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A Meta-Analysis on the Constitutive Behavior of Engineered Cementitious Composite

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A META-ANALYSIS ON THE CONSTITUTIVE BEHAVIOR OF ENGINEERED CEMENTITIOUS COMPOSITE

A Thesis

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ABSTRACT

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A meta-analysis is conducted for the mechanical properties of an Engineered Cementitious Composite (ECC). ECC is a special type of fiber reinforced cementitious composites that is characterized by high ductility (3-5% strain) with 1.5-2 % fiber content by volume. The brittle nature and low tensile strength of concrete result in low resistance to damage formation including cracking. Due to the effects of fiber, ECC has superior cracking resistance and is considered a sustainable alternative for construction and repair. Meta-analysis is a statistical method to remove a possible bias of a single set of data. This method collects and analyzes a large group of data obtained from multiple investigations of the same subject, and eventually can draw highly reliable trends and conclusions. The objective of this research is to identify the relationship between the mixture design and mechanical behavior of ECC through meta-analysis. In this study, more than 500 stress-strain curves of ECC were collected from 180 technical papers. The meta-analysis found that the tensile strength of ECC is largely proportional to the compressive strength. Compressive and tensile strength of ECC depends on water-cement ratio rather than the water-binder ratio in the range of collected data. On the other hand, the ductility of ECC is not influenced by water-content. The strength and ductility of ECC do not show notable improvement by adding pozzolanic additives.

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CHAPTER I

INTRODUCTION

Engineered Cementitious Composite (ECC), a type of high-performance fiber-reinforced cementitious composite (HPFRCC), is a family of fiber-reinforced cementitious composites (FRCC). ECC is optimized through micromechanics to attain strain hardening behavior. This material possesses high ductility and has tight microcrack widths under increasing load while using 2% of fiber volume or less. These features of ECC are achieved through designing the number of materials used and the interaction among the fiber, matrix, and fiber-matrix interface micro mechanically.

The ECC material can maintain a portion of its tensile capacity under considerable deformation and thus improve structural reliability. Substituting some of the main materials designed by Wang and Li (2007) without compromising the designed micromechanics can also make the material sustainable. ECC has become a promising engineering material for construction, not only for the possibility of improving the safety of civil infrastructure but also for making it a greener construction material through the use of ingredients such as recycled Class F fly ash (Yang et al., 2007)

1.1 Problem Statement

From the American Society of Civil Engineers' infrastructure report card, the United States' overall grade for infrastructures is C-. Concrete infrastructure is deteriorating fast because of environmental conditions and social changes such as population growth and everyday use. A sustainable material is needed not only to improve the overall infrastructure either by building something new or used as rehabilitation, maintenance or repair but also reduce waste and help the environment. Traditional concrete mix is a composite made of water, sand, cement, coarse aggregates, and admixtures that is widely used in construction projects. However, the brittle nature of concrete facilitates various damage modes such as cracking and, spalling which expose steel reinforcements to the environment which leads to the deterioration of a structure. Structures are more prone to deterioration when subjected to both mechanical and environmental loadings. In general, demolition is more costly than maintenance or repair of structures, however a more durable construction material or repair material is better economically in the long run. ECC is suggested as a more affordable and sustainable alternative for construction and has been actively investigated in recent years and should be considered both for new construction and structural repair.

Since cement production accounts for 5% of global anthropogenic greenhouse emissions (Lepech & Li, 2010), there is a need to reduce the use of cement by substitution or by use of a more durable material in construction projects. The search for green and sustainable materials is urgent with increased construction in the future for the growing population, while existing infrastructure suffer additional wear and tear. ECC can be an alternative to using traditional concrete. ECC, a material that can be designed to accommodate exactly what a structure needs, is what can resolve the problems traditional concrete faces.

This study concentrated on the use of two percent of polyvinyl alcohol fibers (PVA) by weight which as added during the mixing process. However, PVA fibers are not as tried and tested as steel fibers, so many construction companies are still hesitant to use the material.

There are only a few real-life applications of ECC and most of these are as repair materials and not as structural components. ECC used as a repair material might be an advantage since most of the structures deteriorating will be difficult to replace and the smartest solution would be to repair or maintain them. The real-world ECC applications are a link-slab in Michigan (Li & Lepech, 2004),(Lech & Li, 2005), a repair material for a bridge deck (Li, 2004), a sprayable ECC as a repair material for Mitaka-Dam in Hiroshima, Japan in 2003 and an earth-retaining wall in Gifu, Japan, (Li, 2008b). These are the only field applications of ECC because the material is too novel for construction companies which favor steel fibers that have been tried and tested. The material does not have enough experience in situ.

There are different testing methods and procedures used to evaluate the mechanical properties of ECC. The most common are, tensile and bending tests since ECC doesn't have standardized test specifications. Different fiber types have been tested and other materials have been used as an alternative for cement. Researchers experimented with recycled materials like blast furnace slag, silica fume, limestone powder and other additives. By collecting data from previous literatures, this research aims to analyze how each material in its mixture design affects the behavior and performance of ECC.

1.2 Research Objective

To create more sustainable infrastructure in the future, a more durable material is needed to be used in construction or rehabilitation. PVA-ECC is a possible solution for this problem.

The objective of this research is to analyze the data from collected studies done by previous researchers with different mixes and testing methods to remove bias in the constitutive behavior and performance of ECC so it can be used and smartly chosen by more construction companies for future projects. The results from this study should help with the understanding of ECC and how it can help to make more sustainable construction projects for the future. This study is primarily concentrated on PVA-ECC with 2% or less of fiber volume and does not include other tests besides uniaxial tension and compressive strength, three-point and four-point bending test.

1.3 Method and Scope of Work

This paper utilizes a meta-analysis approach to combine results from multiple studies on ECC and to resolve the uncertainties on conflicting academic papers that use different testing methods. Meta-analysis is a form of study to determine an overall trend from multiple independent studies of the same subject. Meta-analysis is a statistical and quantitative method used to systematically assess multiple previous studies to derive conclusions not evident in the individual studies. Usually done in medical research, meta-analysis is beneficial to the study of ECC because it allows the settlement of conflicts between studies and yield conclusive results when individual studies are inconclusive. An individual investigation may have limitations or may even be biased by poor design. 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.

This paper includes a literature review on the origins of ECC, mixture design of the composite and, a few applications used in real life. This study concentrated the meta-analysis on the behavior of ECC under uniaxial direct tension tests, and flexural tests (both three-point and four-point bending). The data collected from the combination of academic literature about ECC will be compared and the relationship of the ultimate stress and the water-cement ratios will be analyzed.

CHAPTER II

LITERATURE REVIEW

2.1 Background

Concrete is one of the main materials involved in buildings and infrastructure. However, concrete is also a brittle material with higher compressive strength than tensile strength (Li et al., 1995a). Its brittleness has caused many catastrophic failures of buildings and infrastructure. Concrete structures are often exposed to sulfate-rich environments and/or freeze-thaw cycles. Cracking, spalling, and scaling are typical deteriorations of concrete structures due to the low tensile resistance and brittleness. Cracking is one of the most important deterioration mechanisms of structures and interacts with chemical and environmental conditions. Concrete's limited durability is responsible for significant amounts of repair in structures. The inadequate performance of concrete is often because of inappropriate material selection, poor application method or, a combination of both (Li, 2004).

To modify the brittle nature of ordinary concrete, fibers were added into cementitious matrix instead of course aggregates. The mechanical characteristics of the cementitious composite showed improvement. The use of fibers as reinforcement for brittle materials can be traced back to the Egyptians, Chinese, and Japanese using horsehair or straws in mud bricks for constructions. And so, a modern development of using fibers came about and became fiber reinforced composites (FRC), research about the material followed. Fibers are valued for imparting the concrete element with energy absorption capability, corrosion resistance and, fatigue resistance apart from durability. (Li, 2002).

Sustainability issues regarding infrastructures include social, environmental, and economic challenges. Cement production is responsible for 3% of global greenhouse gas emissions (Li et al., 2004). In many ways, roads represent one infrastructure system with significant economic impact. According to the American Society of Civil Engineers, "32% of US major roads are in poor and mediocre condition and 28% of used bridges are structurally deficient or functionally obsolete" (Li et al., 2004). Improving the roadways would reduce accidents but the construction would cause traffic delays affecting the everyday life of people. To continue using cement for repair and maintenance for these infrastructures will cost a lot of money.

In the early 1960s, Romualdi, Batson, and Mandel published the papers that introduced fiber reinforced concrete to the academic and industry research scientists around the world (Zollo 1997.) Conventional FRCs tensile stress decreases after the first cracking resulting in strain-softening which is generally seen in cement-based material such as cement, concrete and mortar, (Wang et al., 1988). Fiber reinforcement in brittle matrix composites of cement-based materials are directed towards enhancing of tensile strength in strain and fracture resistance (Li et al., 1995a) and toughness (Li, 2002). The character and performance of FRC changes with varying concrete binder formulation as well as the fiber material type and physical properties (Zollo, 1997). The use of long fibers may lead to a reduction in toughness, although the strength of the composite will increase continuously as a fiber length increases (Katz & Bentur, 1994).

The tensile response of FRCC after the proportional limit can be divided into strain hardening and strain softening, similarly, the flexural behavior can be divided into deflection hardening or deflection softening. Strain hardening behavior is generally a metallic mechanism after yielding. Deflection hardening can be seen in both tensile softening and hardening.

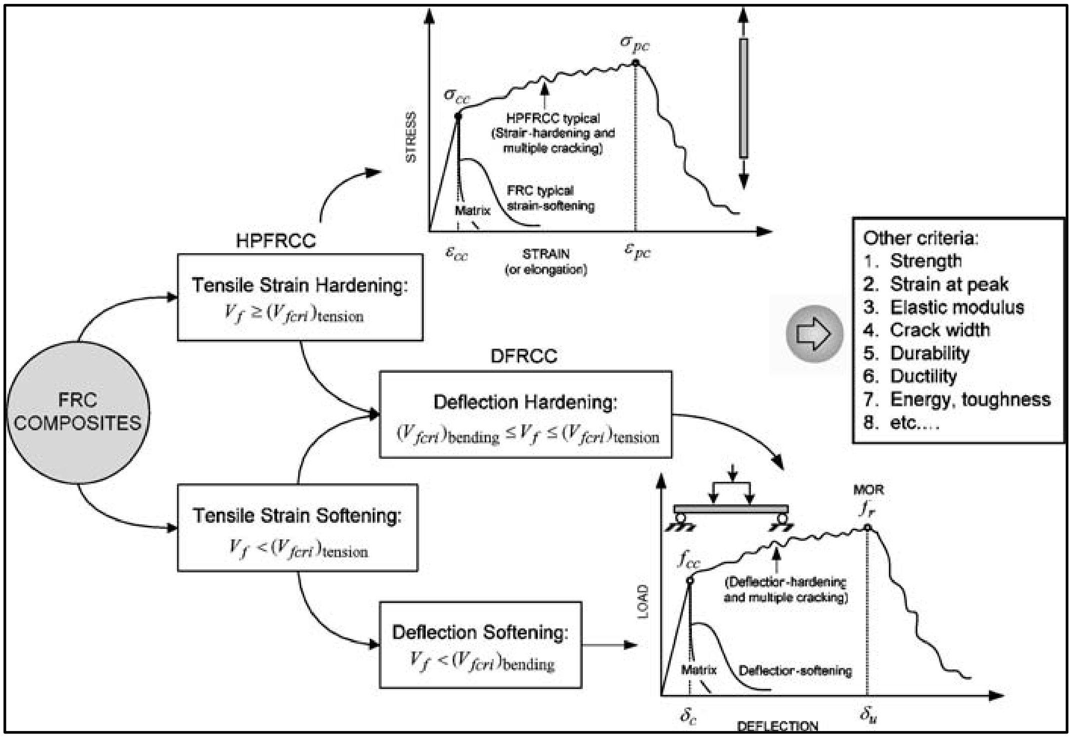


Figure 1. Different behaviors an FRC composite. Naaman and Reinhardt (2006).

FRC can exhibit a quasi-brittle material behavior which means that tension softening is followed by a continuous widening crack after the initial tensile cracking of the concrete matrix. FRC showing tensile hardening behavior is called High Performing Fiber Reinforced Cementitious Composite (HPFRCC). Figure 1 shows the different behavior categories of FRC. The suggestion for the need to develop a new class of FRC that has a strain-hardening property led to the development of a better materials that showed favorable characteristics for structural applications having a moderate low fiber volume fraction, isotropic properties, high performance in ductile behavior under bending, and shear load and can be used in applications in pre-cast or cast-in-place without any requirement of special processing machinery (Li 1997). HPFRCC is a composite material exhibiting multiple fine cracks under uniaxial tensile stress using short fibers.

HPFRCC is a highly ductile material that can show pseudo ductile strain-hardening characteristics that fail after multiple cracking (Fakharifar et al., 2014). A tension strain hardening is a more desirable response which is why the addition of fibers to the brittle cementitious matrix was originally an attempt to strengthen and enhance the toughness of the matrix. HPFRCCs exhibit high ductility and energy absorption based on the unique strain hardening and multiple micro-cracking behaviors and consequently have high damage tolerance as structural components, (Bandelt, 2017). Compared with concrete or normal fiber reinforced concrete, under high rate loads, HPFRCCs enhance the resistance of civil infrastructures (Tran and Kim, 2014).A tensile stress strain curve of a fiber reinforced brittle matrix composite which exhibits pseudo strain hardening is shown in Figure 2.

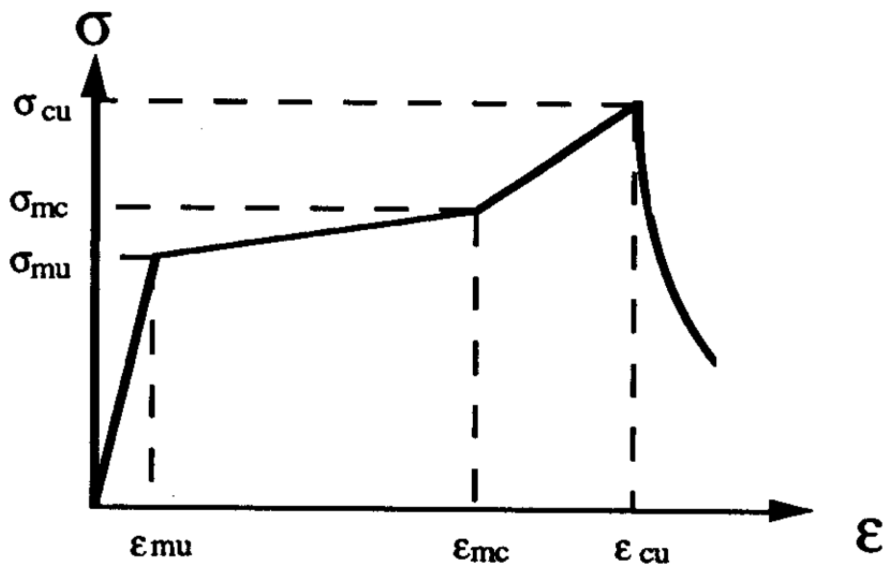


Figure 2. Tensile Stress-Strain Curve with Pseudo-Strain Hardening. (Li and Wu, 1992).

"The first crack strength (σ_{mu}) and first crack strain (ε_{mu}) are generally higher than the matrix tensile strength in strain due to arresting of microcracks by fibers subsequent to first cracking multiple cracking may ensue with many subparallel cracks of small widths spreading across the specimen. At the end of multiple cracking, the strain (ε_{mu}) can be many times larger than the first crack strain. Further increase in loading must be carried by the fibers bridging across the matrix cracks. The ultimate tensile strength (σ_{cu}) is reached when the fiber ruptures by exhausting its tensile strength for the case of continuous aligned fiber composites." (Li and Wu, 1992, p.372).

The concept of pseudo-strain hardening has only been demonstrated with HPFRCC with continuous aligned fiber reinforcement or large fiber volume content in real material systems. But recent advancements of the IPC group research have led to the micromechanically design theory using only a few percent of fiber volume of discontinuous fibers and still demonstrate pseudo-strain hardening (Li et al., 1995a). IPC group is one of the first groups that applied fracture mechanics concept to analyze fiber reinforced cementitious composite systems (Li, 2003).

Micromechanics produces the possibility of predicting the properties for a given composite material structure, also providing control for composite microstructure optimization. These composites are cementitious. Coarse aggregates are not included in the ingredients instead 2% fiber volume or less are used instead. High Performing Fiber Reinforced Cementitious Composites (HPFRCC) and Strain Hardening Cementitious Composites (SHCC) or Engineered Cementitious Composites (ECC) are used interchangeably. These names describe only one material with strain hardening behavior using fiber volume of 2% or less. The term ECC will be used throughout this paper. The micromechanics of each composite is what make ECC different.

ECC is a micro-mechanically designed material and its composite performance is generally affected by flaw size distribution, fiber number, dispersion, and orientation distribution. Tailoring of the cementitious composite can be done by altering the mixture design:

sand, cement, fly ash, water, additives, and the fibers replacing the coarse aggregates. Through the guidance of the micro-mechanics-based design approach (Li, 1993). To create pseudo strain hardening behavior with minimum amount of fiber, it is preferable to aim at low fiber volume (Li, 1993). ECC was invented in the early 1990s by Victor C. Li and his research team in the University of Michigan (Li, 1997). ECC represents a unique group of short fiber reinforced cementitious composite materials with ultra-high ductility (Li et al., 2004) and it shows pseudo strain-hardening, with relatively low fiber volume fraction of 2% or less (Li, 1997). ECC is the result of micromechanics-based approach to engineering designed to achieve high damage tolerance under severe loading and with high durability. The fiber, matrix and, interface of ECC are carefully tailored under the guidance of micromechanical models (Li et al., 2004). It is vital to tailor the ECCs main components: cement, fine sand, supplementary cementitious materials, and high-modulus fibers (Ali & Nehdi, 2017) to achieve flexural ductility and toughness (Jinlong et. al., 2012)

"ECC has a tensile strain capacity of up to 6% and exhibits pseudo-strain hardening behavior accompanied by multiple cracking. It has high ultimate tensile strength of 5-10 MPa, modulus of rapture of 8-25 MPa, fracture toughness of 23-30 kJ/m^2 and compressive strength up to 80 MPa and strain of 0.6%" (Kamada & Li, 2000). After the first crack for high strain capacity of ECC, the bridging fibers continue to carry increasing amount of load across the crack, leading to additional cracks elsewhere. This damage process occurs at increasing load – resulting in a pseudo strain hardening behavior for the composite (Li, 1993). Since strain hardening behavior only appear in metallic materials, the pseudo-strain hardening behavior of ECC looks favorable used in maintenance or constructions that goes under multiple loadings, such as the roads, highway, bridges and other infrastructures.

ECC has undergone significant evolution in both materials development and the range of emerging applications. ECC has a tight crack width self-control to 60 µm without the presence of steel reinforcement. ECC has a lower water permeability and better durability compared with conventional concrete (Zhou et al., 2010). With appropriate control of rheology properties of ECC, the material was developed to be suitable for self-consolidating, casting, spraying and extrusion. Unlike many other HPFRCs, ECC can be prepared in standard concrete mixers (Li et al., 2004). ECC is both highly durable and well suited for large infrastructure applications (Lepech & Li, 2005).

The following figures compare FRC and ECC on a Compression Stress-Strain (Figure 3), Uniaxial Tensile Stress-Strain (Figure 5), Flexural Stress Deflection Curves (Figure 6). A noticeable difference between the FRC and ECC can be seen in the following figures. It can be seen from the figures shows below how ECC has improved the compression, tensile, and flexural properties of FRC.

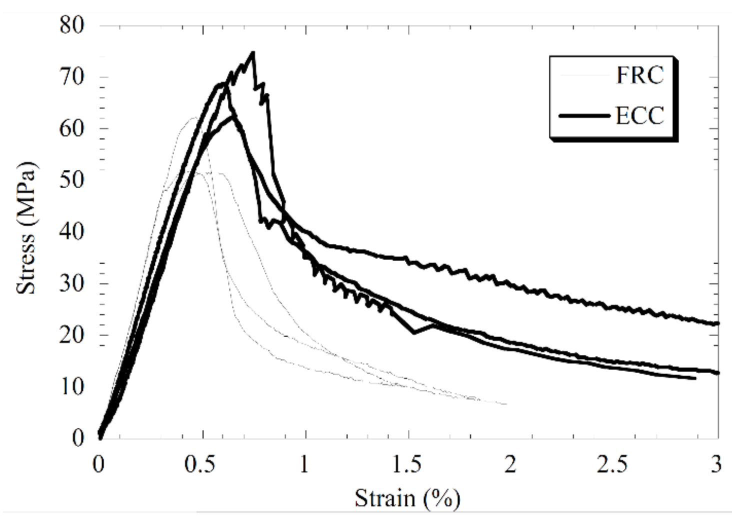


Figure 3. Compressive Stress-Strain Curve of ECC and FRC (Li, 1997)

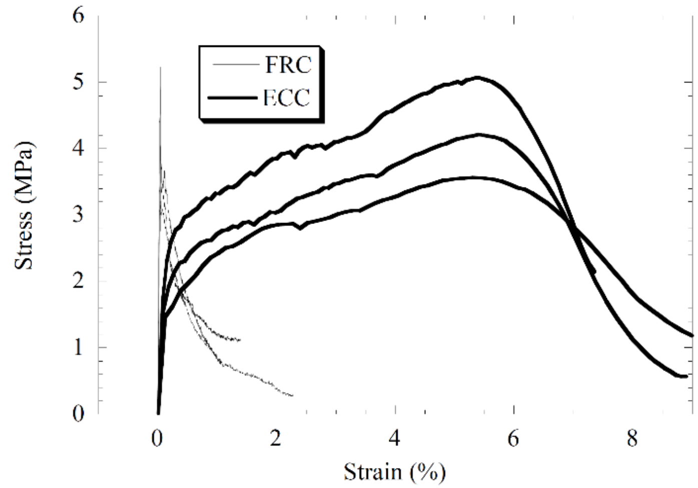


Figure 4. Uniaxial Tensile Stress-Strain Response of ECC with FRC (Li, 1997)

ECC can sustain higher loads than typical concrete because of its multiple-cracking behavior. Instead of one single crack that leads to failure, fine multiple cracks are formed across the material until it fails. The crack pattern of the ECC 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 (Li 1997).

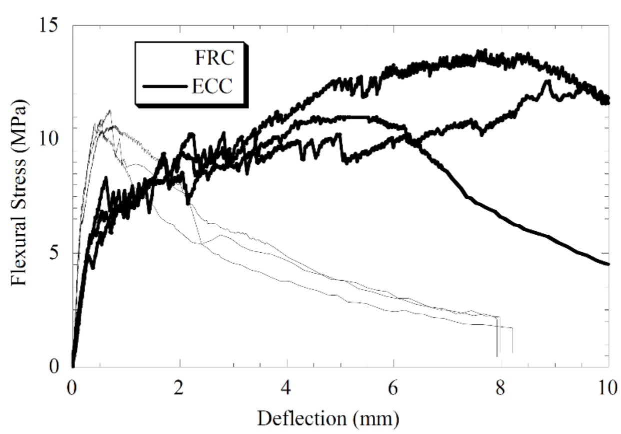


Figure 5. Flexural Stress-Deflection Curves of ECC and FRC. (Li 1997).

Figure 7 shows a typical deformation of ECC. The material continues to sustain the applied load even after the first crack.

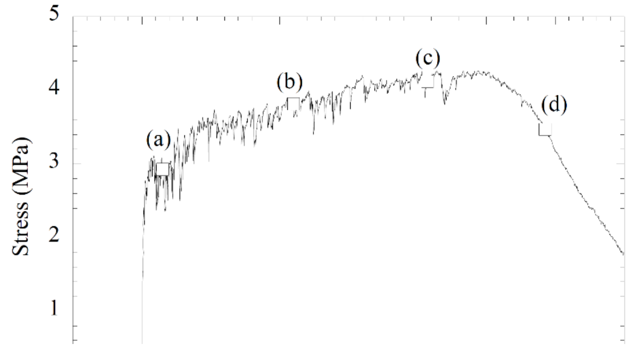


Figure 6. Uniaxial Tensile Stress-Deformation Record for ECC. (Li 1997).

As a construction and repair material, ECC can be designed to have any desirable characteristics such as flexibility, isotropy and or anisotropy, and high-performance by tailoring the fiber, matrix, and interface properties (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. 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. Fiber bridging across the crack can be tailored so that multiple microcracks develop under tension. The fiber bridging also reduces the crack tip stress concentration and slows the progressive crack propagation. These make the ECC materials appropriate for infrastructures such as high-rise buildings, bridges, tunnels, highways, and others. Different types of ECC materials including self-healing ECC, fire-resistive and, green ECC are introduced and studied by various researchers.

2.2 Mechanical Properties of ECC

The mechanical behavior can be measured in three representative test methods: uniaxial compression test, uniaxial tension test, and flexural (bending) test. The fiber/matrix interfacial parameters are specifically designed to allow ECC to dissipate energy through multiple cracking with crack widths less than 100 μm, this is what makes ECC stand out from other FRC's such as steel, polymeric, glass and carbon FRC which exhibits tension softening behavior. By tailoring the microstructure of ECC through micromechanical models, ECC can achieve tensile strain hardening behavior and ductility levels approx. 200-600 times that of conventional concrete under tension. (Li, 2014)

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. Most researcher that investigates the tensile properties of ECC follow 2008 JSCE Recommendations for design and construction of high-performance fiber reinforced cement composites with multiple fine cracks (JSCE 2008).

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. The direct uniaxial tension test is the sole method to validate the true ECC tensile strain-hardening behavior. But some tension-softening material can exhibit pseudo-deflection hardening under bending test. The tensile strain capacity of ECC is approximately 3.5% which is 350 times that of concrete and FRC. The stages of ECC tensile stress-strain curve generally follows the same pattern, (1) initial elastic stage, E, (2) strain hardening stage, multiple microcracking formation, (3) final failure, tension-softening stage, continuous decrease in the ambient load (ECC behaves similar to tension softening FRC materials).

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).

Tosun et al. (2014) main goal is to correlate the tensile strength and ductility of ECC by considering the effects of different processing parameters: the largest flaw size, fiber dispersion, and fiber orientation. A uniaxial tensile test was performed by following ASTM C109. Tensile ductility and ultimate tensile strength can be characterized by fiber dispersion. There is no correlation between the ultimate tensile strength 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).

The compressive strain capacity of ECC at 0.45-0.65% is slightly higher than concrete. The softening branch of ECC compressive stress-strain curve is longer, allowing more ductile compressive failure mode. 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 beam bending tests simulating loading conditions of flexural members measure another indirect tensile strength, which is called modulus of rupture (MOR). Since the flexural loading condition is common in concrete members, MOR values are 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)

Under four-point bending, ECC undergoes an elastic stage followed by deflection-hardening behavior accompanied by the formation of a number of microcracks on the tensile side of the specimen. The deflection-hardening response reflects the tensile ductility of ECC.

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).

Pseudo strain hardening is achieved through sequential formation of multiple cracks in the matrix. A fundamental requirement for matrix multiple cracking is steady state flat crack propagation prevailing under tension for continuous aligned fiber-reinforced ceramics and discontinuous fiber-reinforced cementitious composites (Li, 2014).

Since ECC performs a pseudo strain hardening behavior, it is resistant to major crack formation, instead, microcracks appear. During a ring test the restrained shrinkage behavior of

ECC was observed and showed a high shrinking deformation which can be used as a repair material (Li & Lepech, 2004). Reflective cracking of ECC is eliminated because of its microcracking deformation mechanism, which proves excellent performance in the fatigue environment of transportation applications. It also eliminates delamination and spalling when used as an overlay. This was shown in a fatigue test and overlay bond characteristics. ECC was found to be preferable as a repair material for transportation applications. Including bridge deck patching and link slabs. To ensure steady state crack, the crack tip toughness must be less than the complementary energy calculated from the fiber bridging stress vs the opening curve. The matrix tensile cracking strength must not exceed the maximum fiber bridging strength. Both conditions need to be satisfied in order to have a strain hardening behavior otherwise the composite will behave just like any other FRC resulting in tension softening. High tensile strain capacity results from saturated formation of multiple microcracks

Suthiwarapirak et al. (2004) investigate 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. JCI standard for test methods of FRC was used to perform the flexural static test. 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 considered to extend fatigue life and performance.

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).

Durability and impact test have also been investigated. ECC has a high damage tolerance which was demonstrated even after multiple impacts. 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 balance 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 Mixture Design of ECC

2.3.1 Ingredients

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.

Portland cement, water, fine aggregate, plasticizer, and fibers are the basic components of ECC. 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. PVA fibers provide a higher and more consistent ductility improvement in comparison to other types of fibers.

Another important difference between traditional concrete and ECC, coarse aggregate is not used in ECC mixtures. In some cases byproduct such as fly ash (typically type F) is added to reduce the amount of Portland cement, The lack of coarse aggregate in ECC makes the initial cost higher than regular concrete, and this has limited the widespread use 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. 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)

Lack of information and lack of previous experience using ECC also limits the use of ECC. However, the properties and structural applications of ECC has caught the attention of some engineers enough to actively investigate and apply the material as a novel component in construction and rehabilitation.

Since ECC is a cementitious composite that behaves similarly to metal, standard testing of concrete with metallic behavior is limited. (Flexural test is done to measure the tension). Many researchers follow the guidelines from the Japanese Society of Civil Engineers (JSCE 2007) come up with their own methods to test the mechanical properties of the bendable concrete. A paper experimenting with the use of high volumes of fly ash on ECC became the basis mixture for future studies of ECC referred to as the mixture M45 (Wang and Li, 2007). Usually, the procedure starts with mixing all the dry ingredients: cement, fly ash, and sand. These are mixed for a few minutes and then water and high range water reducing admixture (HRWRA) is added and mixed for a few more minutes until it is homogenous. Next, fibers are slowly added and mixed until it is evenly distributed in the mixture. The mixtures are cast into molds and de-molded after 24 hours. The specimens are first cured with sealed bags at room temperature for 7 days, then air-cured at room temperature before testing. Compressive, tensile and flexural tests are done other tests such as fiber pull-out, impact tests are also conducted. Depending on the standard procedure the researchers are following, there are different dimensions for each test. JSCE uses a dog bone specimen when doing tensile tests. A three-point bending test or a four-point bending test is also used. A servo-hydraulic testing system was used in the displacement control mode to conduct the tensile test.

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 toughness from fine aggregates leads to a higher critical fiber volume fraction, decreasing the water to cement ratio gives a similar effect. Research to find a 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.

2.3.2 Fiber Properties

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).

Short discontinuous fibers such as polyethylene, polyvinyl alcohol and polypropylene fibers are some of the fibers that have been used in ECC. Instead of using coarse aggregates, ECC use short discontinuous fibers. Fibers are often used in controlling shrinkage cracks, a role played by steel reinforcing bars or steel wire mesh. Fibers are valued for their imparting the concrete element with energy absorption capability. The fibers in some industrial applications are not expected to contribute to the load-carrying function in that element. (Li, 2002). The length of the fiber segment strongly influenced by this elastic stress field is dependent on the ratio between fiber modulus (E) and the fiber cross-sectional area (Wang et al 1988).
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. Table 2.1 shows part of the collected data on the type, dimension, and mechanical properties of fibers used in mixtures of ECC.

Table 1. Part of the collected data of fibers used for ECC.

Authors	Year	FIber ID	L (mm)	D (mm)	Specific Gravity	Tensile 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.	1995a	Polyethylene	12.7	0.038	0.97			
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			
Fischer et al.	2003	PVA			1.3			
Kanda et al.	2003	PVA	12	0.04	1.3	1690	40600	
Kim et al. double ch	2003	PVA Fiber	8	0.039	1.3			
Kim et al.	2003	PVA	8.12	0.039	1.3	1620	42800	6.0%

If the fiber length is small, it can be completely pulled out, if the fiber length 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 of self-control to 60 µm without the presence of steel reinforcement. That is why multiple studies on the fiber properties are done, including investigation in hybrid fibers.

Ranade et al. (2012) investigated an ECC material using short randomly distributed PVA fibers in a cementitious matrix containing high volumes of Class F Fly ash. This research showed the possibility of preferential alignment of PVA fibers in ECC when casting in a dog-bone shaped specimen. Flaw size distribution also affects the shape of the stress-strain curve of high-volume fly ash ECC.

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. One of the main raw materials of ECC that researches and even construction companies use is PVA because of its mechanical properties alone as a material and it is also cheaper than using other fibers. PVA fibers are hydrophilic, making the fibers have a strong chemical bond with the matrix. But this chemical bond can cause fiber ruptures, so studies on how to prevent this are investigated.

Liu et al. (2018) investigated and quantify the role of PVA fibers in high temperatures and what role the fiber pays to create a network that is much more permeable than a plain matrix. This paper demonstrates the efficiency of PVA fiber in protecting the ECC from spalling. The melting of the fibers does not affect preventing explosive spalling from happening. The melted products are attached to fiber channel walls and cannot diffuse into the matrix.

2.3.5 Mixture Proportions

Comprehensive data on the mixture proportioning of ECC were collected and tabulated in a spreadsheet. Sample mixture proportioning of ECC, 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 are in table 2.2. The components of ECC can be summarized as follows:

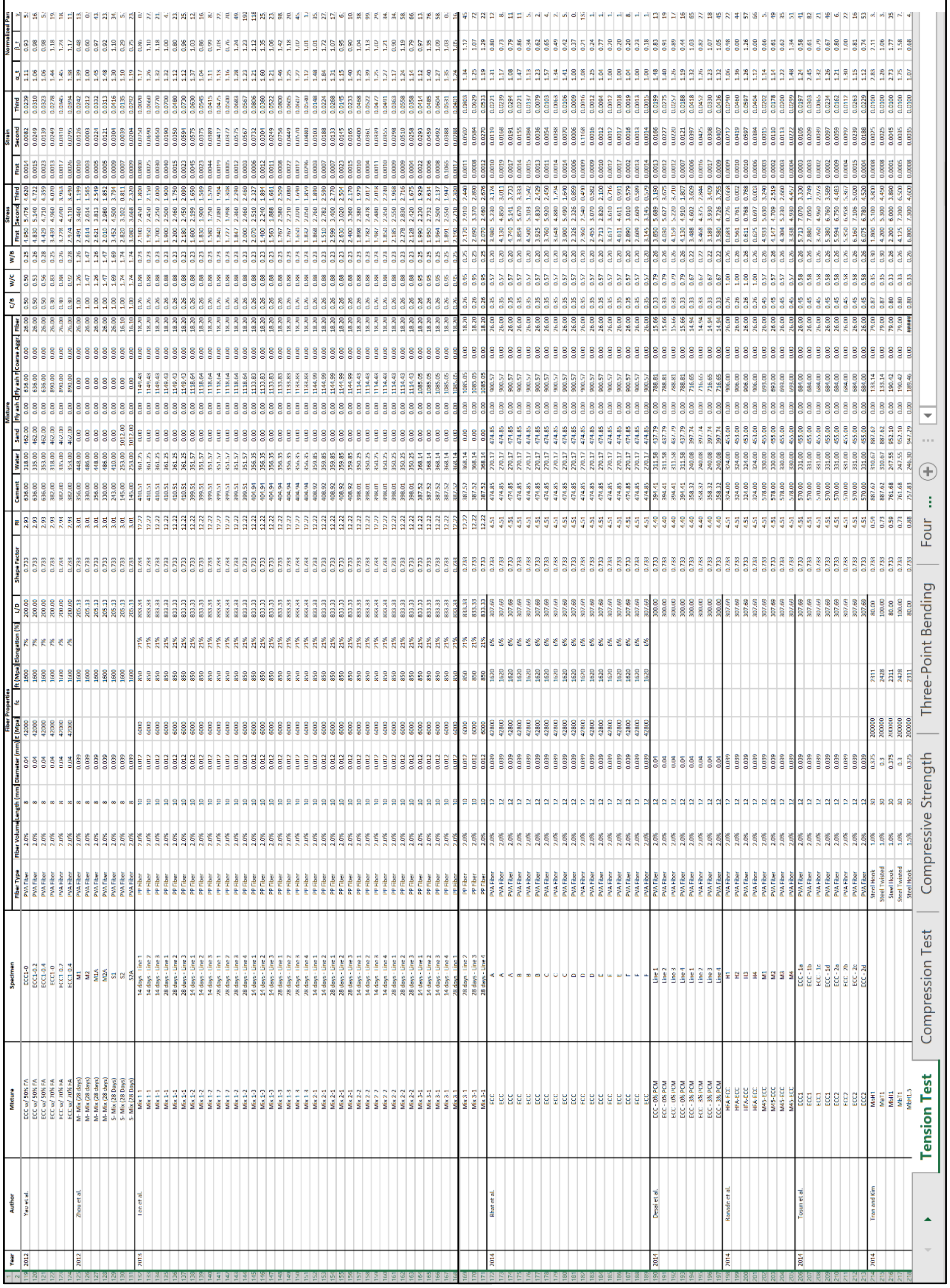
- Portland cement (C)
- Water (W)
- Fine aggregate (typically Silica sand, S)
- Fly Ash (mineral admixture)
- Fiber
- Chemical admixtures
    - High-range water reducer (HRWR)

    - 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)

The contents of data are:

- Author/Year of Publications
- Fiber dimensions: L (length), D(diameter), and specific gravity
- Mechanical properties of fibers: tensile strength, bond strength, Young's modulus, and elongation
- 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

Table 2. Sample of collected mixture design of ECC.



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 2.3.

Table 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

2.3.4 Raw Materials

Besides the normal materials used for ECC such as water, cement, sand fibers, and other additives. Other materials have been investigated; some have a different purpose. Qian et al. (2009) investigated the use of calcium carbonate as the main cause of cementitious composites self-healing, this help reduces water permeability. Özbay et al. (2013) studied the ECC mixtures using slag instead of fly ash, partial replacement of slag reduces the environmental burden. The increasing amount of slag in EC led to an increase in ductility and a decrease in residual crack width.

Yang et al. (2007) substituted a large amount of cement with recycled Class F fly ash resulting in high volume fly ash ECC (HVFA-ECC), expecting to promote infrastructure sustainability through simultaneous enhancement of material greenness and infrastructure durability through tight crack width control. The increase in fly ash reduces the compressive strength of ECC. HVFA-ECC with different compressive strengths can be selected for different applications. High fly ash content reduces the crack width in ECC. High interface frictional bond restrains the slippage of fiber and is responsible for the tight crack width. This promotes self-healing in ECC and benefits durability.

Another raw material that is added and investigated is a super absorbent polymer (SAP). Yao et al. (2012) studied used a water-SAP ratio of 10:1 or 30:1 to satisfy 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 similarly to ASTM C1580-04.

Limestone powder and blast furnace slag were also investigated. The use of blast furnace slag does not only improve the workability, durability and the mechanical properties of the mix but also reduces the cost and increases the greenness of ECC. The limestone in (Zhou et al., 2010) is considered as an inert filler material, resulting in a lower tensile strength. Qian et al., 2009 and Zhou et al., 2012 also investigates the use of limestone powders.

Many researchers are also looking into local materials or recyclable materials to substitute the typical ingredients to make it more cost-effective without changing the mechanical properties that make ECC unique. ECC also provides very low water permeability in rehabilitated infrastructures. The high tensile stress near the interface causes ECC to go into strain-hardening and accommodate the local stress with microcrack inelastic deformation.

Studies on ECC using local materials are mentioned making it a sustainable material without compromising the durability, and strain hardening behavior. Various studies on sustainability using different methods and materials are discussed below. Yang et al. (2007) used recycled materials to improve the crack width and tensile strain ductility of ECC. Lepech and Li (2010) compared the carbon emission of plain concrete, ECC and hot mix asphalt. Khan et al. (2016) studied the effect of local material, white sand, on the workability if incorporated into the 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.

Yang et al. (2007) using recycled material according to their study improved many properties of the ECC study focusing on using a high dosage of Class F fly ash for substitution for the cement to make ECC a sustainable material. Incorporating waste stream material ingredients does not mean lower composite material performance. As long as the governing mechanisms for deterioration are controlled.

Different sand sizes available locally found in Saudi Arabia, Khan et al. (2016) attempted to use white sand as a local ingredient substitute for ECC. White sand was collected from the desert with different ratios and was tested to reach an optimized mixture to achieve appropriate workability. Portland cement conforming to ASTM C150 was used as a binder from Al-Yamama

Saudi Cement Saudi Arabia. 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 smaller fine aggregate sizes required more superplasticizer to maintain a certain level of workability.

Snoeck and De Belie, (2012) used flax and cottonised flax to compare with polyvinyl alcohol in an attempt to substitute the material. But using the flax fibers made it difficult to achieve acceptable workability of mixture, the mixture was too stiff leading to a compacted product. flax fibers appear to be a good replacement for synthetic fibers and flax fiber-reinforced cementitious materials are an interesting alternative for future building applications.

2.4 Fiber-Matrix Interface Bond

ECC is not dependent on fiber type, ECC does not rely on increasing fiber volume to achieve strain hardening behavior, in instead ECC design emphasizes on the synergistic interaction between the fiber, matrix, and fiber-matrix interface. Besides fiber properties, the bond and interface interaction of the fiber and the matrix are also investigated. Fiber pull-out test is often used to study the fiber-matrix bond behavior in FRCCs. 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 studies on fibers include a volume of the oiling agent added to the fibers to avoid fiber ruptures when the fibers are pull-out under loadings. The high chemical bonding of the PVA fiber with the matrix causes fiber rupture and limited tensile strain capacity. Strong slip-hardening can also cause shear delamination failure of the fiber.

Chemical debonding and fiber slippage, occurs in the fiber/matrix but it does not lead to fiber rupture. Slip hardening causes more damage to the fiber/matrix bonding than the frictional bond strength. An oiling agent helped the fibers to slip out, exhibiting pseudo strain hardening, instead of rupturing.

When the fiber/matrix interface is too weak, pull-out of fibers occurs, resulting in a low peak strength. when the interface is too strong, the springs cannot stretch, and multiple cracking does not occur. extensive research has shown that the fiber bridging property across a matrix crack is the most fundamental property of a fiber reinforced cementitious material. There are two criteria for multiple cracking, one is the matrix cracking strength, this strength which included the first crack strength associated with the first crack must not exceed the maximum bridging stress which is the cracking strength subjected by the matrix flaw size. The second criterion is the mode of crack propagation which in turn is governed by the energies of crack extensions.

If the complementary energy is large, the crack will remain flat as it propagates so that the steady state crack opening is less than the critical opening and maintains tensile load carrying capacity. Load can be transferred from this crack plane back into the matrix and cause the formation of another crack, repetition of this process creates the multiple cracking.

Redon et al. (2001) investigated the slip hardening effect resisting a complete fiber pull-out by using an oil coating in the fibers. It was demonstrated that by using an oil coating the interfacial bond values within certain restrictions can be lowered. A strong chemical bond and frictional bonding are strong in the observed PVA fibers. The slip hardening effect resists a complete fiber pullout. Li et al. (2002) increased the oiling agent and the tensile strain capacity increased with a larger crack width and reduced crack spacing. It also allowed the fibers to slip out with less damage enhancing the bridging properties and composite tensile strain capacity.

Zhou et al. (2010) investigated the substitution of Portland cement with limestone powder and blast furnace slag. Using these materials can lower the cost of ECC and enhance the greenness of the material. Limestone and Blast furnace slag also improves the properties of fresh and hardened concrete such as workability and durability. As the fiber slips out of the matrix, the frictional bond between the fiber and the matrix increases. ECC shows a lower water permeability and better durability compared.

Li et al. (1995) emphasize the effect of matrix parameters and the interfacial bond strength on composite pseudo-strain-hardening behavior. If 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 through pseudo strain hardening.

Lim and Li (1997) used the interface fracture mechanics to serve as an analytical tool to predict whether the interface crack will propagate along with the interface or whether it will kink-out from the interface. An ECC overlay system with a trapping mechanism can prevent common failures in infrastructures such as delamination and spalling. The interface crack is trapped inside the interface due to the effectively toughened interface. ECC trapping mechanism with the repair system can achieve durable rehabilitation in aged infrastructures.

Kamada, T., and Li, V.C. (2000) investigated the micromechanical parameters associated with fiber, matrix, and interface are combined to satisfy two criteria: the first criteria are crack stress, the second is steady-state cracking to achieve strain hardening behavior. This paper also investigates the influence of surface preparation on the kink-crack trapping phenomenon. There is not much of a difference between the material 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.

2.5 Sprayability and Self-Consolidation

ECC material can be cast, extruded, and sprayed. 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 to fill in smaller voids that would otherwise be unfilled by larger particles, making it more resistant to chloride ion ingress.

The effects of high volumes of fly ash in the mixture design of ECC are investigated by Wang and Li, (2007). ECC mixtures with a high volume of ash needed Hydroxypropyl methylcellulose (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.

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 the 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.

Ali et al. (2017) investigated polycarboxylate-based high-range water-reducing admixture (HRWRA) meeting the requirements of ASTM standard C494 to adjust workability. Five different ECC mixtures incorporating various dosages of shape memory alloy (SMA) and/or

PVA short-fibers were tested. The study found that the addition of PVA and SMA fibers into the ECC matrix changed the failure mode of ECC specimens under the effect of impact loading from brittle to ductile.

According to Ali and Nehdi (2017), fiber-reinforced cementitious composites need to be carefully optimized to eliminate the effects of workability on mechanical performance. The compressive strength of ECC decreased due to PVA fiber addition at all testing ages. The shape memory alloy fiber did not have a significant effect. The tensile and flexural strength of ECC was enhanced due to fiber addition. Higher fiber dosage did not achieve superior tensile and flexural capacity due to fiber clustering and higher porosity.

2.6 Self-Healing and Self-Sensing

The first observation of self-healing of small cracks in the presence of moisture was by the French Academy of Science in 1863 (Kan et al. 2010). Qian et al. (2009) investigated the self- healing behavior of pre-cracked strain hardening fiber reinforced cementitious composites with 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 are effective in using to enhance self-healing. Yang et al. (2009) found that self-healing in transport and mechanical properties achievable. On the limited study, the mechanism of self-healing in ECC is the growth of calcites inside the tight cracks. Cracks width must be controlled to be below 150 µm to engage noticeable self-healing behavior.

Sisomphon et al. (2013) studied the self-healing behavior of strain-hardening cementitious composites incorporating calcium sulfoaluminate based expansive additive (CSA) and crystalline additive (CA). The study resulted in wet/dry conditions showed optimum mechanical recovery. The mixture with 10% CSA along with 1.5% CA addition showed the optimum mechanical recovery. The formation of calcium carbonate is preferable in terms of water tightness. The major internal crack healing product is a mixture of CaCO3. 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.

Qui et al. (2018) developed a study on the effects of self-healing on the 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 fiber bridging strength.

A study showed that resonant frequency is directly related to the recovery of mechanical properties and can be used as a method to quantify healing. So, Kan et al. (2010) investigated whether the crack characteristics and resonant frequency are used to identify self-healing after the chemical composition of healing products. Results showed less self-healing was observed with crack widths at 50 µm.

Li, M., and Li, V. C. (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 failure mechanisms in concrete.

2.7 Nonstructural Functions

Many studies have been conducted in the nonstructural functions of ECC such as fire-resistant, water-resistant, and self-consolidation. The nonstructural functions of ECC also studies the effect of the freeze-thaw cycle on ECC. Sahmaran et al. (2011) investigated that PVA fiber is beneficial in helping ECC overcome vapor pressure build-up under high temperatures and avoiding spalling by melting at 230 degrees Celsius. The study conformed to ASTM C618 requirements. 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 a 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 high-water absorption which is favorable in fire-resistive materials. FR-ECC shows superior compressive ductility in compression tests, far higher than the minimum for fireproofing material. Lightweight, low strength and superior deformability FR-ECC can be a potential substitute for fireproofing material of steel structures to address the durability issue 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. The authors investigated an ECC mixture to overcome the lack of durability of typical (SFRM) combining thermal insulation property, sprayability, and light-weightiness of ECC. Superfine grade vermiculite is chosen as an aggregate for the spray-applied fire-resistive ECC(SFR-ECC). An acrylic latex bonding agent was added to improve the adhesive properties of steel. High tensile polypropylene fibers are explored for economic reasons since they cost significantly lower. 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 compared to a conventional SFRM.

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. Exposing steel structures to the threat of fire. Authors in this study aim to develop 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 developed FR-ECC by Yang et al. (2019) is satisfactory thermal insulation property and is a suitable fire-proofing material for steel structure.

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

2.8 ECC Applications

ECC showed a good abrasion and wear resistance to heavy traffic after an ECC specimen was subjected to 4 million tire passes to simulate long-term wear. Freeze-thaw durability factor of ECC is calculated to be 100, compared to 10 for the non-air entrained concrete. The non-air entrained ECC survived 300 cycles with no degradation of dynamic modulus. Additionally, uniaxial tension test was performed on the ECC coupons after exposure to 200 cycles of freezing and thawing and revealed no significant decrease on tensile strain capacity. The increased toughness of ECC leads to increased resistance to disintegration.?

The production of Portland cement is contributing to greenhouse emission, so Lepech and Li (2010) compared plain concrete to ECC and hot mix asphalt (HMA) through a bridge demonstration application done in Michigan and ECC. The ECC application showed an improved performance in shrinkage cracking behavior, fatigue, freeze-thaw exposure, abrasion and wear testing, long term performance and accelerated weather tests compared to the plain concrete and HMA.

A review of the use of ECC in hot arid coastal conditions is done by Kewalramani et al. (2017) it 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 strength of ECC becomes more ductile under uniaxial compression. Durability performance in cracked and uncracked ECC samples was found to be comparable or lower than normal concrete of the same strength without cracks. Application in Michigan, USA, and Osaka, Japan are showed in Figures 5 and 6, respectively.

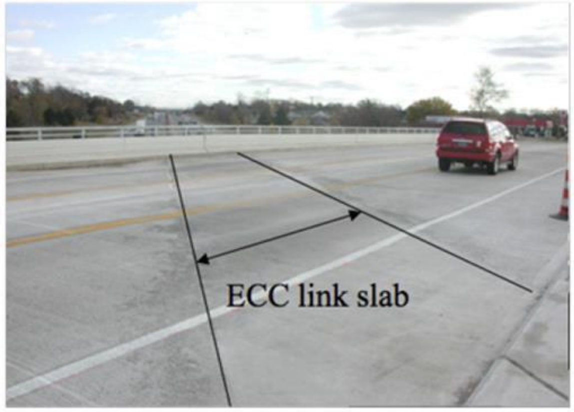


Figure 7. ECC link slab in bridge deck, Michigan,USA. (Kewalramani et al. 2017)

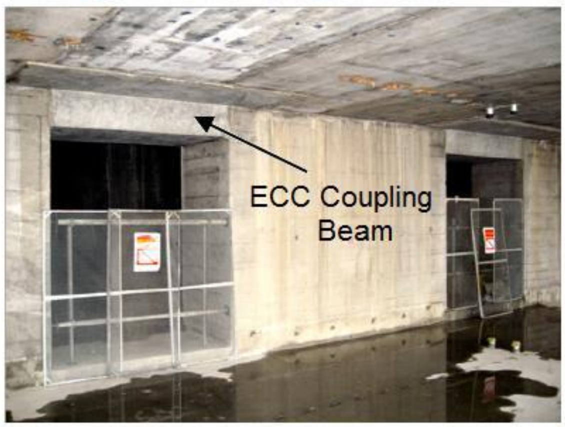


Figure 8. ECC coupling beams, Japan (Kewalramani et al., 2017)

ECC has been used as a bridge Link-Slab from Li and Lepech (2004). Leaking in bridges allow water and other corrosives to penetrate below the deck and corrode bridge beams, that is why many bridge owners use continuous bridge decks with no expansion joints to overcome this problem. But this approach can only be done on new bridges and cannot be used on simple span bridges currently in service. An alternative solution to overcome the leaks on simple span bridges are link slabs and ECC link slabs show better performance over concrete link slabs.

Another one for a jointless bridge deck from Lepech and Li (2005). Major concerns about concrete bridge deck are the continuation of deterioration and leaking expansion joints. ECC has shown that it can be highly durable and well suited for large infrastructure applications. Lepech and Li designed a link slab that can changed these concerns and even considered different materials to be used. A demonstration project was scheduled for construction in the summer of 2005 in Michigan. The ECC link slab measure 5.5m x 20.25m, the 25.5 m^3 ECC was delivered on-site from a nearby batching plant.

In Li (2014), Water leakage through the joints can cause beam-end corrosion, spalling and deterioration of pier caps so a high performance and durable link slab made of ECC was constructed in Michigan to replace expansion joints for a multi-span simply supported bridge. Mihara bridge, an ECC steel composite bridge deck in Hokkaido, Japan was constructed in 2004. The deck is a 38mm thin layer of ECC placed on top of steel. This design is to protect the underlying steel from penetration of moisture and chloride. Because of 40% weight reduction, it qualifies as a super light-weight design. It has an expected service life of 100 years and the life cycle costs associated with maintenance, repair, and rehab are expected to be lower than conventional bridge deck systems.

Kewalramani et al. (2017) mentions the use of ECC coupling beams for a 60-story reinforced building in Osaka, Japan experiencing different temperatures, humidity, and rainfall. The ECC coupling beam enhanced seismic safety and durability by absorbing energy during an earthquake.

ECC has been used mostly as a repair material. In Li (2004) ECC has been used as a repair material on a bridge deck. There is a need for durable infrastructure repair. HPFRCCs are excellent repair materials because it is characterized by tensile strain-hardening after first cracking. ECC shows a high tensile strain capacity and since it is one of the most important properties in a durable material it is a good candidate to be used to repair failures.

Li and Lepech (2004) Durability tests, long term performances, long term strain capacity and early age strength development of ECC was investigated on a bridge deck patch repair in michigan. The First visit (2 days after patching) no visible crack on ECC but a clear visible 300 µm crack on concrete appeared. After 4 months, small cracks roughly 50 µm had formed on the ECC patch and the concrete crack had widened to 2mm and was surrounded deteriorating and spalling concrete. The only downside was the mixing time was longer than a typical concrete.

Another application as a repair material on a bridge can be seen on (Li 2004b). This field performance showed the ECC durability in harsh environment of Michigan winters and heavy traffic loads. High early strength ECC patch repair in Michigan showed as a better durable repair material than Thoroc 10-60, a repair material used by MDOT, in harsh environmental conditions combined with restrained shrinkage, freeze- and thawing, exposure to deicing salts and temperature changes.

ECC has been used as a repair material but as a sprayable material has been used in Rokugo et al. (2009), A wet type direct sprayed HPFRCC with PVA fibers was retrofitted to protect a deteriorating concrete surface of an aged same structure. A viaduct retrofitting was applied on girders and beams as protection by HPFRCC layer on the bottom surface. Reinforced HPFRCC was applied in building structure in a coupling beam connecting two structural walls in a 27-stiry high rise reinforced concrete building. These were designed to expect an exceptionally large drift of 1/30 under very large earthquake considering minor damage without repair on the building.

The repair of Mitaka Dam in Hiroshima-prefecture in 2003. This dam had severely damaged concrete surface. Cracks, spalling and water leakage were concerns, ECC was used as a cover layer, a 20 mm layer was sprayed onto approx. 600 m^2 of upstream dam surface. (Li, 2008b). Earth-retaining wall in Gifu, Japan was damaged by alkali-silicate reaction in the form of macro-cracking. ECC was used to control the cracking of surface layer. After one year of installation only 50 μm width could be observed.

(A) (B)

Figure 9. ECC joint and completed shear keys. (Yildirim et al. 2018)

Figure 9 is the most recent field application of ECC. The shear keys of bridges with adjacent box beams and voided slabs, completed by the Virginia Department of Transportation (VDOT) in 2014. Bridge designs in the United States have grouted shear keys to transfer load between beams. However, shear key cracks frequently occur and leak, even with a waterproofing membrane in place.

To extend the life of reinforced concrete in bridges, VDOT used low-permeability grouts as shear key repair materials. Three different cementitious materials, including non-shrink grout commonly used by VDOT, standard ECC mixture, and ultra-high-performance concrete (UHPC) were used in the shear keys of the bridges.

The performances of all grouting materials were recorded during site visits. From this unique comparison, ECC performed the best, even though it had the highest shrinkage among the tested composites. As a result of this outstanding performance of ECC in shear keys, VDOT selected ECC as a new grout material.

Through this literature review, properties and characteristics were discussed and shown. This background information should help with future research. Each literature review has its own, data that can be compared to each other to come up with a standard criterion on the behavior and performance of ECC.

CHAPTER III

METHODOLOGY

3.1 Modeling of ECC Behavior

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.

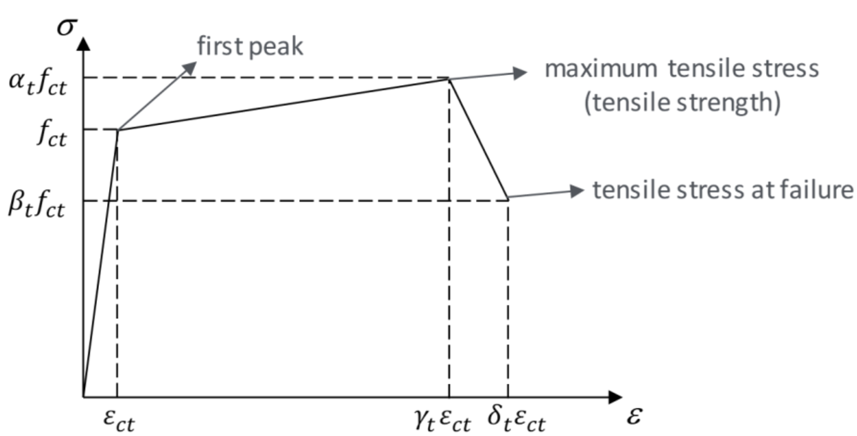


Figure 10. Simplified Model for Tensile Behavior of ECC (Shi et al. 2020)

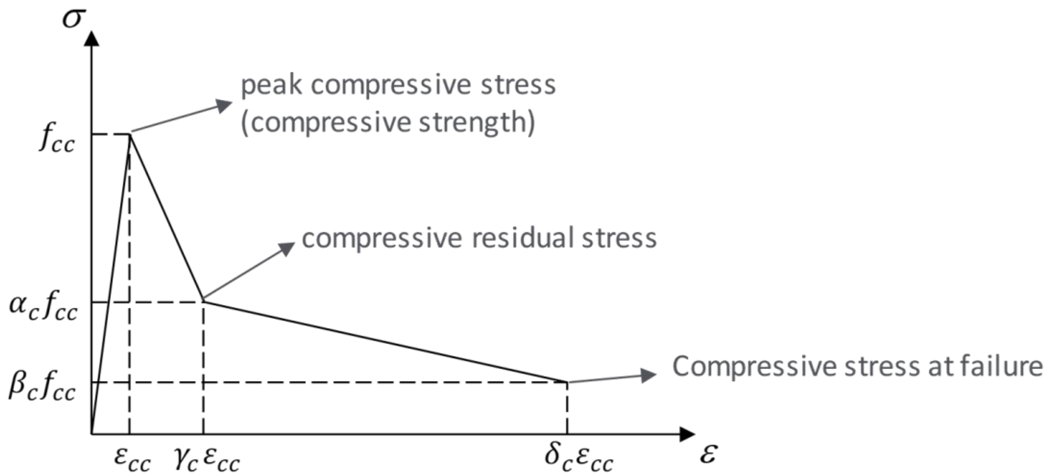


Figure 11. Simplified Model for Compressive Behavior of ECC (Shi et al. 2020).

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 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 behavior 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.

3.2 Data Collection

The academic journals were divided into three groups: papers that performed uniaxial tension test, compression test, and flexural with three and four-point bending test. The data collected were organized in the same manner as the papers in three excel spreadsheets. The data collected were categorized and organized by the tests that were performed on the specimens by mix designs and fiber types. Stress strain graphs, deflection-load graphs and tables were collected to obtain first and second peak and the failure of tensile, compressive, and bending tests data from academic journals that researched the mechanical behaviors of ECC. In addition to the points collected from the graphs, the fiber properties, mix designs and binder ratios were also collected. The fiber properties include the fiber type, volume fiber by weight, length, diameter, density, tensile strength, modulus of elasticity, elongation, and oil content by weight if applicable and/or available. The mix design shows the weight of cement, sand, water, fly ash, and additives, including the cement-binder ratio, water-binder ratio and water-cement ratio.

The graphs collected were manually digitized using GetData Graph Digitizer application and compiled in an excel spreadsheet. The yield, ultimate and failure points were collected and analyzed in excel. The three peak points of the stress and strain obtain from tension, compression and flexural test were graphed with the water-cement ratio and the water-binder ratio using a scatter plot.

3.3 Parameters for the Meta-Analysis

With 180 academic papers, the data were collected in excel spreadsheets for uniaxial tension tests, compression tests, and bending tests. The collected parameters are listed as follows:

- Reference: the year and authors of the paper

- Type of Testing
- Fiber Properties:
    - Fiber Types: PVA, Polypropylene, Polyethylene, etc.
    - Fiber Shape Factor: 1.0 = hooked, 0.733 = straight
    - Fiber Length (mm)
    - Fiber Thickness (Diameter, mm)
    - Young’s Modulus of the Fiber (GPa)
    - Tensile Strength of the Fiber (MPa)
    - Elongation of the Fiber (%)
    - Fiber Volume Fraction (V_f, %)
    - Reinforcing Index (RI)
- Mixture Information:
    - Mixture Description
    - Mixture ID
    - Specimen ID
    - Compressive Strength at 28 day
    - Mixture Proportion:
        - Cement (C)
        - Water (W)
        - Sand (S)
        - Coarse Aggregate (G)
        - Fly Ash (F)
        - Other Pozzolanic Additives (F)

        - Notes on the Additives
        - Cement-Binder Ratio, C/(C+F)
        - Pozzolanic Additive-Binder Ratio, F/(C+F)
        - Pozzolanic Additive-Cement Ratio, F/C
        - Water Cement Ratio, W/C
        - Water Binder Ratio, W/(C+F)
- Stress-Strain Curve Information
    - First Peak Stress (MPa)
    - Second Peak Stress (MPa)
    - Stress at Failure (MPa)
    - First Peak Strain (%)
    - Second Peak Strain (%)
    - Strain at Failure (%)
    - Normalized Parameter, α_t
    - Normalized Parameter, β_t
    - Normalized Parameter, γ_t
    - Normalized Parameter, δ_t

CHAPTER IV

META-ANALYSIS RESULTS

In general, the compressive strength of cementitious materials is controlled by water-cement ratio, - composites with low water-cement ratio have high compressive strength. In case of ECC, adding another pozzolanic additive, such as fly ash, is common, hence, the water contents are typically controlled by water-binder (binder =cement + pozzolanic additives) ratio rather than water-cement ratio. The tensile strength of fiber reinforced cementitious composites is influenced by the tensile strength of matrix, chemical/frictional bonding at fiber-matrix interface, fiber type and strength, fiber aspect ratio, fiber contents, and aggregates in ECC mixtures.

The fiber volume content (typically 2%) and fiber type (PVA) are mostly fixed. Figure 12 below shows the relation between compressive strength and tensile strength of ECC. The data plotted with transparent grey dots so that darker dots indicate that multiple data overlap each other. Although the scatter range is large, Figure 12 are due to the difference in the amount of pozzolanic additives, fiber geometry and surface treatment of fibers. A few data points as pointed out in the figure are the data from sprayable ECC. ECC has extremely high water-binder ratio because it needs to have high workability enough to be sprayed on to surfaces

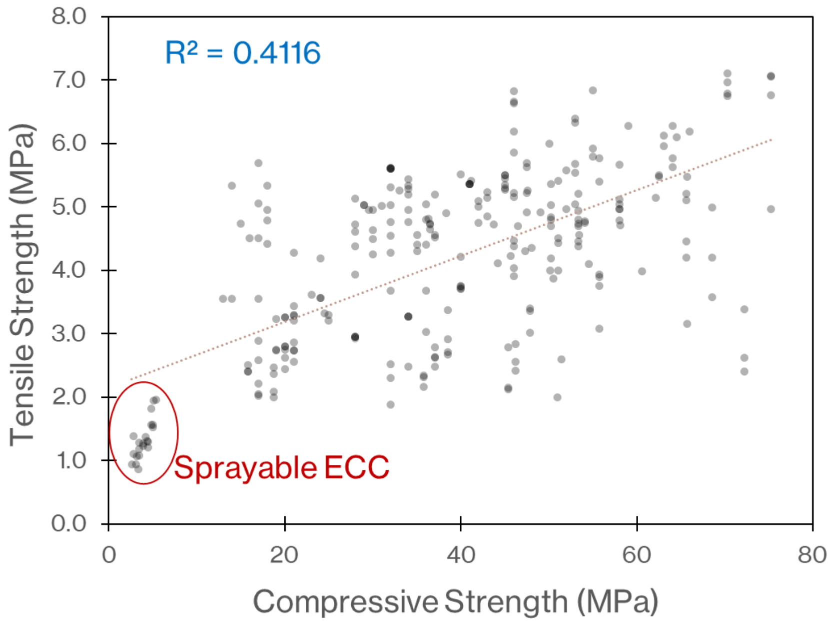


Figure 12. Relation between compressive strength and tensile strength.

The effects of water-cement ratio and water-binder ratio on compressive strength are shown in Figure 13 and 14, respectively. The wide scatter observed in Figure 12 appears again, but there is a clear trend of inverse correlation between the water-cement ratio and the compressive strength of ECC. On the other hand, as shown in Figure 14, most investigators used controlled water-binder ratio within the range of 0.2 – 0.4 (except for the sprayable ECC), hence it is difficult to find a trend in such a narrow range.

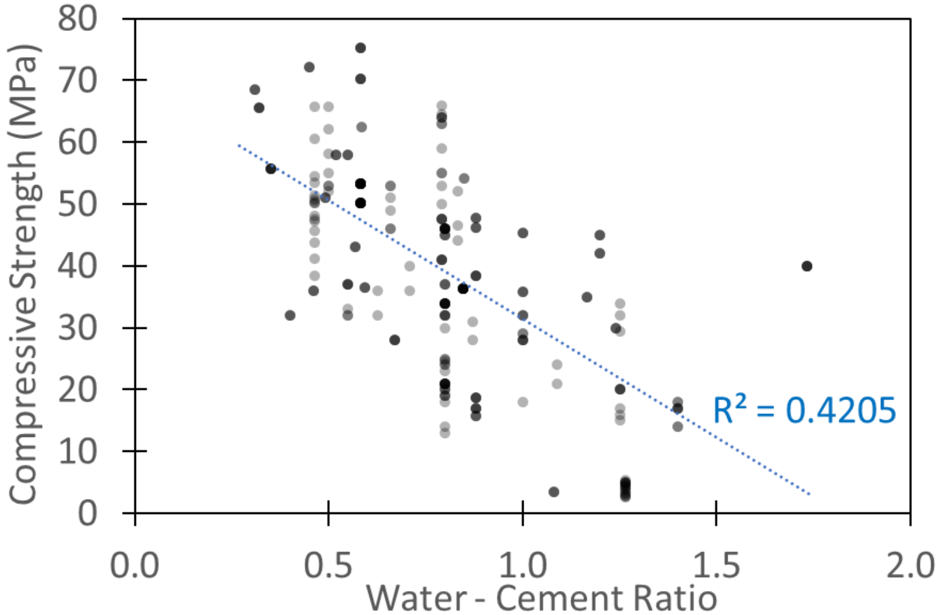


Figure 13. Water-Cement Ratio on Compressive Strength.

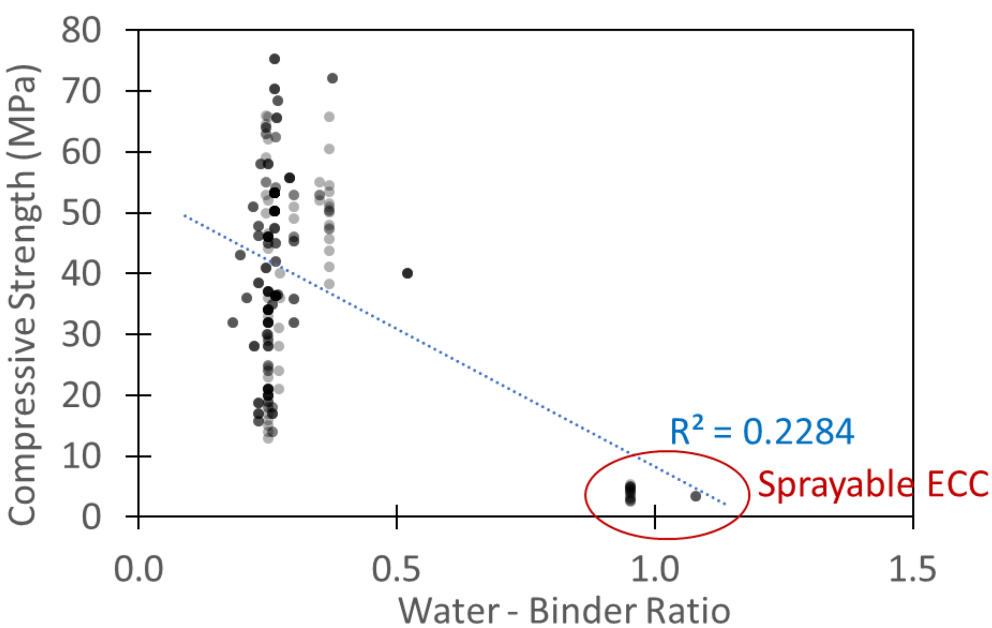


Figure 14. Water-Binder Ratio on Compressive Strength.

The effects of water-cement ratio and water binder ratio on tensile strength are shown in figures 15 and 16, respectively the following figures. The tensile strength of ECC ranges from 1-7 MPa. Similar to the case of compressive strength (Figure 13), Figure 15 shows that there is a weak inverse correlation with wide scattering between the water-cement ratio and the tensile strength of ECC. Similar to the case of compressive strength (Figure 14), it is difficult to find a clear correlation between water-binder ratio and tensile strength in Figure 16.

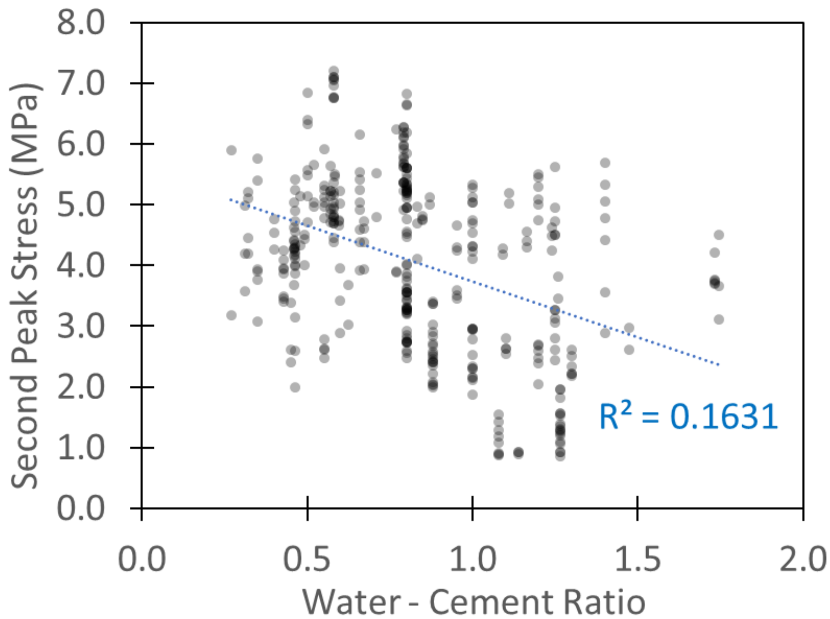


Figure 15. Water-Cement Ratio vs Second Peak Stress (Tensile Strength).

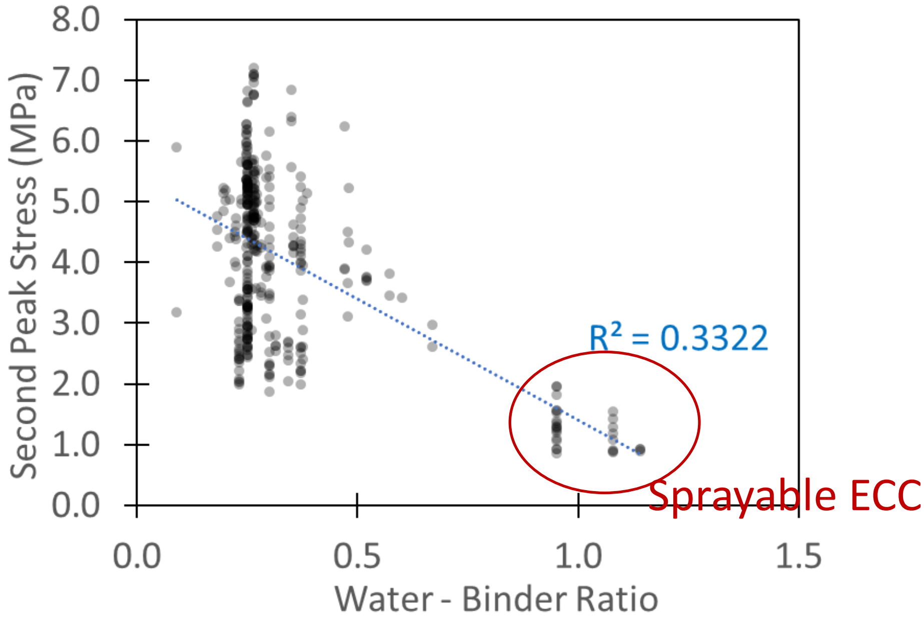


Figure 16. Water Binder Ratio vs Second Peak Stress (Tensile Strength).

ECC is a strain hardening material, and the tensile strength is obtained at the second peak (Figure 10) Considering the fracture mechanism of fiber reinforced composites, the second peak stress is dominated by the fiber bridging effect while the first peak is the point where the matrix starts cracking. Therefore, it was expected that the stresses at the first peak have a stronger correlation with water-cement and water-binder ratio. The effects of water-cement ratio and water-binder ratio on first peak stress are shown in Figures 17 and 18, respectively. As shown in Figure 17, the first peak stress has an inverse correlation with water-cement ratio, which is similar to the case of the second peak stress. However, the first peak stress does not have a stronger dependency on water-cement ratio than the second peak stress which is different from the expectation. These results indicate that the strength of matrix plays an important role in the second peak stress as well as the first peak. The first peak stress versus water-binder ratio shown in Figure 18 shows similar trend to Figure 16.

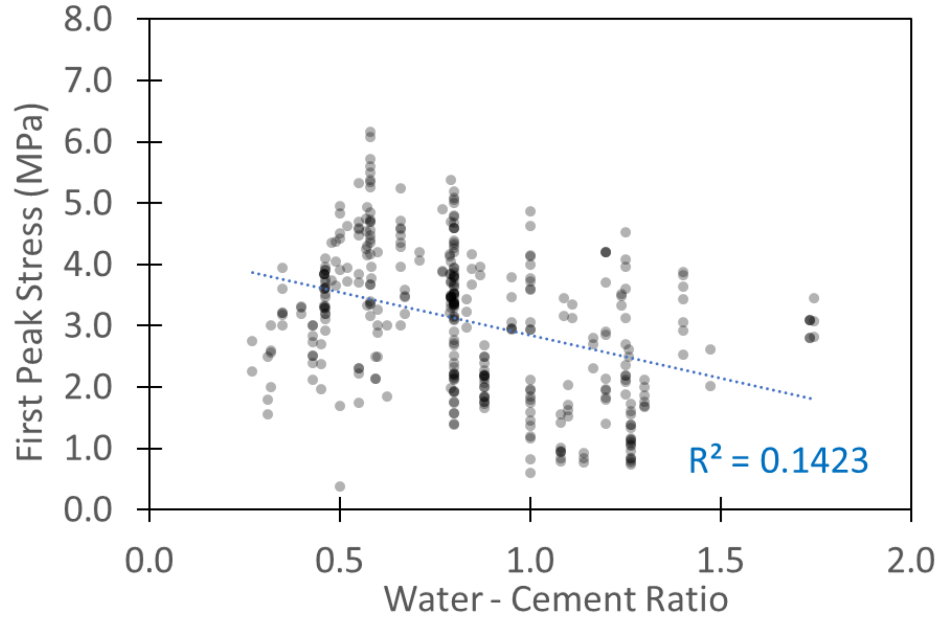


Figure 17. Water-Cement Ratio vs First Peak Stress.

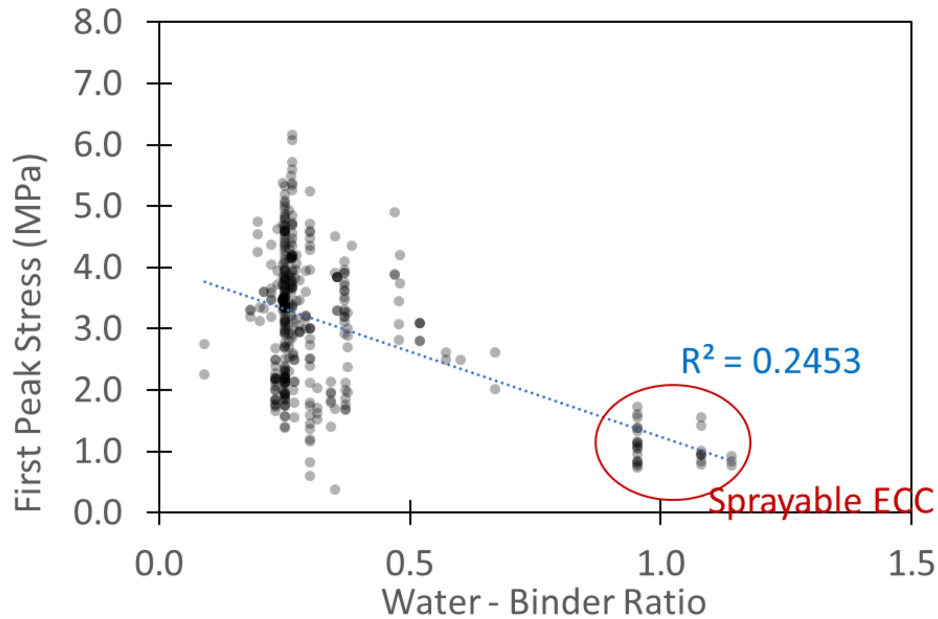


Figure 18. Water-Binder Ratio vs First Peak Stress.

The effect of water-cement ratio and water-binder ratio on ductility (strain at failure) is shown on Figures 19 and 20, respectively. Figure 19 and 20 show that the ductility of ECC is not influenced by water-cement ratio or water-binder ratio. Likewise, the strain at second peak does not show a specific relation with water-cement and water-binder ratio as shown in Figure 21 and 22. One notable thing is that the sprayable ECC has relatively lower ductility than the regular ECC.

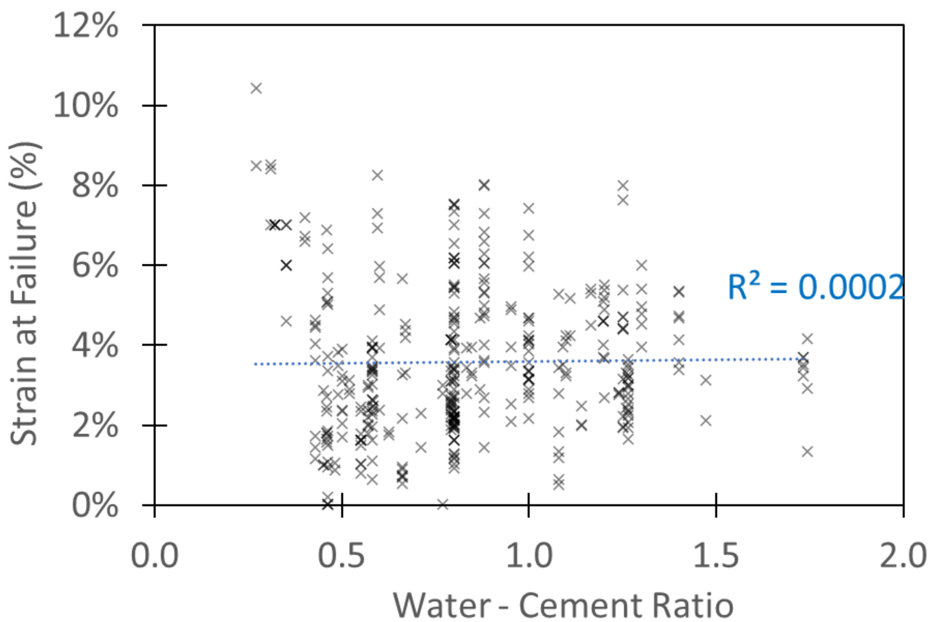


Figure 19. Water-Cement Ratio vs Strain at Failure.

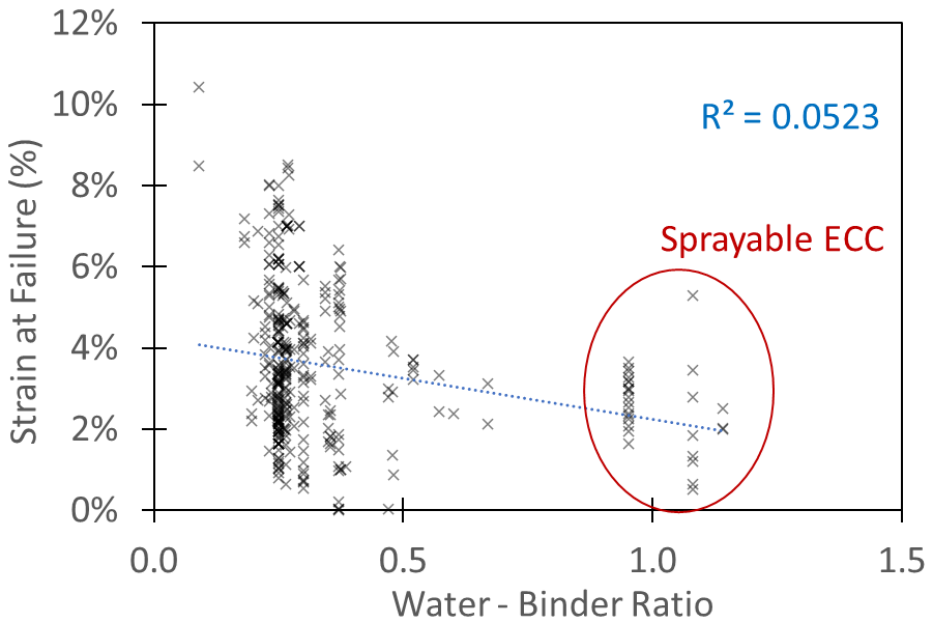


Figure 20. Water-Binder Ratio vs Strain at Failure.

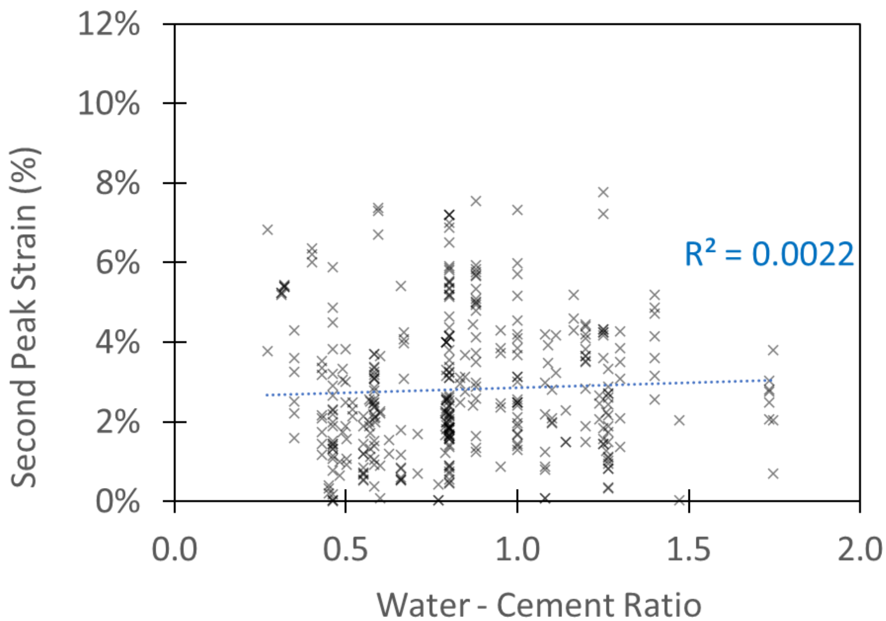


Figure 21. Water-Cement Ratio vs Second Peak Strain.

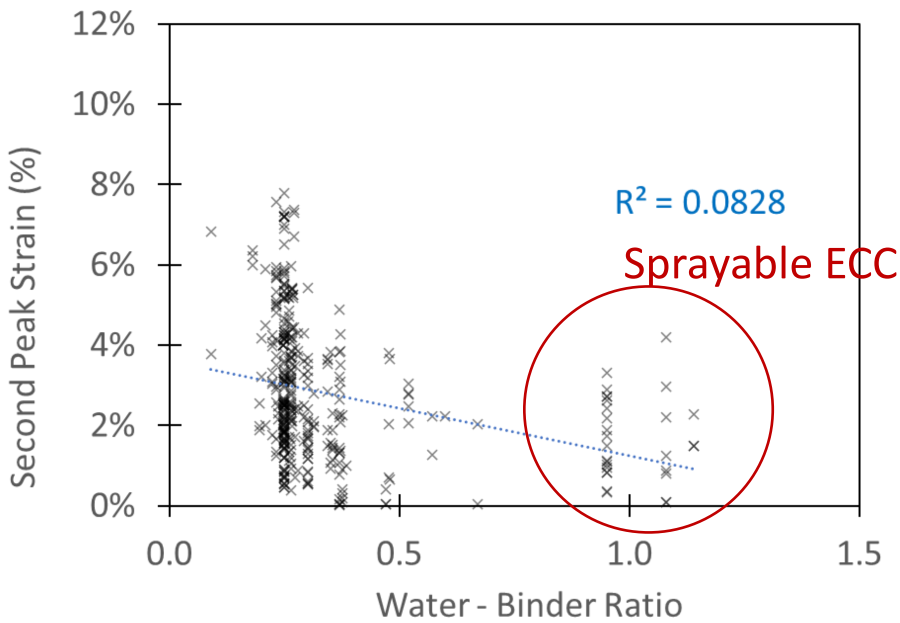


Figure 22. Water-Binder Ratio on Strain at Second Peak.

The effects of pozzolanic additives on tensile strength and ductility are shown in both Figure 23 and 24. Previous investigators assumed that pozzolanic additives such as fly-ash can reduce the use of cement without losing the strength. As shown in Figure 23 (the first peak stress) and Figure 24 (the second peak stress), the strength parameters are not influenced by the amount of pozzolanic additives. Previous investigators also stated that the increase in ductility is expected by adding pozzolanic additives. Figure 25 (the second peak stress) and Figure 26 (the strain at failure) show that the ductility parameters slightly increase with the amount of pozzolanic additives. However, considering the wide scale scattering range of the data, it is difficult to say that the increase in ductility by adding pozzolanic additives is practically meaningful.

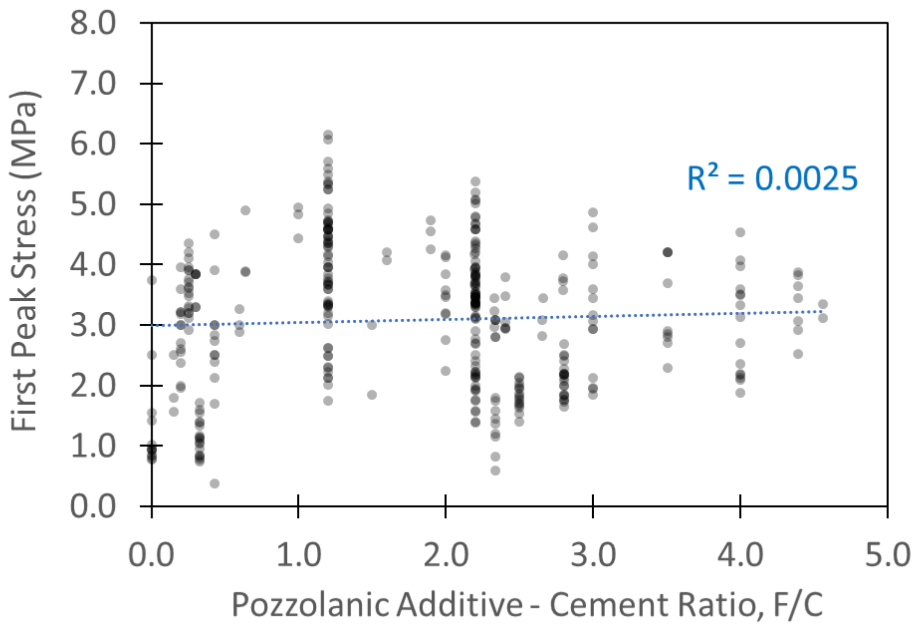


Figure 23.Pozzolanic Additives-Cement Ratio on First Peak Tensile Stress.

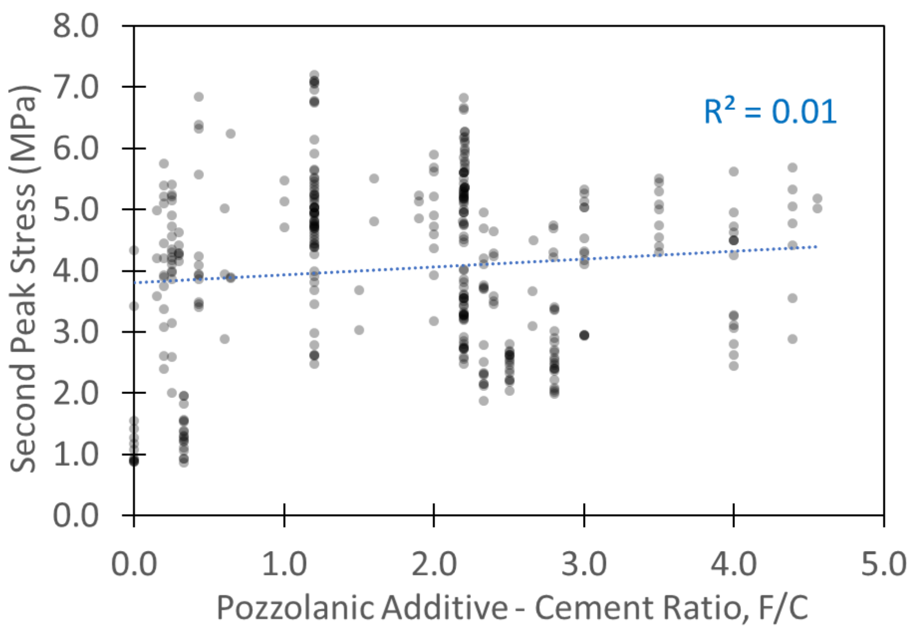


Figure 24. Pozzolanic Additive – Cement Ratio on Tensile Strength.

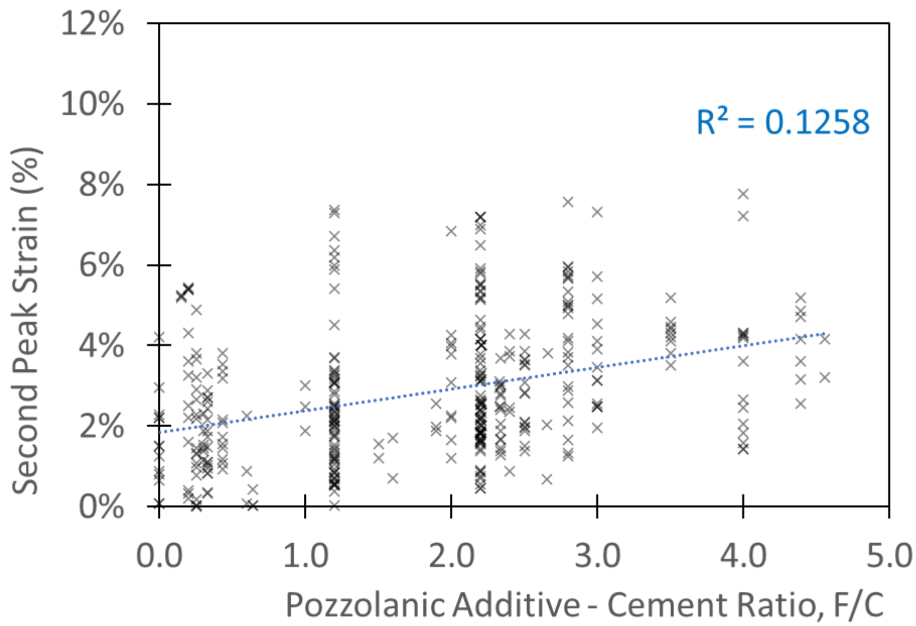


Figure 25. Pozzolanic Additives – Cement Ratio vs Second Peak Strain

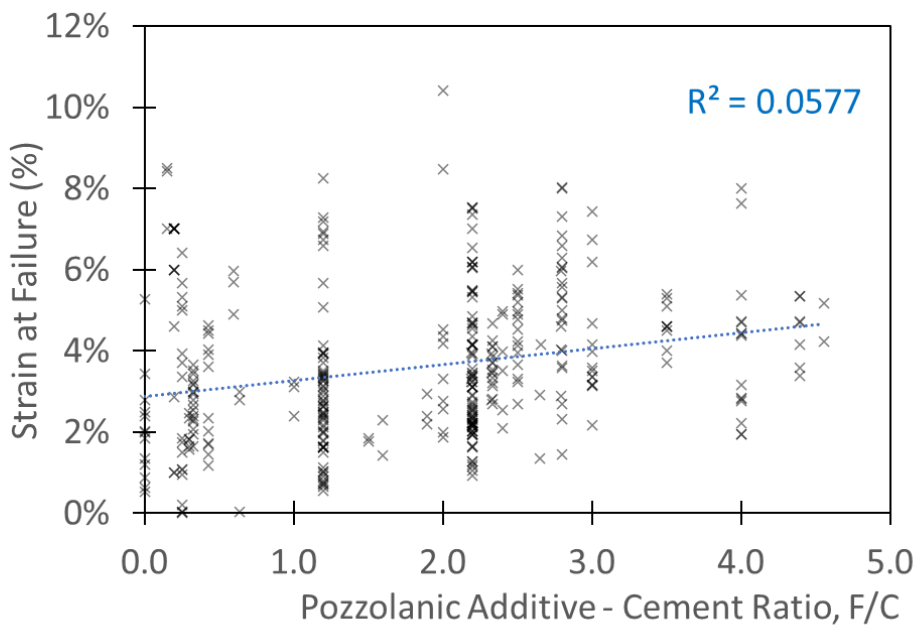


Figure 26. Pozzolanic Additives – Cement Ratio on Strain at Failure

As explained in Chapter 3, the reinforcing index is a parameter representing the effectiveness of fiber reinforcement. The effects of reinforcing index on tensile strength is showed in Figures 27 and 28. The RI is a function of the fiber shape factor (straight fiber = 0.733), fiber aspect ratio, and fiber volume content. ECC uses straight fibers and the volume contents of the fibers were 2.0% in most cases. The collected RI ranges from 2.0 – 12.5 due to various fiber contents (V_f = 1-3%) and fiber length/diameter, but the majority of the data used PVA fibers with two aspect ratios: 8 mm and 12 mm fiber length with 0.04 mm thickness (the corresponding aspect ratio are 200 and 300, respectively). Because of these, the data are concentrated at RI = 3.0 (using 8 mm PVA fibers) and RI = 4.4 (using 12 mm PVA fibers). Figure 27 on the first peak stress and Figure 28 on the second peak stress shows a similar pattern. The assumption of using RI is that the higher RI provide the better reinforcing effects, but Figure 27 and 28 show that the expectation is not true. As marked in the figures, the data that have the RI higher than 8.0 used PP (polypropylene) fibers with higher aspect ratios and may have totally different trend from the case of using PVA fibers. Even if the ECC with PP fibers are excluded, the data using PVA fibers do not show a clear tendency. Therefore, it can be said that the strength of ECC (both the first and second peak) in the RI range of 2.0 - 8.0 is not influenced by RI. It should be noted that a clear improvement in the strength with increase of RI is observed when we focus on the data for the ECC with PP fibers, which supports the effectiveness of RI assumed by the previous investigators. On the other hand, in case of the data for the ECC with PVA fibers, there should be another factor (such as oiling treatment on fiber surface) that influence on the strength.

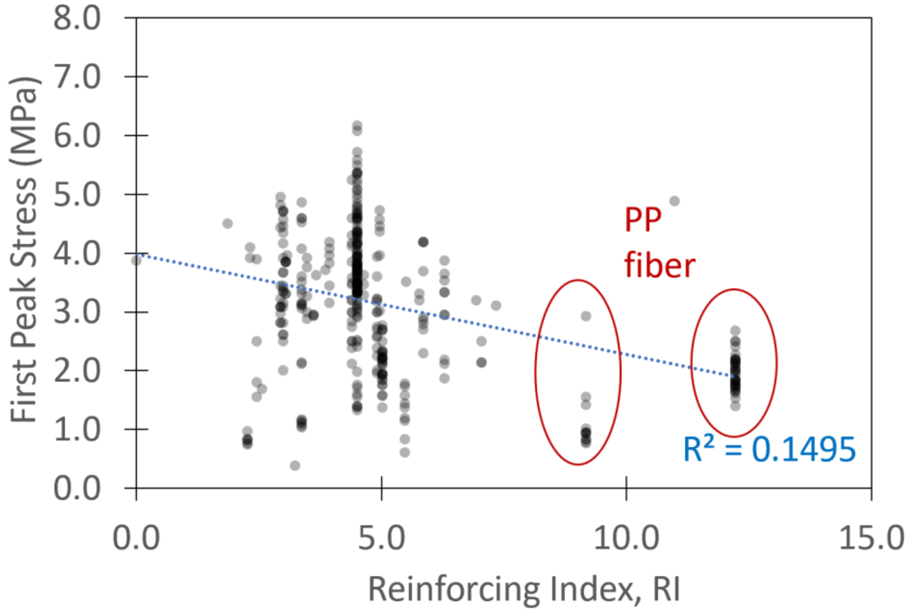


Figure 27. Reinforcing Index on First Peak Stress.

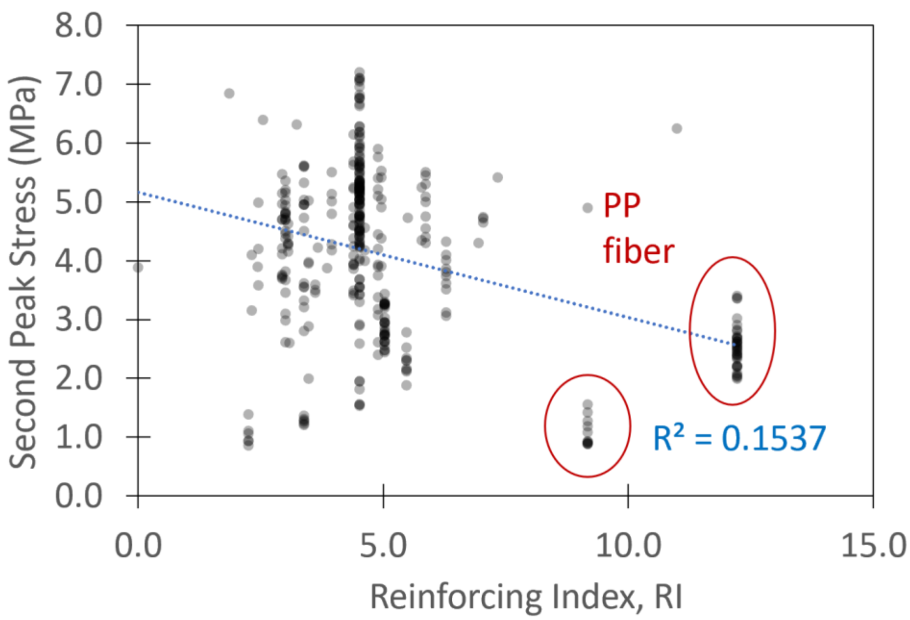


Figure 28. Reinforcing Index on Second Peak Stress

On the other hand, the ductility of ECC seems to be slightly influenced by the RI. Effects of RI on Ductility is shown in Figure 29 (the second peak strain) and Figure 30 (the strain at failure). There is an insignificant difference between Figure 29 and 30. When the data for PP fibers and PVA fibers are separated, like the case of the strength, the ductility parameters of the data for PP fibers increase with the increase of RI. For the data for PVA fibers, this trend is not as clear as the data for PP fibers.

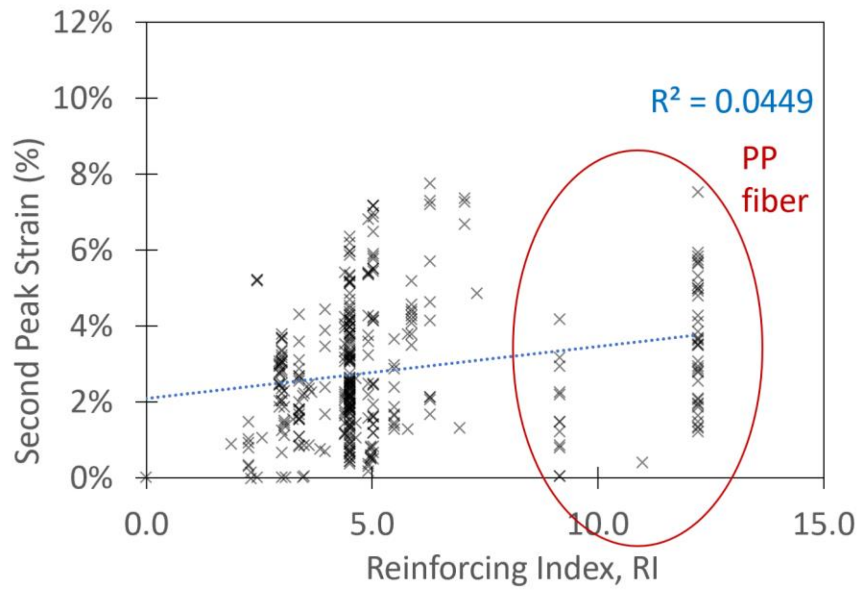


Figure 29. Reinforcing Index on Second Peak Strain

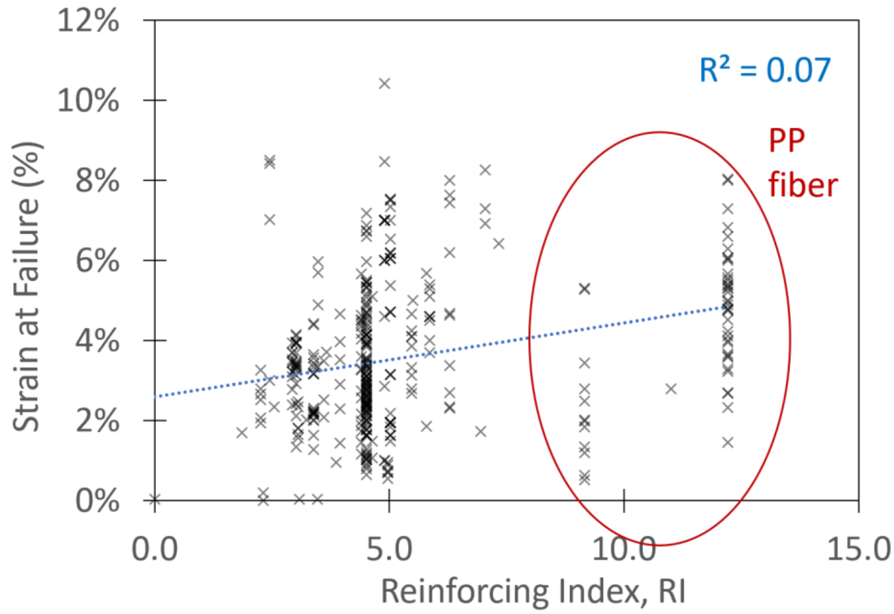


Figure 30. Reinforcing Index on Strain at Failure.

The effects of water contents (water-cement ratio and water-binder ratio), pozzolanic additives, and RI on the strength and ductility of ECC are discussed herein. The high level of the data scatter makes the analysis difficult. Some of the scatters may cause by the nature of cementitious composites, but there are additional factors that was not considered in this analysis. For example, the oil treatment on the PVA fiber surface was one of the research interests in the collected papers but was not properly considered in this analysis. The type of pozzolanic additives (fly ash, silica fume, silica powder, slag, etc.) and fine aggregates (local sands, uniformly graded silica sand, soda lime glass, glass bubble, etc.) are the other factors that can influence on the strength and ductility of ECC. Following future work using the collected data is suggested:

- Identify additional factors that should be considered in the analysis.
- Regroup the collected data based in the additional factors
- In-depth statistical analysis on the regrouped datasets.

CHAPTER V

CONCLUDING REMAKRS

The effects of water contents (water-cement ratio and water-binder ratio), pozzolanic additives, and RI on the strength and ductility if ECC are investigated by collecting data from previously published papers. The data from uniaxial tension tests were collected from various investigators using different mixture designs and fibers. This paper utilizes a meta-analysis approach to combine results from multiple studies on ECC and to understand the relation between the mixture design and mechanical properties. Meta-analysis is a form of study to determine an overall trend from multiple independent studies of the same subject. By statistically evaluating the group of datasets produced by multiple studies and various investigators, the meta-analysis can give more reliable answers to an engineering questions than can be derived from a single study with a limited dataset.

The following conclusions were obtained through the meta-analysis on ECC behavior:

- Although there are wide scatterings of the data, the tensile strength of ECC shows a trend proportional to the compressive strength. This trend shows a possibility that the tensile properties can be approximated from compressive test data.
- Compressive/tensile strength of ECC is inversely proportional to water cement ratio. The average water-cement ratio is 0.807 and the tensile strength ranges from 2 MPa

- Since typical ECC contains pozzolanic additives (most common choice is fly ash) the water contents have been controlled by water-binder (cement + pozzolanic additives) ratio. Most of the data has water-binder ratio ranged from 0.2 – 0.4. If the data for sprayable ECC were removed, it is difficult to find a relation between water-binder ratio and compressive/tensile strength.
- The strain at failure and strain at the second peak that represent the ductility of ECC is not influenced by water-cement ratio or water-binder ratio.
- The amount of pozzolanic additive was known to increase tensile ductility without losing strength. As expected, the strength of ECC do not vary with the amount of pozzolanic additives. On the other hand, the ductility parameters (the strains at failure and at second peak) show slight increase with the increase of pozzolanic additive contents. However, because of the wide scattering range, it is difficult to say the relation is clear. The average pozzolanic additive-cement ratio is 1.81, and most popular choice of pozzolanic additive-cement ratios were 1.2 and 2.2.
- Since most of studies use 2% PVA fibers with the 0.4 mm diameter and 8 mm or 12 mm length, the variation of RI is limited. Because of this, it is difficult to draw a relation between strength/ductility and RI for ECC.

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