*."

The survey question 9 (Q9) asked what the best ECC application in Texas is considering Texas climate. Figures 6-8 and 6-9 show the results. Comparing to Figures 6-4 and 6-5 (rank suitable ECC applications in general), the results in Figures 6-8 and 6-9 do not use weight points, i.e., each vote was counted as one point. The results for Texas do not show much difference when compared to the earlier results in Figures 6-4 and 6-5. The applications to a, b, c, and d were considered as the best ECC applications. One of the responses from an expert in education sector explains these results: "*I see ECC's advantage is more on mechanical behavior, rather than environmental/climate (as such in shrinkage cracking). With that, I don't see much difference in the different locations in Texas*." The other comments on Q9 are listed below:

- An expert in research sector: "*Although, there is not much temperature change in Texas as in Midwestern area of US and the use of deicing salt is limited, there are still bridges near the coastal area where it is exposed to the marine environment and since bridge decks and pavements will have restrained shrinkage cracks from the start of their service life, there will be transverse cracks that becomes the path of deterioration in many bridge decks, overlays, and pavements. Either repair, or new construction for bridge decks, overlays, and pavements using ECC would be the best ECC applications in Texas. Since there is less temperature change, joints may last longer than the cases in Midwest*."

- An expert in education sector: "*Compared to the northern states, bridges might be less prone to corrosion (except for the south-east Texas closer to the Gulf) – so d and c might not be important. e and g could be useful for resilience against extreme events in Texas such hurricanes and fires*."

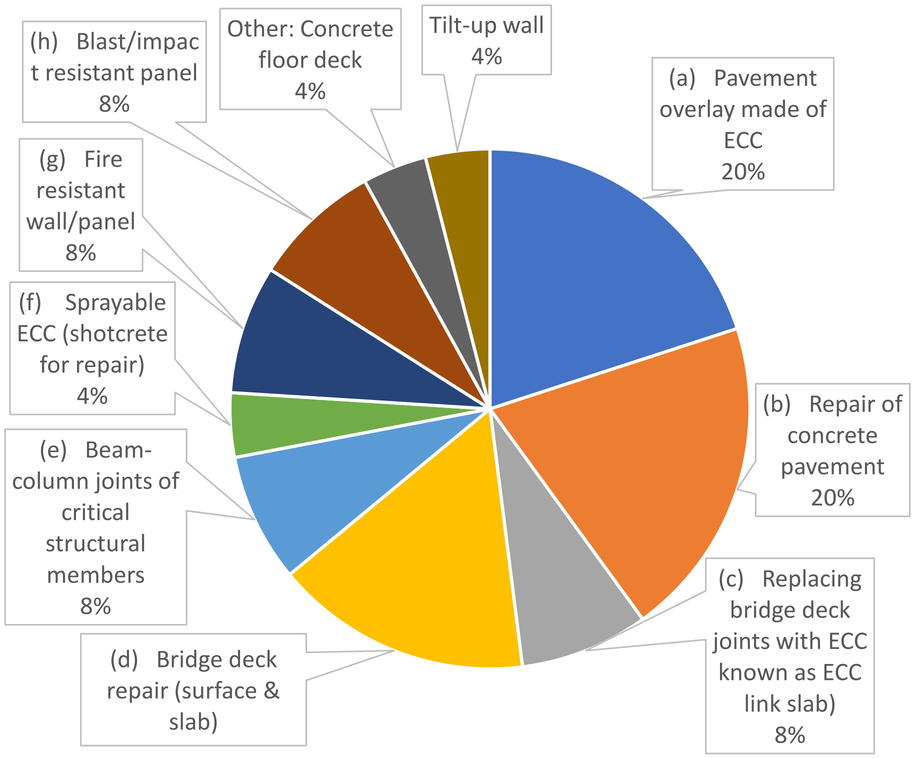

Figure 6-8 The Suitable ECC Applications in Texas

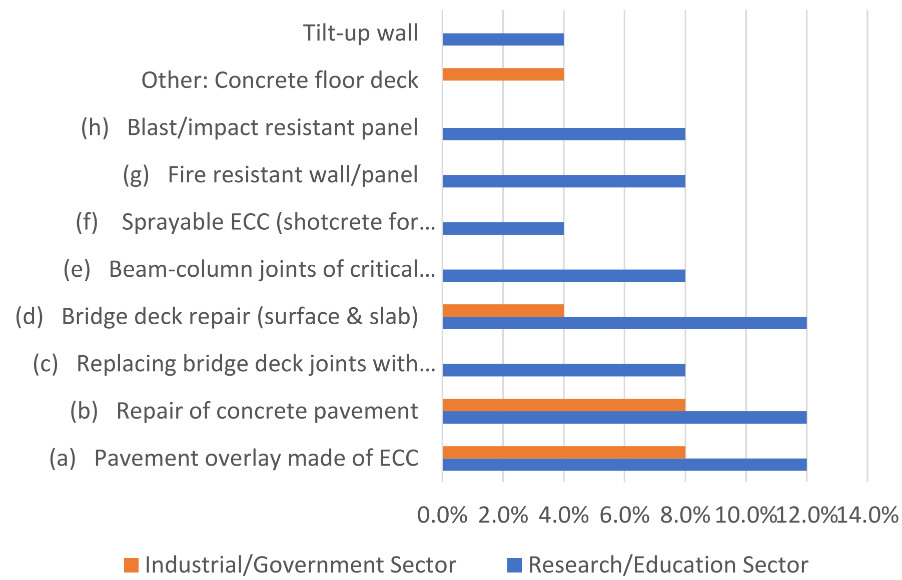

Figure 6-9 The Suitable ECC Applications in Texas Voted by Two Groups of the Experts: Industry/Government Sector and Research/Education Sector

6.2.3 The Barriers Against ECC Applications

The survey question 10 (Q10) asked about the barriers to practical applications of ECC. Figures 6-10 and 6-11 summarize the responses to Q10. Followings are the list of barriers mentioned in the responses:

- Quality control (lack of standard material test for ECC, 26 %): The most important benefit of ECC is the superior tensile ductility with strain-hardening, and hence, a standardized method for evaluating the tensile properties is essential for the quality control of ECC (and for fiber reinforced concrete). The difficulty in quality control caused by the lack of standard material test was the most frequently mentioned barrier in practical ECC applications. This barrier was pointed out by both expert groups in industrial/government and research/education sectors.
- No experience in using ECC (21 %): The lack of previous experience was the second frequently mentioned barrier with the high initial cost. The lack of previous experience was mentioned more by the experts in industry/government sector (the group with less experience in ECC). In research/education sector, only one expert stated that no-experience is a barrier. This divided opinion between two group can be explained by experts in research/education sector having more direct/indirect experience of using ECC. The divided opinion also implies that the state-of-the-practice of ECC is validated in research but not widely used in practice. The barrier of no-experience is somewhat related to another barrier – lack of information that will be discussed later.

- High initial cost (21%): High initial cost of ECC is selected as another frequently mentioned barriers in this survey. High initial cost is the first question asked by practical engineers when ECC was introduced. There are many LCCA and LCA results which show that the life-cycle cost of ECC can be lower than traditional concrete, and the economic benefit of ECC need to be promoted to practical engineers. The interesting observation is that none of the experts in industry/government group mention high initial cost as a barrier.
- Lack of information or preconception (16 %): The lack of information or preconception on ECC was mentioned as a barrier, mostly by the experts in industry/government group.
- Lack of standard specification (11 %): The lack of standard specification was mentioned by both expert groups. Even though the need for the standard specification was ranked fifth, this is an important barrier that must be resolved. If the standard specification of ECC is provided, practical engineers may not suffer from the lack of information and experience. At the federal level, ACI committee on fiber reinforced concrete is working on ACI specification.
- Lack of material suppliers (5 %): The lack of material supplier is pointed out as a barrier. PVA fiber is typically used for ECC, but the quality of PVA fiber varies widely with the producers. In addition, according to an expert with a lot of experience in ECC, it is difficult to find good quality fly ash. This issue can be resolved with the growth of ECC or fiber reinforced concrete market but fostering raw material producers may be needed in the initial stage of ECC applications. In addition, relevant standards for PVA fibers and acceptance tests or certifications will be needed to assure fiber consistency.

Selected comments on Q10 from industry/government sector are listed below:

- "*Quality Control: Controlled mixture practice and Perception: lack of coarse aggregate may prove to have traditional methods have preference*."
- "*Lack of contractors' experience with ECC, lack of material quality tests, and the "fear" of the unknown for those that have never used ECC on their projects*."
- "*No standard material specification available*."
- "*Lack of promotion for ECC to agencies*."
- "*Lack of construction experience of both agencies and contractors*."

Selected comments on Q10 from research/education sector are listed below:

- "*High initial cost. Might not be in the specifications in different DOTs*."
- "*Initial material cost is high but not a barrier for strategic applications with minimal use of ECC (e.g. link slab). Cost of ECC is significantly lesser than UHPC*."
- "*Biggest barrier is lack of material supplier. Good quality fly ash (a key component of ECC) is not readily available – resulting in huge variability of material properties*."
- "*Lack of experience in handling the material*."

- "*The initial barrier was possibly the high initial cost and lack of test data and construction experience. However, there has been more than two decades of research data regarding ECC applications, and adding fiber into concrete mixes are no longer a huge barrier due to the increased number and accumulated construction experience over the past two decades. With the increase in use of high-strength reinforcement nationwide, there is also a change in the technical committees nationwide to investigate into the possibilities of implementing ultra-high or high performance concrete which will only help the increase of use of ECC which is the subgroup of UHPC or HPC. In addition, in terms of the life cycle cost of these deteriorating/aging structural applications, it makes sense to increase the ECC applications where problems are observed in a repeated manner.*"

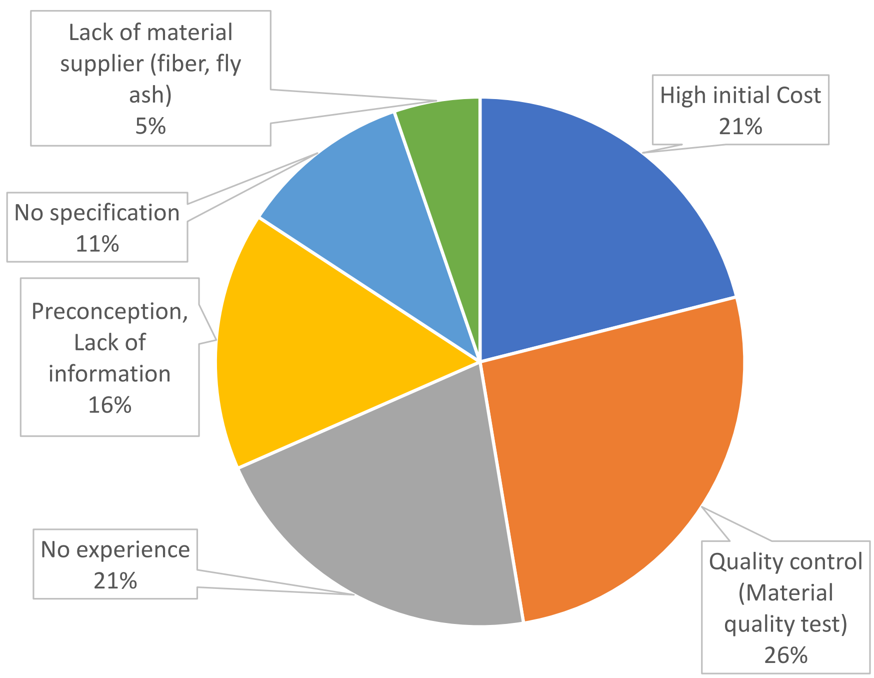

Figure 6-10 The Barriers Against the Practical Applications of ECC

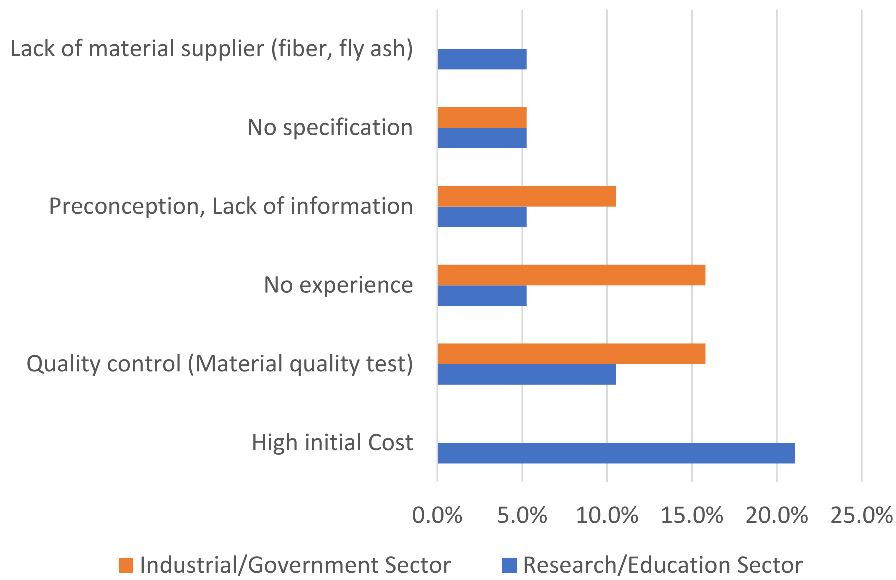

Figure 6-11 The Barriers against the Practical Applications of ECC Voted by Two Groups of the Experts: Industry/Government Sector and Research/Education Sector

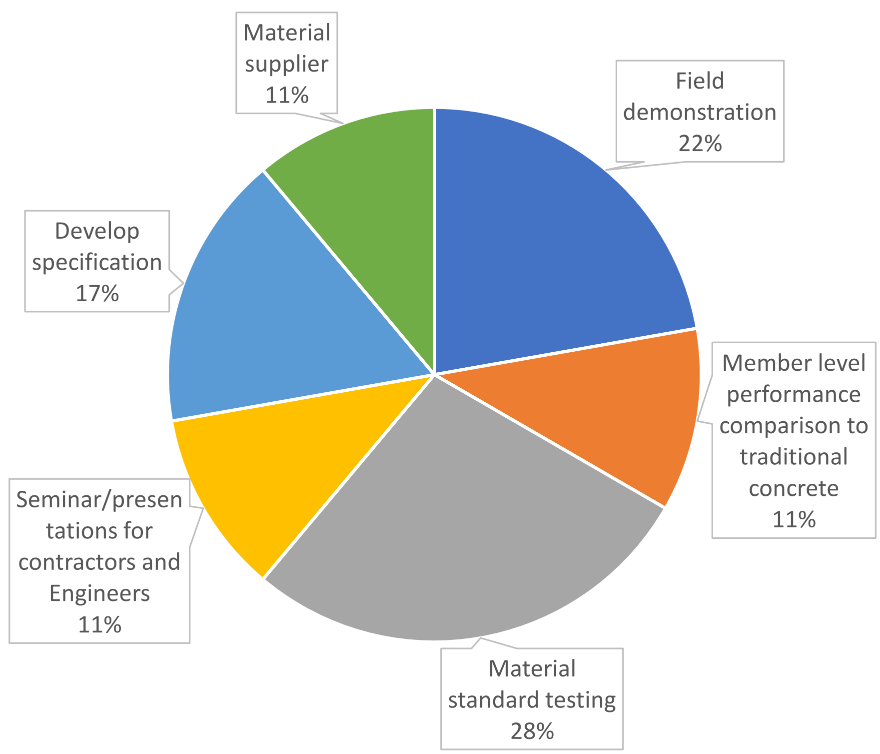

Figure 6-12 The Demands for Research and Supports for ECC Applications

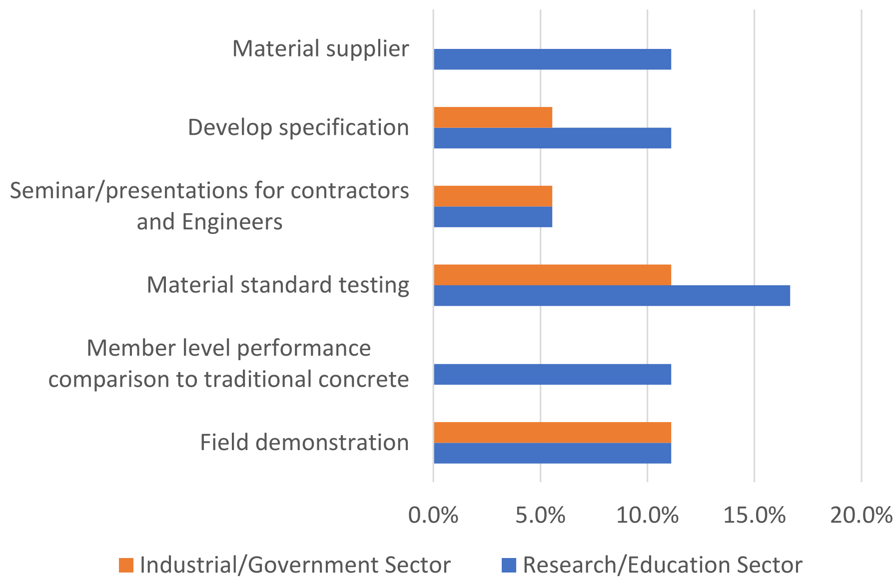

Figure 6-13 The Demands for Research and Supports for ECC Applications Voted by Two Groups of the Experts: Industry/Government Sector and Research/Education Sector

The survey question 11 (Q11) asked about the research/support demands to overcome the barriers of ECC applications asked in Q10. The responses to Q11 are summarized in Figures 6-12 and 6-13.

Selected comments on Q10 from industry/government sector are listed below:

- "*Materials testing research of ECC and seminars/presentations on ECC applications for Contractors and Civil Engineers*."
- "*Develop material standards for ECC. Since ECC has traditional concrete materials, develop an ACI Committee specialized in researching ECC and practical design methodologies that will bridge the gap between research and practice*."
- "*For horizontal applications, national and state entities such as FAA and DOT's need to incorporate it into their specifications and their most practical benefits. For vertical applications, entities such as ACI, ICC, UL, and ASTM need to develop material standards and specifications for it. Obviously, this implies more material quality testing and substantiating ECC exceeds the performance requirements of its respectively application competitors currently in practice*."
- "*Application in flexural/compression members and side by side comparison to traditional approaches. Comparison in capacity, initial cracking results, and environmental exposures*."

- "*Look for test sections to evaluate the performance of ECC*."

Selected comments on Q10 from industry/government sector are listed below:

- "*Quality control methods for testing ECC*."
- "*Structural design guidelines are needed for implementation*."
- "*It would be helpful for the state DOTs to implement ECC applications for new construction in more cases and by collecting field measurement data over a long-term may prove that in terms of the life-cycle cost, ECC applications would be more beneficial and work well for the DOT applications. In addition to the material testing that has already been conducted in previous research, structural testing (flexural and shear) for such applications would be helpful to increase the number of test data for verification*."
- "*Start with some demonstration projects for DOTs and work with them to get it included in DOT specs*."
- "*Optimization of ECC mixture for applications in Texas by using local available materials should be investigated. For example, domestically manufactured PVA fibers with no surface coating and locally available river sand might be used to successfully develop ECC mixture with desired high impact resistance and low cost*."
- "*ECC development with less reliance on fly ash*."

The responses shown in Figures 6-12 and 6-13 and the comments listed above can be summarized as follows:

- Development of a material testing standard for quality control of ECC
- Development of standard specification for ECC
- Demonstration of ECC performance through field applications or member level experiments
- Promotion and dissemination of ECC information
- Further materials research: tests of local materials and ECC with less reliance on fly ash

An interesting observation from the comments is that most of the comments from industry/government group emphasize the demands for standard specifications (materials test and construction) while the comments from research/education group emphasize the needs for field/member level demonstrations.

The survey question 12 (Q12) asked to share their experience about ECC or fiber reinforced concrete. Below are the responses to Q12:

- An expert in industry sector: "*On certain commercial projects that I have worked on, I've noticed certain contractors use fiber reinforced concrete whenever the Civil Engineers allow it on their projects and when the rebar size is small, in comparison to the traffic loading parameters. As a materials testing lab engineer, our CMT technicians test the fiber reinforced concrete in the same manner as traditional PCC mixes in terms of its slump, air content, etc*."

- An expert in industry sector: "*I have experience with plain FRC slabs-on-grade. This was a VE exercise to reduce costs and majority of the slab-on-grade reinforcing was removed. Reinforcing was only provided close to the perimeter edge where the flexural moment exceeded the cracking moment. On strength using the FRC is that there is virtually little to no cracking in the slab, even after months of it in place. A weakness is that owners, architects, and contractors developed a misconception that you don't have to provide mild steel reinforcing in FRC; thus, structural engineers are burden with the explanation of why elevated concrete framing still need mild steel*."

- An expert in research sector: "*We have been conducting large-scale testing (flexural and shear tests) with fiber reinforced concrete used at longitudinal or transverse joints between single T beams. We compared these test results with the case using mechanical joints with threaded bars, commercial mixes, and mixes developed in our university. Flexural and shear strengths were highly improved when steel fibers were added into the mix as expected. Yet, to improve the workability of the commercial mixes available, we have been developing our own mixes with steel fibers that are flowable (comparable to self-consolidating concrete) in order to cast large amounts of mixes in a limited time frame. Improved workability would be crucial and important thinking of the amount needed to be poured at a real bridge site within a limited hardening time*."

- An expert in research sector: "*I have done a couple of projects related to FRC and UHPC. To me, ECC, FRC, and UHPC are all in the same family, but with different focus and different applications. It will be good to expand the spectrum of the family to cover different needs based on cost, applications, and material characteristics*."

6.3 Summary and Conclusion

Among the reported ECC applications, the survey respondents recommended the following four applications as suitable. Both expert groups (industry/government sector and research/education sector) show similar opinions on these recommendations.

- Pavement overlay made of ECC

- Repair of concrete pavement
- Replacing bridge deck joints with ECC known as ECC link slab)
- Bridge deck repair (surface & slab)

In addition to the listed applications, the application to tilt-up wall and concrete floor deck was suggested.

The survey also investigated the barriers against practical ECC applications, and following six barriers were mentioned in the responses:

- Quality control (lack of standard material test for ECC)
- No experience in using ECC
- High initial cost
- Lack of information or preconception
- Lack of standard specification
- Lack of material suppliers

In order to overcome the barriers, the following research/support efforts were proposed by the respondents:

- Development of a material testing standard for quality control of ECC
- Development of standard specification for ECC
- Demonstration of ECC performance through field applications or member level experiments
- Promotion and dissemination of ECC information
- Further materials research: tests of local materials and ECC with less reliance on fly ash

Chapter 7. Life Cycle Assessment (LCA) and Life Cycle Cost Analysis (LCCA) of ECC Applications

7.1 Introduction to LCA and LLCA

Life-cycle assessment (LCA), is an environmental approach to assess the use of resources from “cradle to grave” and any release of pollutants associated with the manufacturing of the product. The environmental assessment includes the energy consumed from the extraction of the raw materials, production, operation and maintenance of the product, and the disposal of the product. LCA is used to evaluate the environmental merit of the project.

Life-cycle cost analysis (LCCA), is a method used to evaluate all the costs associated with the project. This method considers initial costs, capital investments, purchases, installation costs, future cost, energy costs, operating, maintenance, replacement, salvage, and disposal costs. LCCA is used as an engineering economic analysis for comparing the merit of different projects. Cost-Benefit Analysis is the process where the project is evaluated entirely through an economic standpoint. Belay et al. (2016) defines the Cost Benefit Analysis (CBA) as an analytical tool that uses theory, data, and models to determine the most appropriate alternatives. The project is evaluated and selected by comparing the benefits to the cost.

There have been a few publications on the LCA or the LCCA of ECC. Zhang et al. (2010), Qian et al. (2012), and Zhang et al. (2008) came to the same conclusion that ECC overlays produce 32-37% less overall pollution and a 39.2-55.7% reduction in costs compared to HMA and traditional concrete overlays. The authors of these publications shared the same overlay parameters needed for the analysis (mixture design and structural design of the overlay systems). These analyses uses a 10 km strip of road, with an AADT of 70,000 vehicles including 8% heavy traffic. Keoleian et al. (2005) conducted the LCA for ECC link-slab and traditional expansion joints. Compared to the conventional steel expansion joints, the ECC link-slab requires 40% less energy and 38% less raw material consumption.

Most publications regarding the LCA/LCCA of ECC have been led by the University of Michigan. Currently, there is no known publication regarding the LCA/LCCA of an ECC application in Texas. An LCA/LCCA analysis of using ECC in Texas can be tailored to consider local traffic, maintenance, and climate conditions.

The objective of this analysis is to compare the environmental and economic impacts of ECC to those of traditional alternatives using parameters that are suited to the traffic and DOT guidelines of Texas. A series of LCA and LCCA were conducted for two ECC applications: pavement overlay and bridge link-slab. The economic, environmental, and social impacts of ECC are compared to traditional pavement overlays (HMA and concrete) and bridge expansion joints.

In the LCA, the analysis was divided into six modules: materials production, construction, distribution, traffic congestion, usage, and end of life (EOL). The social impact is evaluated by determining the effects on the user's everyday life. This could be monetary impact, or health impacts. Previous investigators claimed that more than 80% of the total cost for overlay systems comes from user cost (Zhang et al. 2010; Keoleian et al. 2005; and Lepech and Li 2010).

The LCCA accounts for 3 costs: internal costs (agency costs), user costs (social costs), and environmental costs (Zhang et al. 2008). The agency costs include the expenses for construction and maintenance, while the user costs accounts for the expenses of users generated by detours or traffic delays due to construction activities. Environmental costs accounts for the damage to the environment as a result of the material production and any other related events.

7.2 Methodology

LCA and the LCCA can be conducted by using software. Choi et al. (2016) and Rew et al. (2018) used EIO-LCA (economic input–output lifecycle assessment) developed by Carnegie Mellon University (CMU 2011) to evaluate the environmental impact of pavement systems and airfields. Zhang et al. (2010) used MOVES (MOtor Vehicle Emission Simulator, previously known as MOBILE 6.2) provided by US Environmental Protection Agency (EPA) to consider the effects of traffic congestion caused by road constructions.

EIO-LCA is used in this research to evaluate the environmental impact of the materials used for ECC and traditional materials. As basic information, the database of EIO-LCA utilizes various public datasets provided by government agencies such as the EPA, The United States Census Bureau, Department of Commerce, and many others.

EIO-LCA is an LCA tool for general civil infrastructures and does not consider the effects on traffic due to road constructions. The ECC applications considered herein – pavement overlay and bridge link-slab – are the parts of roads, and the considerations for the traffic delay due to construction are mandatory in these analyses. To evaluate congestion and usage of roads, MOVES ONROAD is used in this research. This software uses data collected by the agency to evaluate vehicle emissions during construction. In addition, the condition of roads also influences vehicle emissions. The variation of IRI (International Roughness Index) during the life of pavements was considered to evaluate the vehicle emission.

The FHWA's RealCost 2.5 was used to determine the Life Cycle Cost and help determine the Cost-Benefit of the project. RealCost 2.5 requires inputs from the initial construction costs, traffic data on that location, and data from the costs of maintenance and rehabilitations. This software can create a cash flow chart to describe the use of money throughout the life-cycle and Present Values (PV). Figures 7-1 and 7-2 illustrate the LCA and LCCA models used in these analyses.

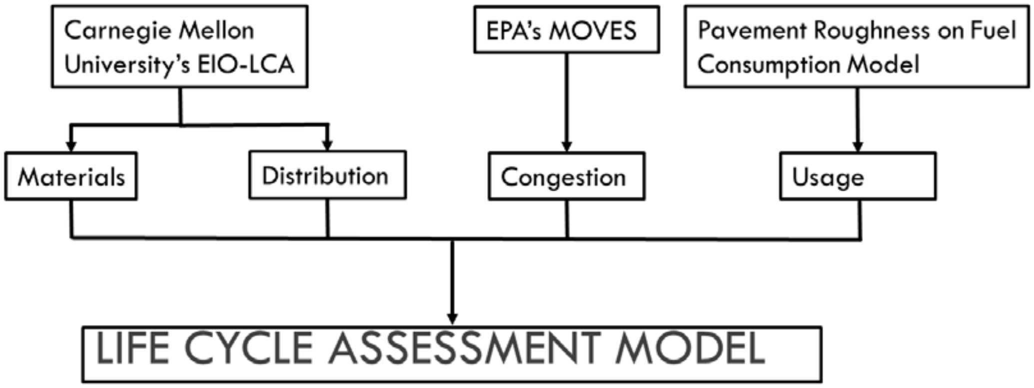

Figure 7-1 LCA Model Showing the Assessment Strategy

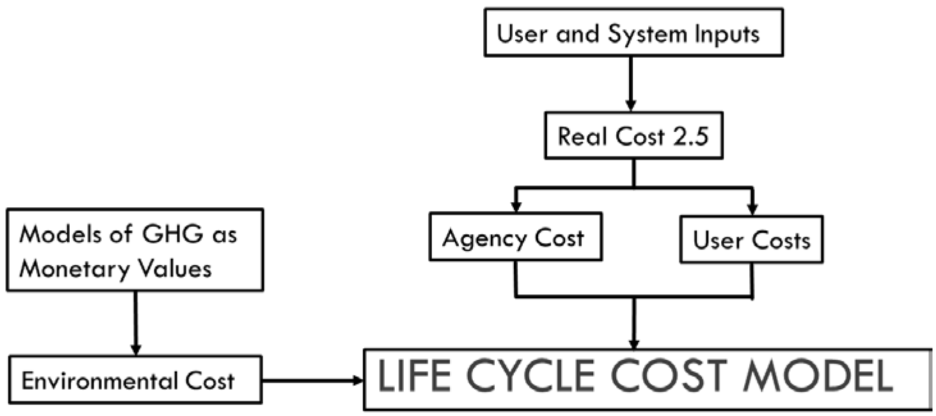

Figure 7-2 LCCA Model Showing the Analysis Strategy

7.3 Assumptions and Scenarios

To compare and evaluate the environmental and economic impacts of various materials, a set of scenarios were created with real life assumptions. Two ECC applications were compared to traditional materials:

- ECC overlay compared to conventional concrete and HMA overlays
- ECC link-slab compared to traditional bridge expansion joints

In the analyses of overlay systems, two maintenance timelines and analysis period were used: 1) the timelines used by Zhang et al. (2010) and 2) the timeline based on TxDOT LCCA guidelines for pavement (Texas DOT 2019).

Zhang et al. (2010) conducted LCA for pavement overlay systems made of ECC, concrete, and HMA. This analysis assumed that the overlay systems are installed for a length of 10-miles with two lanes in both directions. The life cycle analyzed was 40 years. The first analysis on overlay systems in this study adopted the same structural design and maintenance schedules as Zhang et al. (2010). The cross sections of the overlay systems are shown in Figure 7-3, and the maintenance schedules are shown in Figure 7-4. The mixture design, required machinery, and net cost for each construction activity for overlay analyses are summarized in Table 7-1, 7-2, and 7-3, respectively.

The second analysis of the overlay systems adopts maintenance timelines based on TxDOT LCCA guidelines with the 70-year analysis period as shown in Figure 7-5. Except for the maintenance timelines, all other analysis conditions including the mixture design, structural design, and construction cost are the same as Zhang et al. (2010). In the second analysis, an annual maintenance for each overlay is assumed. Because of the annual maintenance, ECC overlay has a major rehabilitation 60 years after its initial construction. For the conventional concrete overlay, a major rehabilitation is done 35 years after initial construction, and again 30 years later. HMA overlay is assumed to have a major rehabilitation every 12 years from its initial construction. The same traffic and weather parameters as the first analysis are used. During major rehabilitation, it is assumed that the existing overlay is removed and reconstructed, but no further maintenance is performed on the sublayers. The pricing of major rehabilitation and the initial construction are assumed to be the same.

In the analyses of the ECC link-slab and bridge expansion joints, a 528 ft long and 48 ft wide (4 lanes – 2 lanes in each direction) bridge deck was used based on the previous study by Keoleian et al. (2005). The bridge deck is assumed to be a reinforced concrete (CRCP) with 9-inch thickness. The lifespan for the analysis was 60 years. The superstructure of the bridge is shown in Figure 7-6, and the construction/maintenance timeline of each joint is shown in Figure 7-7. The mixture design, required machinery, and net cost for each construction activity for bridge joints are summarized in Table 7-4, 7-5, and 7-6, respectively.

In this study, the locations of the overlays and bridge were assumed to be a road in Austin, Texas, and correspondingly, the traffic and meteorology data were obtained from the TxDOT database. The road has an AADT of 190,000 vehicles in both directions with 8% truck traffic. The AADT is assumed to be constant during this Life Cycle. The costs of materials are obtained from national data, material companies, and online retailers.

The analyses provided herein uses the maintenance timelines, structural designs, and mixture designs of previous publications (Zhang et al. 2010; Koeleian et al. 2005), but is distinguished from the previous analyses by following considerations:

- TxDOT data on traffic for a road at Austin, Texas
- Meteorological data obtained from Austin, Texas
- Different software (EIO-LCA, MOVES, and RealCost 2.5) used to analyze LCA and LCCA
- Costs of materials, machinery, manpower were obtained using recent data
- Social costs of vehicles were obtained from TxDOT

- The maintenance timelines were modified based on TxDOT LCCA guidelines
- Annual maintenance costs for flexible and rigid pavements provided by TxDOT
- Different interest rate that was obtained from the national average

7.3.1 Assumptions and Inputs for Overlay Analysis

Table 7-1. Material Compositions by Weight % for Each Overlay

Material Composition	Concrete overlay	ECC Overlay	HMA Overlay	Unit:
Cement	14	28	0	%
Fly ash	2	34	0	%
Gravel	45	0	71	%
Sand	32	22	17	%
PVA fiber	0	1.2	0	%
Superplasticizer	0	0.8	0	%
Bitumen	0	0	7	%
Limestone	0	0	5	%
Water	7	14	0	%

Table 7-2. Machinery Required for Each Overlay

Equipment	Power	Concrete overlay	ECC Overlay	HMA Overlay
Unit	kW	hours	hours	hours
Crawler-mounted hydraulic excavator	320	256	128	256
Air compressor	260	128	64	128
Dumper	17	336	192	288
Hydraulic hammer	75	160	64	128
Motor grader	123	32	32	32
Water truck	335	64	64	64
Vacuum truck	132	64	64	64
Wheeled front-end loader	175	416	192	384
Signal boards	4	65,338	35,404	79,401
Concrete paver	186	662	435	0
Concrete truck	223	662	435	0
Resonant breaker	447	0	0	200
Asphalt paver	150	56	0	902
Asphalt roller	93	16	0	310
Asphalt truck	223	56	0	843

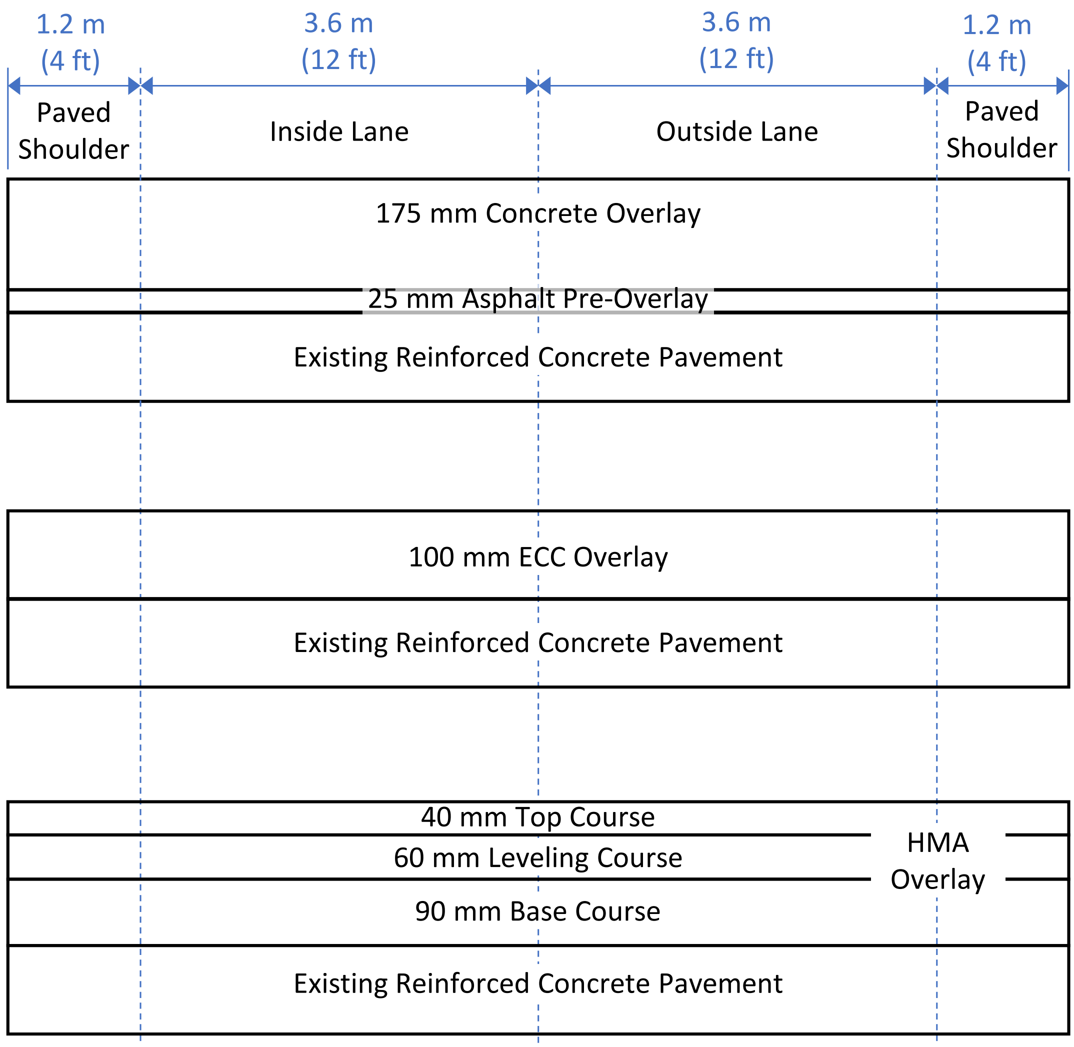

Figure 7-3. Overlay Structure and Thickness on one direction (reproduced from Zhang et al. 2010)

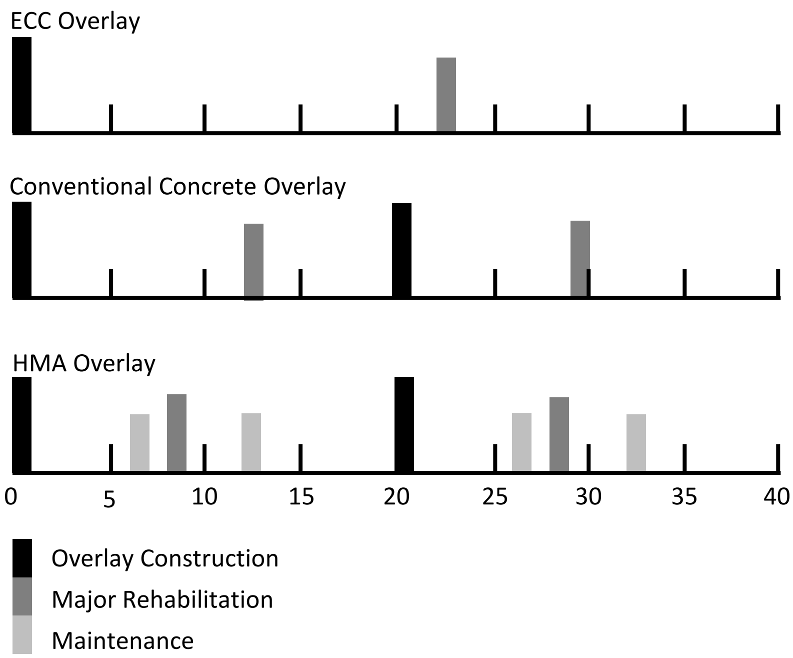

Figure 7-4. Construction and Maintenance Timeline for Each Overlay Used by Zhang et al. (2010)

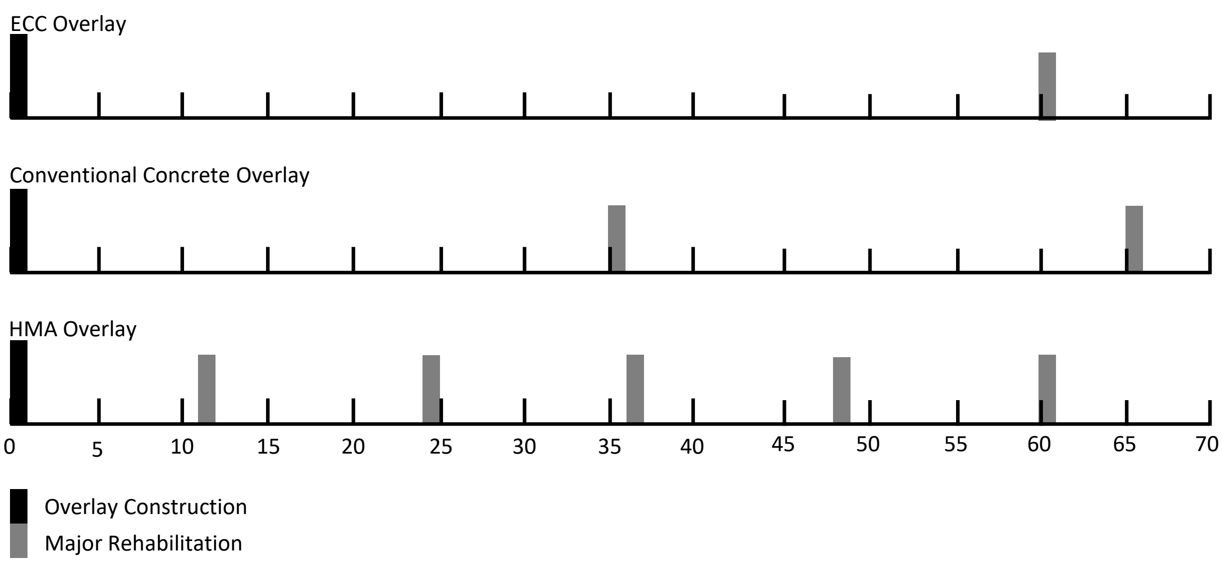

Figure 7-5. Construction and Maintenance Timeline for Each Overlay based on TxDOT LCCA Guidelines (Texas DOT 2019)

Table 7-3. Net Cost for Each Construction Period for Each Overlay

Unit: $1,000		Conventional Concrete Overlay	ECC Overlay	HMA Overlay
Timeline by Zhang et al. (2010)	Overlay Construction	10,057	10,928	10,778
	Major Maintenance	3,353	3,643	4,145
	Minor Maintenance			1,658
Timeline based on TxDOT LCCA Guidelines	Overlay Construction	10,057	10,928	10,778
	Major Rehabilitation	10,057	10,928	10,778
	Yearly Maintenance	74	74	131
	Salvage	980	993	1,676

7.3.2 Assumptions and Inputs for Link-Slab Analysis

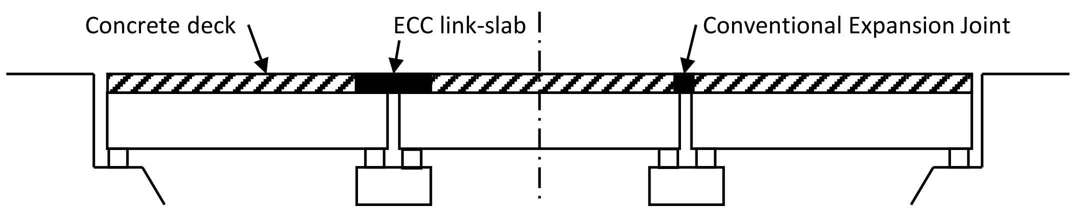

Figure 7-6. Bridge Deck with ECC link slab and conventional mechanical steel expansion joint (Reproduced from Keoleian et al. 2005)

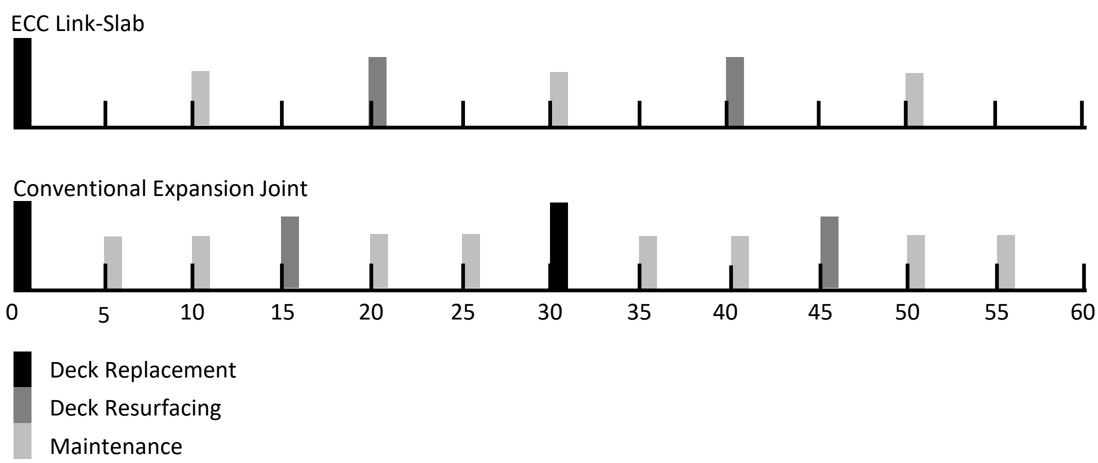

Figure 7-7. Construction Timeline for Bridge Expansion Joints (Reproduced from Keoleian et al. 2005)

Table 7-4. Materials Used for Bridge Expansion Joints

Materials	Conventional System	ECC	Unit
Cement	608	327	ton
Gravel	1203	553	ton
Sand	840	425	ton
Fly Ash	0	58	ton
PVA	0	2124	kg
Super Plasticizer	0	1429	kg
Section steel	754	377	ton
Rebar steel	63	31	ton
Epoxy	45	22	kg
Rubber	353	0	kg
Wood	58	0.8	ton

Table 7-5. Machinery for Bridge Expansion Joints

Equipment	Power	Conventional system deck replacement with joints	ECC system deck replacement with link slabs	Conventional system resurfacing and joint replacement	ECC system resurfacing	Maintenance and repair
Unit	kW	hour	hour	hour	hour	hour
Crawler-mounted hydraulic excavator	319	128	128	0	0	0
Air compressor	261	64	128	48	0	0
Concrete mixer	6	0	0	0	0	16
Concrete paver	186	96	32	32	32	0
Concrete truck	224	32	32	32	32	0
Crane, 50t	132	176	176	0	0	0
Dumper	17	128	192	80	32	0
Hydraulic hammer	75	64	128	0	0	0
Motor grader	123	0	0	16	16	0
Signal boards	4	18,000	24,480	7,680	4,992	0
Vacuum truck	132	0	0	32	32	0
Water truck	336	0	0	32	32	0
Wheeled front-end loader	175	624	688	48	0	0

Table 7-6. Net Cost for Each Construction/Maintenance Activities for the Bridge Joints

Unit: $1,000	Conventional System	ECC System
Deck Replacement	1,293	1,635
Deck Surfacing	392	253
Maintenance	1.37	1.37

7.4 Results

7.4.1 The First Analysis of Overlay Systems

Table 7-7 and Figures 7-8 to 7-11 are the results from the environmental and economic analyses of ECC, conventional concrete, and HMA overlays over a period of 40 years using Zhang et al.'s (2010) timeline. ECC has the least environmental impact (GHG), as well as the lowest agency costs. Because of the superior mechanical properties (tensile ductility and crack resistance), ECC tends to require less frequent maintenance and rehabilitation. As a result, it consumes less material and requires less machinery and manpower throughout its life cycle. The Present value of each overlay is calculated through the rehabilitation and reconstruction periods and the Average Historical discount rate. Figures 7-9 to 7-11 show the contributions of various sectors to economic activity, GHG emission, and energy consumption for three overlay systems. In these figures, five sectors with the highest contributions are shown and the rest are classified as 'other'.

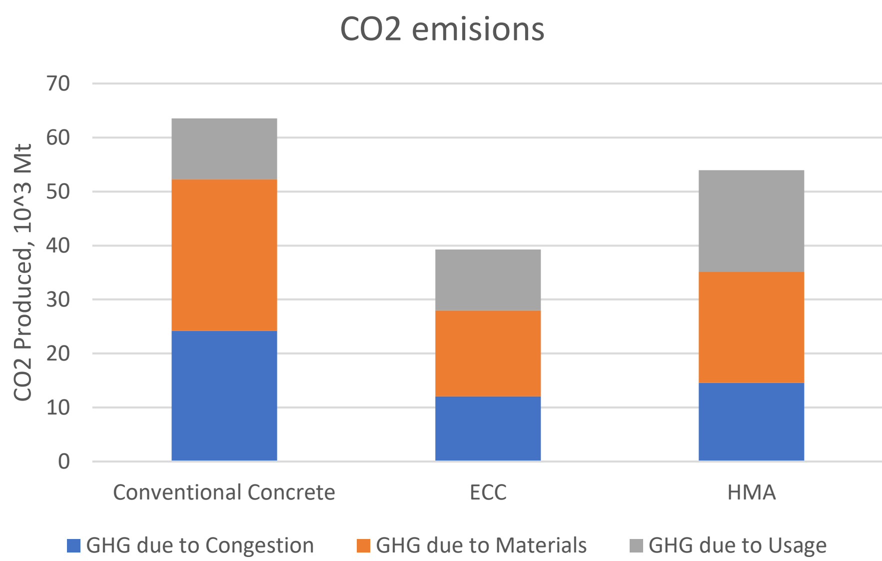

Figure 7-8. Comparison of the Environmental Impacts of the Overlay Systems Using the Maintenance Timelines by Zhang et al. (2010)

Table 7-7. Comparison of the Life-Cycle Costs of the Overlay Systems Using the Maintenance Timelines by Zhang et al. (2010)

	Unit: $1,000	**Net Total Costs**	**Present Values**
Conventional Concrete Overlay	Agency Cost	26,818	18,306
	User Cost	2,723,868	1,806,469
ECC Overlay	Agency Cost	14,571	12,559
	User Cost	1,361,934	1,111,220
HMA Overlay	Agency Cost	33,162	24,113
	User Cost	1,523,023	1,006,033

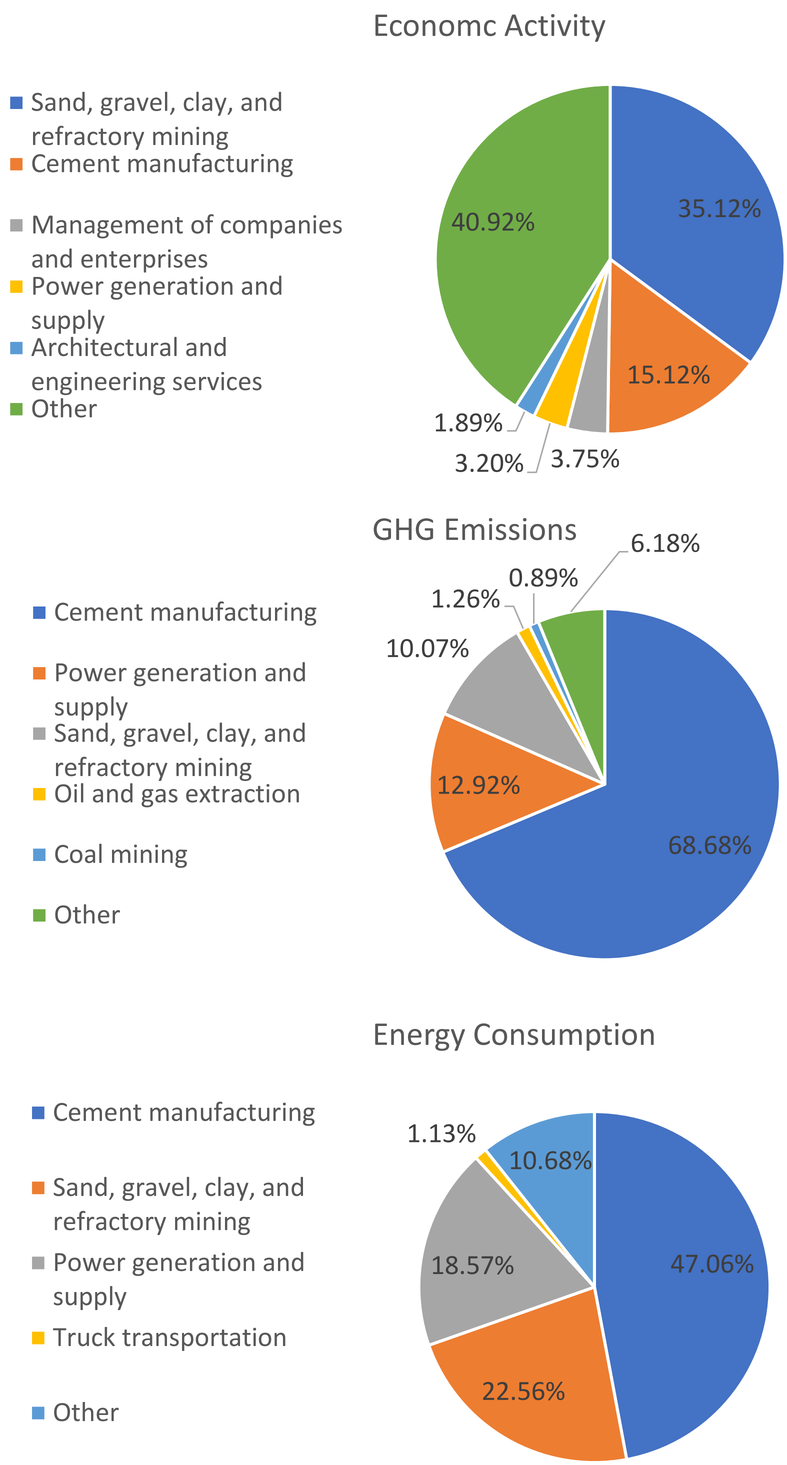

Figure 7-9. The Contribution of Each Components on the Environmental Impacts Obtained from EIO-LCA: Traditional Concrete Overlay Using the Maintenance Timelines by Zhang et al. (2010)

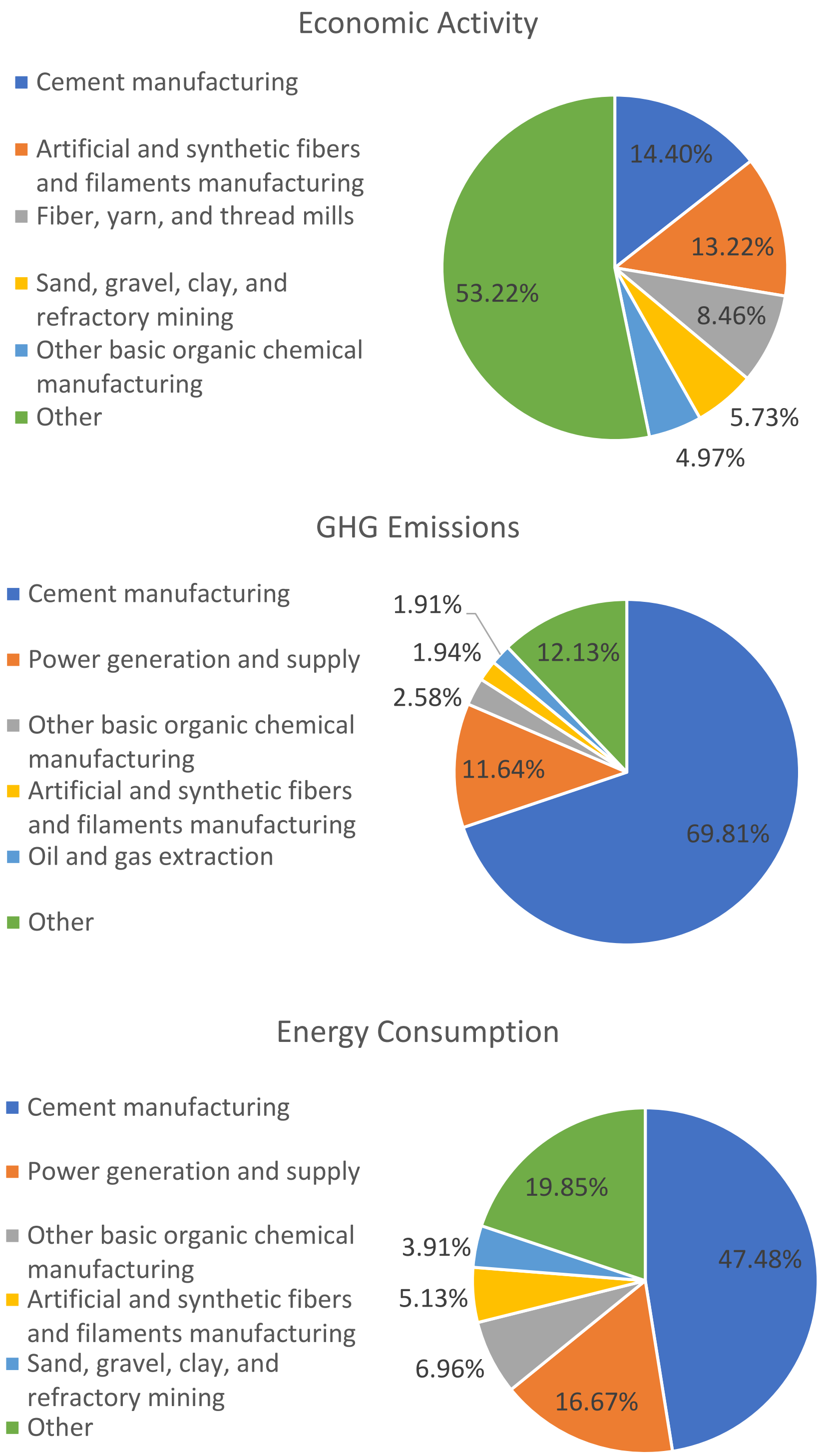

Figure 7-10. The Contribution of Each Components on the Environmental Impacts Obtained from EIO-LCA: ECC Overlay Using the Maintenance Timelines by Zhang et al. (2010)

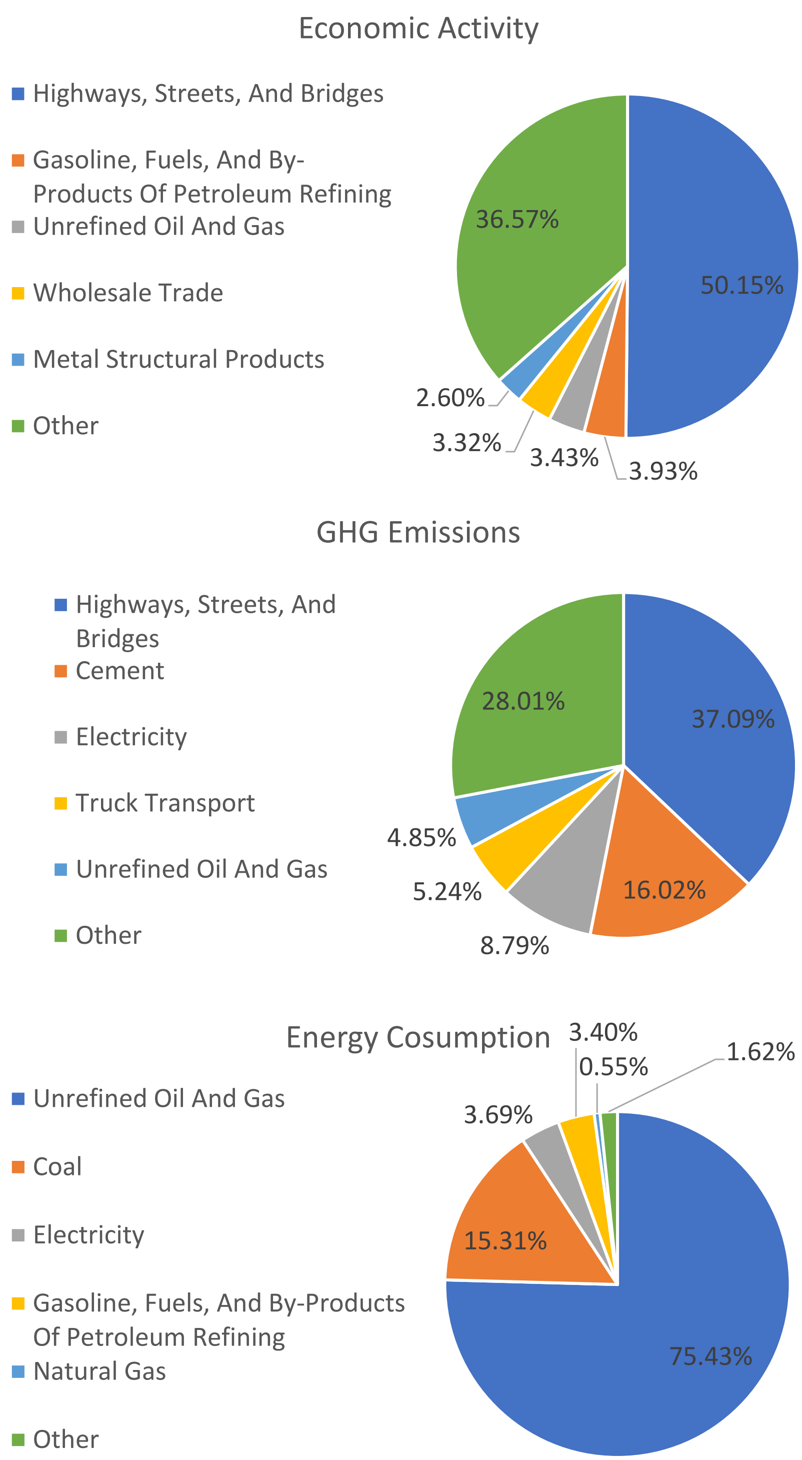

Figure 7-11. The Contribution of Each Components on the Environmental Impacts Obtained from EIO-LCA: HMA Overlay Using the Maintenance Timelines by Zhang et al. (2010)

7.4.2 The Second Analysis of Overlay Systems Using TxDOT LCCA Guidelines:

Figures 7-12 – 7-15 and Table 7-8 show the results of the environmental and economic analysis of ECC, HMA, and Conventional Concrete following TxDOT's LCCA guidelines. By using the different maintenance timelines and analysis period (70 years) from Zhang et al. (2010), the total GHG emissions and costs are higher than the first analyses set. However, the overall trend – ECC has the lowest agency costs and environmental impacts – is similar to the first analyses. Figures 7-13 – 7-15 show the contributions of various sectors to economic activity, GHG emission, and energy consumption for three overlay systems with the maintenance timelines based on TxDOT LCCA guidelines.

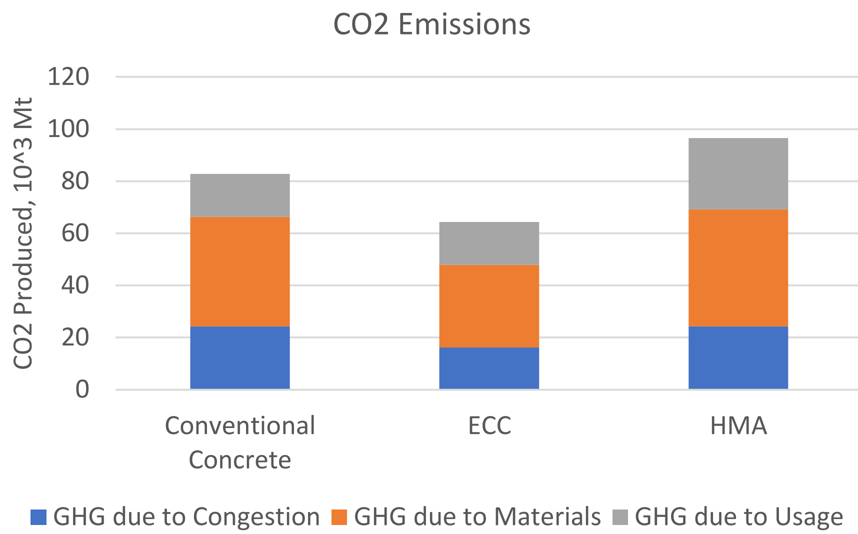

Figure 7-12. Comparison of the Environmental Impacts of the Overlay Systems Using the Maintenance Timelines Based on TxDOT LCCA Guidelines

Table 7-8. Comparison of the Life-Cycle Costs of the Overlay Systems Using the Maintenance Timelines Based on TxDOT LCCA Guidelines

	Unit: $1,000	**Net Total Costs**	**Present Values**
Conventional Concrete Overlay	Agency Cost	33,419	15,453
	User Cost	2,572,542	1,233,606
ECC Overlay	Agency Cost	25,861	13,881
	User Cost	1,733,371	1,003,019
HMA Overlay	Agency Cost	72,092	31,140
	User Cost	2,682,597	1,183,864

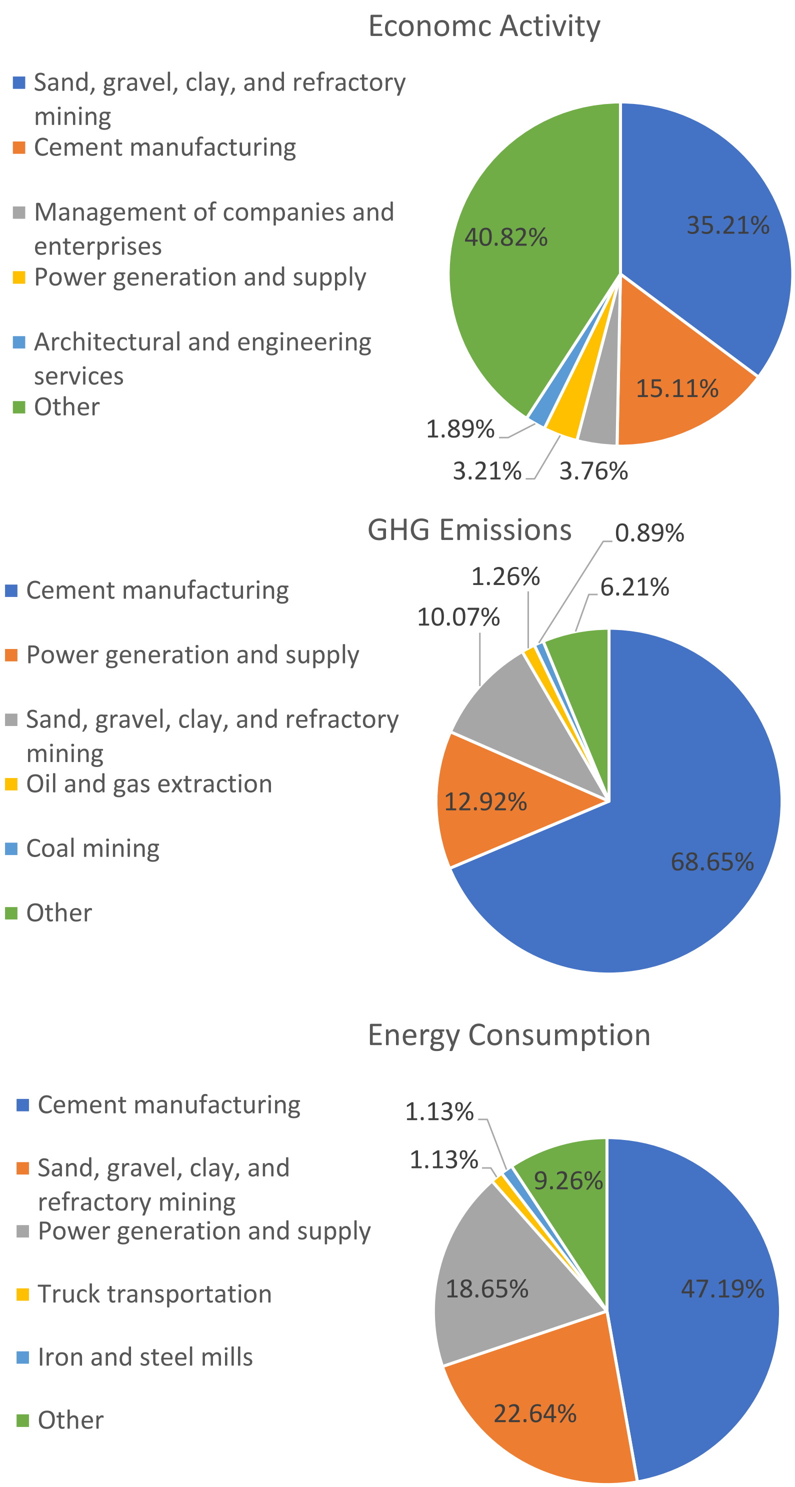

Figure 7-13. The Contribution of Each Components on the Environmental Impacts Obtained from EIO-LCA: Traditional Concrete Overlay Using the Maintenance Timelines Based on TxDOT LCCA Guidelines

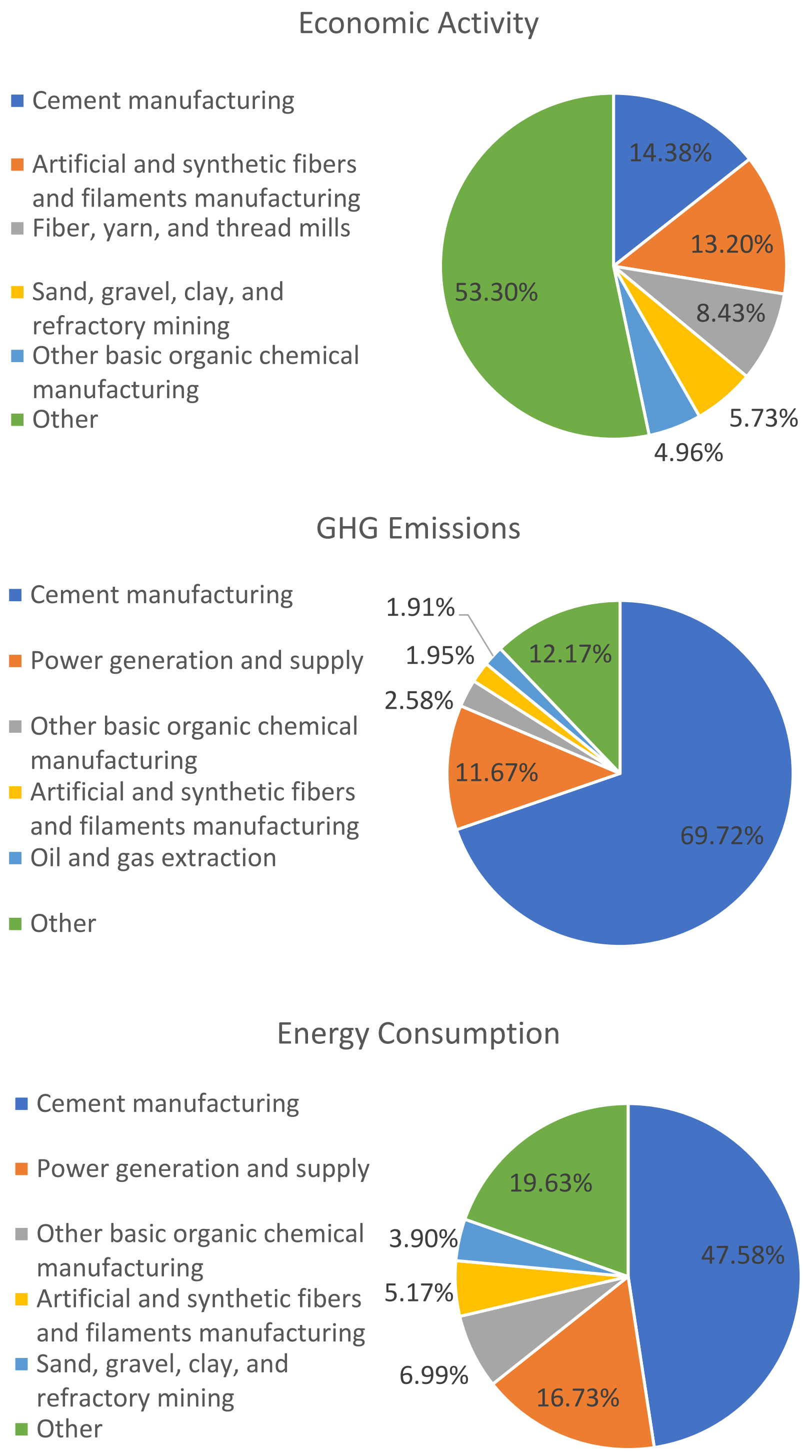

Figure 7-14. The Contribution of Each Components on the Environmental Impacts Obtained from EIO-LCA: ECC Overlay Using the Maintenance Timelines Based on TxDOT LCCA Guidelines

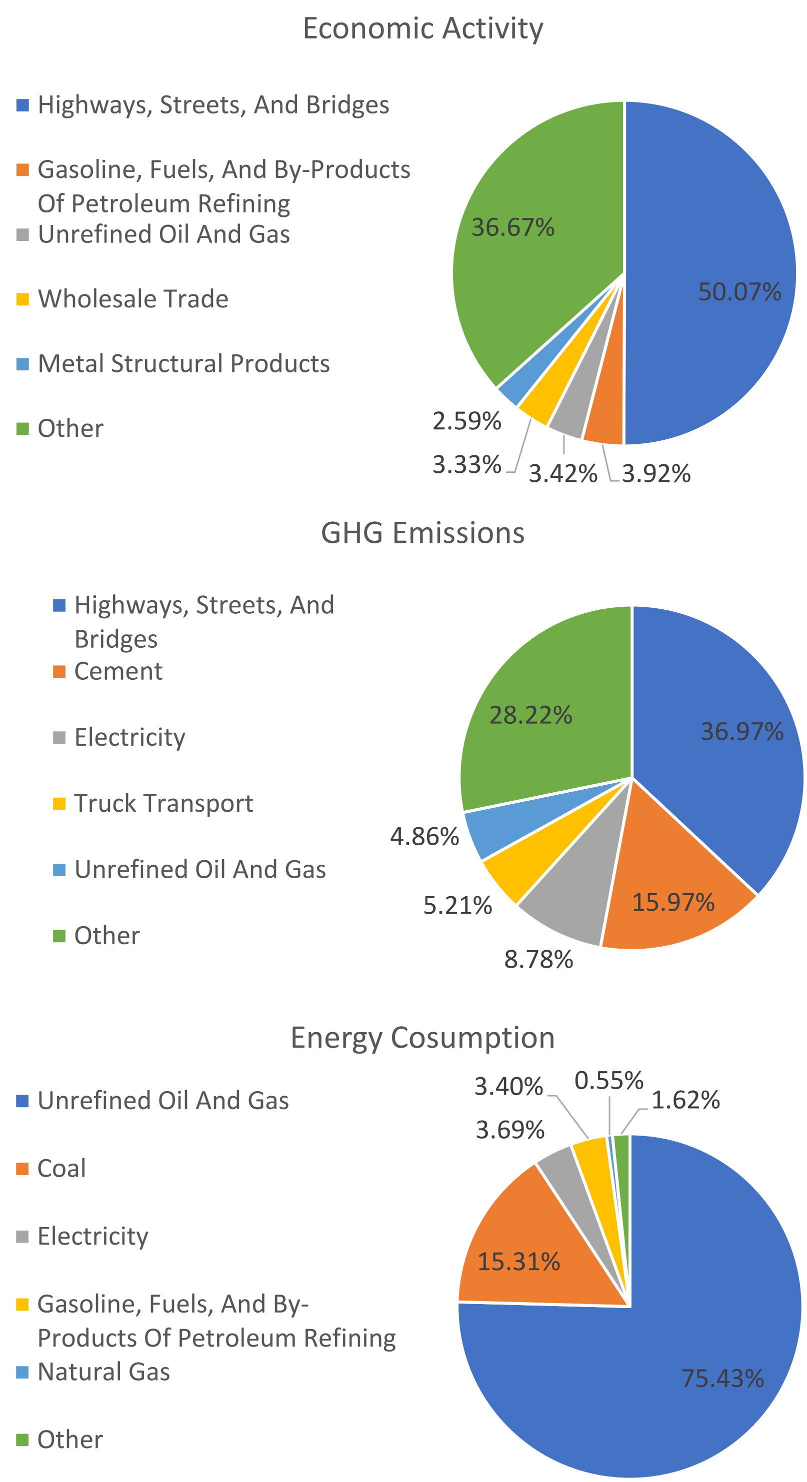

Figure 7-15. The Contribution of Each Components on the Environmental Impacts Obtained from EIO-LCA: HMA Overlay Using the Maintenance Timelines Based on TxDOT LCCA Guidelines

7.4.3 ECC Link Slab and Conventional Steel Expansion Joint:

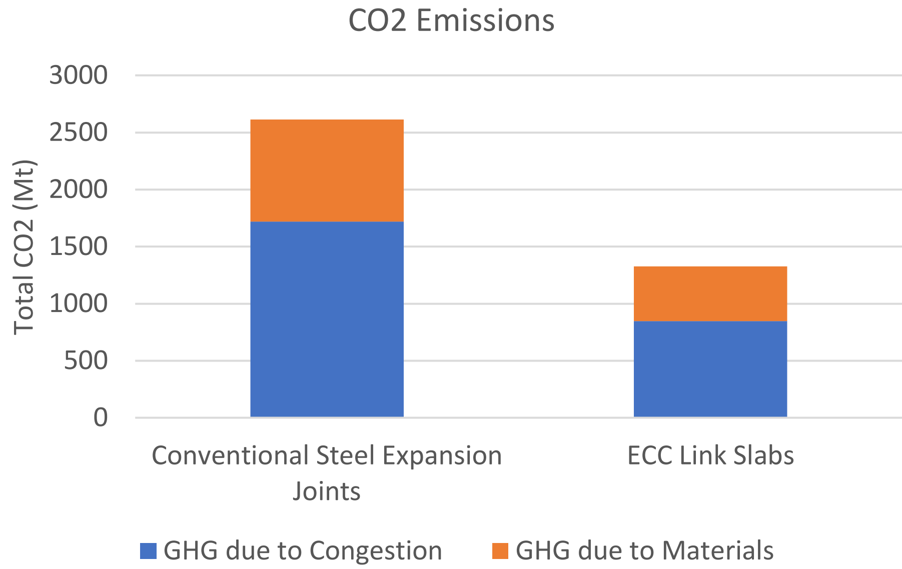

Figure 7-16. Comparison of the Environmental Impacts of the Bridge Joints

Table 7-9. Comparison of the Life-Cycle Costs of the Bridge Joints

	Unit: $1,000	**Net Total Costs**	**Present Values**
Conventional Expansion Joint	Agency Cost	3,382	2,032
	User Cost	2,841,024	1,608,795
ECC Link-Slab	Agency Cost	2,146	1,817
	User Cost	1,859,846	1,249,367

Above are the results of the environmental and economic evaluations of the ECC link-slab and conventional steel expansion joint. Compared to the conventional joint, ECC link-slab tends to produce fewer CO2 emissions, and has a lower life-cycle cost. This is primarily due to ECC's structural properties that require less maintenance. As a result, ECC requires less material, machinery, and manpower during its 60-year life cycle. Figures 7-17 and 7-18 show the contributions of various sectors to economic activity, GHG emission, and energy consumption for the conventional expansion joint and ECC link-slab.

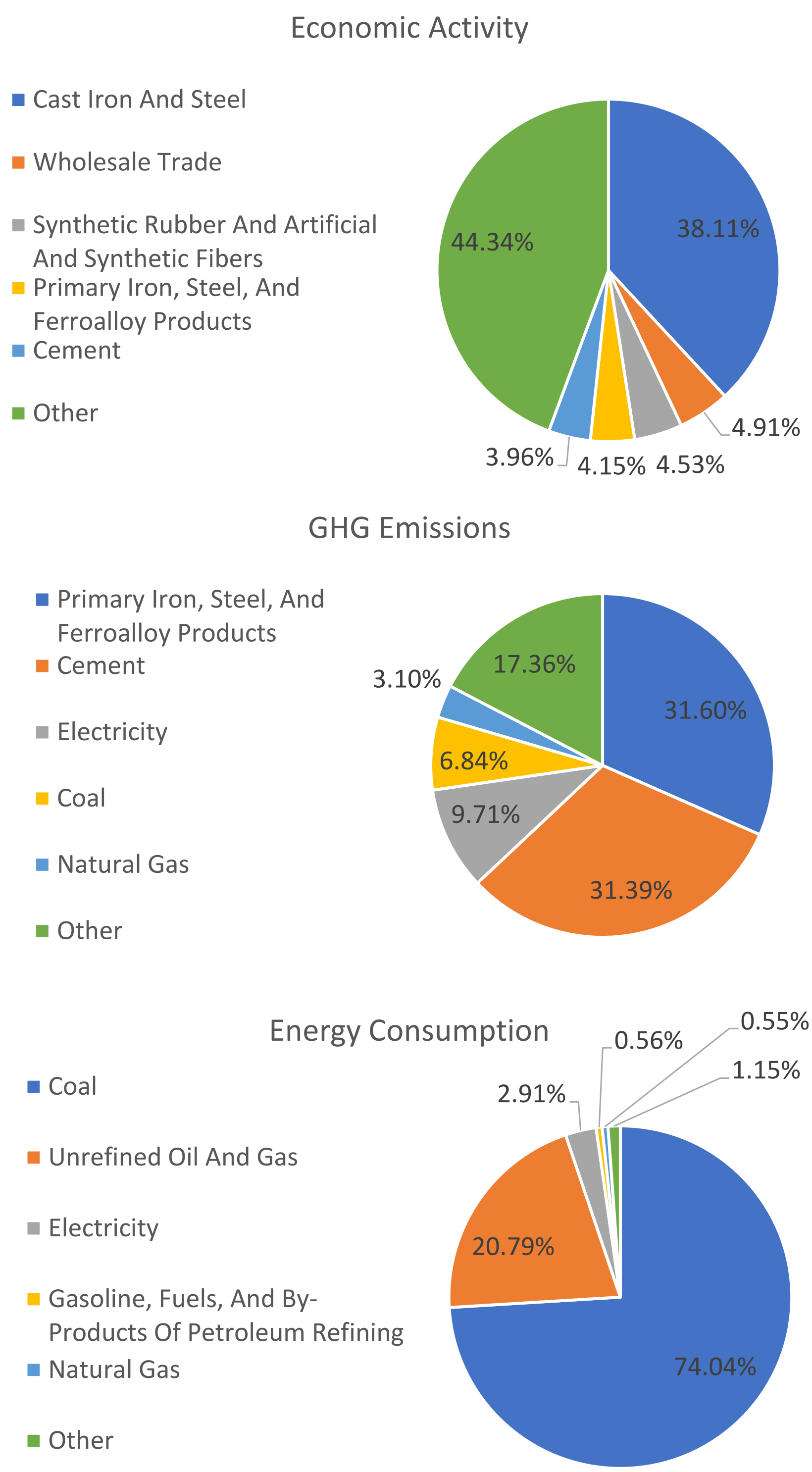

Figure 7-17. The Contribution of Each Components on the Environmental Impacts Obtained from EIO-LCA: ECC Link-Slab

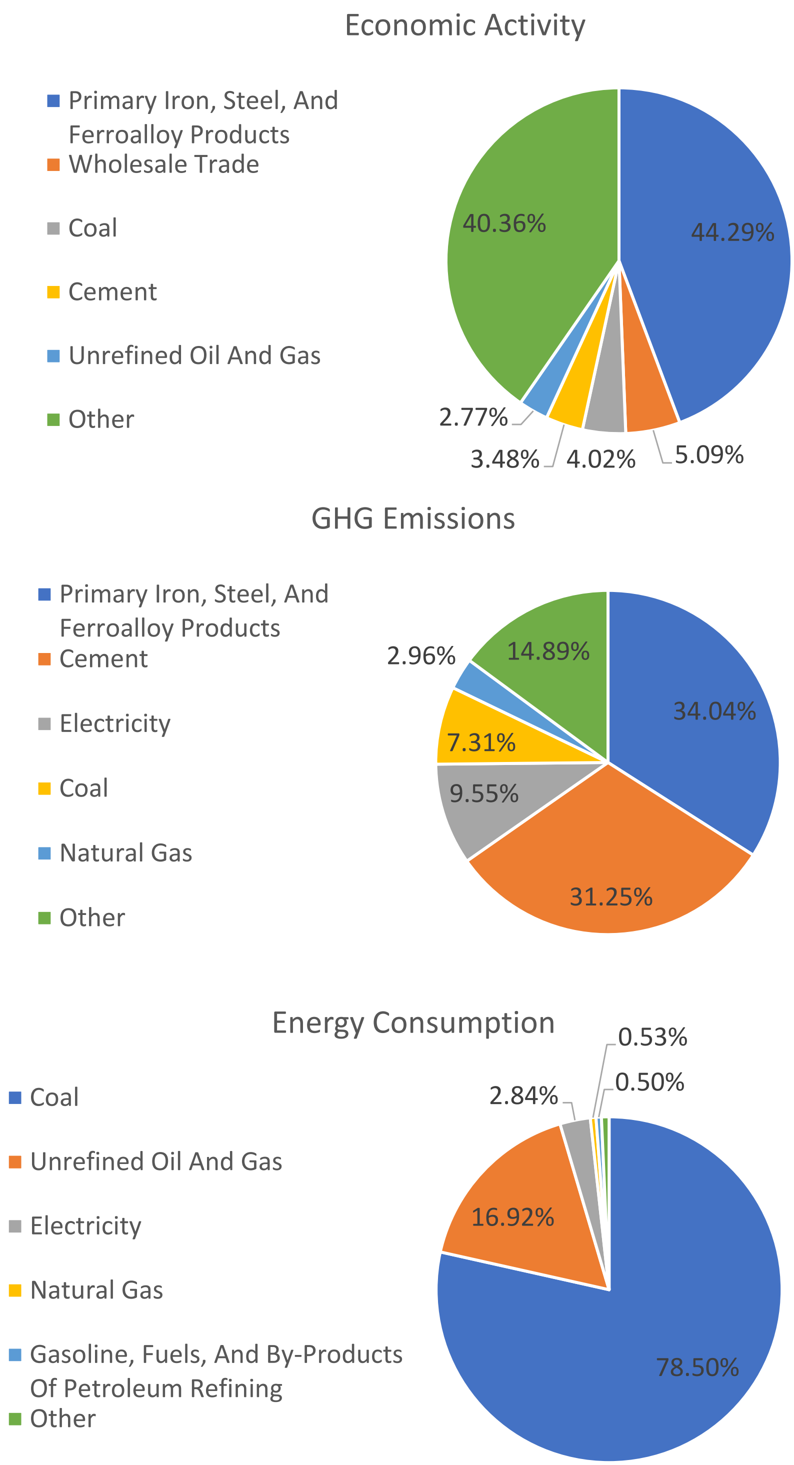

Figure 7-18. The Contribution of Each Components on the Environmental Impacts Obtained from EIO-LCA: Conventional Expansion Joint

7.4.4 Summary

Because of its superior tensile performance, ECC deteriorates slowly and has longer service life than concrete. Due to this, ECC structures requires less maintenance over long periods. The LCA and LCCA results show that ECC overlay produces significantly less GHG emission than either HMA or the conventional concrete overlays. The agency costs (present value) of the conventional concrete and HMA overlays are 44% and 92% higher than that of ECC overlay when Zhang et al.'s timelines were used.

The pavement management plan included in the TxDOT LCCA guidelines consists of annual maintenance and rehabilitations after initial construction. In the LCA and LCCA using this maintenance timelines with 70-year analysis period, the ECC overlay produces less GHG emission and requires lower agency and user costs than the HMA and Conventional Concrete overlays similar to the first analysis. The agency costs (present value) of the conventional concrete and HMA overlays are 11% and 124% higher than that of ECC overlay when the maintenance timelines when TxDOT LCCA guidelines were used.

In the LCA and LCCA for ECC link-slab and conventional expansion joint, the maintenance timeline by Keoleian et al. (2005) was used with a 60-year analysis period. Because the ECC link-slab requires less material, construction, and labor than the conventional expansion joint, the ECC link-slab produced less (54%) GHG emission. The agency and user costs (present value) of conventional joint was 12% and 29% higher than the ECC link-slab, respectively.

The lower life-cycle costs, GHG emission, and energy consumption of ECC compared to traditional systems are mainly caused by the reduced maintenance and extended service life of ECC applications. The analyses in this study used the maintenance timelines suggested by the previous investigators, but the timelines were just assumed without any experimental validation. In order to improve the accuracy of LCA and LCCA, an experimental study is needed to evaluate the extended life of ECC compared to traditional materials considering various damage modes including fatigue cracking, chemical attack, and temperature variation.

Chapter 8. Recommendations and Considerations on the ECC Applications

Comprehensive information on ECC were collected through three activities: (1) a literature review with in-depth meta-analyses, (2) a survey for state, federal, and international agencies, and (3) life-cycle cost analyses and life-cycle assessments for selected ECC applications considering the operational factors for the Texas environment. Synthesizing the collected information, several recommendations for ECC applications in Texas are provided.

8.1 Applications

Based on the results of the three activities and discussions with the project team, the following three applications are recommended with higher priority than others for applications in Texas:

- ***ECC pavement overlay***: ECC overlay has been tested by Michigan DOT and is expected to provide an expanded service life and reduced maintenance efforts. This was the one of the applications highly recommended by the survey respondents (15 %, Chapter 6). In addition, the life-cycle assessments conducted by previous investigators and by this study (Chapter 7) indicate that both the agency cost and user cost throughout a life-cycle are lower than those of HMA overlay and traditional concrete overlay because of the reduced maintenance efforts.
- ***Bridge link-slab***: Because of the high ductility of ECC, link-slabs made of ECC can replace traditional expansion joints in bridges. The ability of ECC link slab to accommodate thermal expansion/contraction was validated in previous investigations. ECC link slab provides smooth ride conditions on bridges and mitigates the deterioration of bridge girders below the expansion joints by preventing the leakage of water from bridge surfaces. Link slab was one of the survey respondents' highly recommended applications (15 %, Chapter 6). The life-cycle assessments conducted by previous investigators and by this study (Chapter 7) also indicate that both the agency cost and user cost of ECC throughout a life-cycle are lower than those of conventional expansion joints.
- ***Repair of existing concrete structures***: Since the high initial cost of ECC has been pointed out as a barrier to large volume applications, the repair of existing concrete structures such as bridge deck and concrete pavement is more in keeping with cost constraints than application to complete decks or pavements. Damaged parts of concrete structures typically undergo severe mechanical and environmental conditions, and the high ductility and the ability to redistribute localized stresses shown by ECC may prevent early deterioration of the repaired parts. Mixtures can be designed to be sprayable or self-consolidating, and the mechanism of multiple micro-cracking enables the control of crack opening of existing cracks and the delamination at the repaired interface due to shrinkage. The self-healing capability is another strength of ECC as a repair material. The application of ECC for concrete repair earned the highest vote from the survey respondents (35 %, Chapter 6).

8.2 Mixture Design

The ECC mixture with 55 % fly ash-binder ratio, 24 % water-binder ratio, and 53 % water-cement ratio, which is known as M45 (45 indicates that the weight fraction of Portland cement in binder – cement + class F fly ash – is 45 %), is considered as a standard mixture in recent studies. Since M45 has the largest experimental dataset, it is recommended for the general applications of ECC. The mixture proportioning of M45 is shown in Table 4-3.

8.4 Costs and Benefits

LCA and LCCA were conducted for the ECC applications to pavement overlay and bridge link-slab. The life-cycle costs including agency and user costs, GHG emission, and energy consumption of ECC were lower than HMA overlay, concrete overlay, and conventional expansion joints. The main reason for the lower life-cycle costs and environmental impacts of ECC compared to traditional systems was the reduced maintenance effort throughout the analysis periods. Since the maintenance timelines used herein were assumed, quantified evaluations of the resistances to fatigue cracking and environmental attack are needed to confirm the benefits of using ECC.

8.5 Research Needs

The literature review and the state-of-the-practice survey reveal that the following studies are needed to facilitate the practical applications of ECC:

- ***Standard material test protocol for quality control of ECC***: The tensile strength and ductility data collected from various investigators show a wide scattering range even for the same ECC mixture design. Such wide scatter indicates that thorough quality control is important to ensure the intended mechanical performance. The lack of a standard material tests to evaluate tensile properties was also pointed out as one of the barriers to application in the state-of-the-practice survey. However, direct tension tests for cementitious composites are difficult and expensive, and instead, existing standard tests such as split tension test or bending test can be considered as alternatives to evaluate the tensile properties indirectly. To use the indirect test methods, correlations between the tensile properties and the alternative test data should be provided along with a standard protocol to conduct the tests and to translate the data obtained into effective tensile properties.
- ***Standard specifications for ECC constructions***: The lack of the standard specifications for ECC construction was also pointed out in the state-of-the-practice survey. The standard specification should include the required minimum tensile and compressive properties, the methods of quality control, and the procedures for mixing, placing, and curing. The standard specifications can be developed through the field demonstration project that is described below.
- ***The resistance of ECC to fatigue cracking and environmental attack***: Durability tests of ECC have been conducted by the previous investigators, but the data for long-term

durability is still limited. Since the economic and environmental benefits of ECC come from the reduced maintenance efforts, the evaluation of long-term durability are needed to confirm its benefits. Comparative experimental investigation of the resistance to fatigue cracking and environmental attack of ECC and traditional materials will provide useful information for accurate predictions of the benefits. The experimental program should consider the loading and environmental conditions of specific applications.

- ***Field demonstrations***: Other important barriers to ECC applications mentioned by the experts' survey were the lack of field application experience and information on these materials. The field demonstrations of applications can be a starting point for the accumulation of experience and would provide the opportunity to disseminate the information to the engineering community. Long-term performance monitoring of ECC structures will be valuable both in the performance validation provided and in the promotion of ECC for applications in Texas.

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