Fiber reinforced concrete: Tailoring composite properties with discrete fibers

by

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The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this thesis. The Graduate College will ensure this thesis is globally accessible and will not permit alterations after a degree is conferred.

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DEDICATION

This thesis is dedicated to my family and friends in gratitude for their support and encouragement throughout my studies. To my parents, Murray and Diane, who have supported me through all of my experiences, encouraged me to set high goals, and shown me the value of hard work. To my fiancé, Keylee, who has been so supportive and understanding during my studies.

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ABSTRACT

Concrete is one of the most widely used building materials in the world. The single largest limitation of concrete is its weak and brittle nature under tensile stress. In order to improve this material behavior, reinforcement materials that are strong in tension are embedded into the concrete to avoid brittle failure and increase tensile load capacity. Besides the traditional methods of embedding continuous aligned reinforcement in anticipated zones of tensile stress, random discrete fibers can be dispersed into the concrete during the mixing procedure to create a composite material called fiber reinforced concrete (FRC). In this study, a comprehensive review of the relevant and recent literature pertaining to FRC is provided, establishing basic principles and highlighting the possible contributions to composite properties that different types of fiber can deliver. Once the capabilities and limitations of FRC are well established from previous works, an experimental investigation is described, in which flexural testing of 3 different types of synthetic concrete fibers was performed to determine their performance in the fresh state as well as hardened state under flexural loading. The experimental work is then extended to investigate how carbon microfibers and concrete admixtures affect concrete strength development and shrinkage behavior for applications in which high early age strength and shrinkage control is desired. The outcome of this study is anticipated to contribute to the state of FRC knowledge and practice by providing important findings from previous work, supplemented by experimental data which effectively highlights the capabilities that the addition of discrete fibers can impart to concrete.

CHAPTER 1: INTRODUCTION

1.1 Research Significance

Despite the widespread use of concrete as a building material for numerous applications in the construction industry, concrete has a number of undesirable material properties that must be overcome in order to utilize the material to its full potential. Although concrete is characteristically strong under compressive stress, the opposite is true for tensile loading, under which concrete is relatively weak and brittle. These characteristics can result in poor longevity and even sudden and catastrophic failures of improperly designed concrete structures. In order to combat these shortcomings and take advantage of the high compressive strength of concrete, materials that are strong and ductile under tensile loading are strategically placed in the anticipated zones of tensile stress within the concrete. Besides conventional methods of reinforcing concrete with continuous and aligned reinforcement bars (rebar), the tensile properties of concrete can be improved by randomly dispersing discrete fibers to the mixture during the mixing process. Concrete with random, discrete fibers can generally be termed fiber reinforced concrete (FRC) although many specific nomenclatures exist for cement based materials including fiber. This type of modification to cement based composites has been utilized since ancient times, however the state of knowledge for FRC has advanced considerably in the last decade. Despite the multitudes of studies pertaining to FRC present in the literature, there is still much to discover due to the ever advancing general concrete technology and fiber properties coupled with the complexity of the possible variables involved that can affect composite properties.

1.2 Objectives

The main objectives of this research are to first establish the state of knowledge pertaining to FRC, then to contribute to that knowledge through experimental work. In order to achieve this objective, this thesis is divided into three main chapters.

Chapter 2 consists of a comprehensive review of relevant and recent literature with the objective of establishing the state of knowledge pertaining to FRC. Parameters independent of fiber material are presented, then different fiber materials that have been subject to testing in FRC are discussed, focusing on their contributions to properties in the fresh state and hardened mechanical properties. Fiber capabilities, limitations and typical applications in cement based composites are presented.

Chapter 3 presents the findings of an experimental study conducted on FRC beam specimens made with varying volumetric dosage rates of typical synthetic concrete fibers. The objective of the study is to compare the contributions of each fiber type to workability and performance under flexural induced tensile loads to determine the most effective fiber type for crack control applications.

Chapter 4 presents the results of an experimental investigation involving the use of carbon microfiber and concrete admixtures to achieve a high early age strength material while controlling the shrinkage behavior. The objective of the study is to achieve an effective cast-in-place concrete material for use on accelerated construction projects, while controlling the shrinkage behavior normally associated with methods of accelerating the cement hydration process. The study shows how the addition of high strength microfibers can be an effective tool for achieving certain characteristics in concrete.

CHAPTER 2: REVIEW: FIBER IN CEMENTITIOUS COMPOSITES – CAPABILITIES AND LIMITATIONS OF DIFFERENT FIBER TYPES IN FIBER REINFORCED CONCRETE

Abstract

Builders have been adding discrete fibers to cementitious matrices since ancient times. Extensive past research has identified effective ways to utilize this technology. As fiber material properties advance, so do the potential properties of the cementitious composites that include these fibers. This work intends to serve as a baseline approach to review the relevant and recent literature pertaining to different fiber material types that have been subject to testing in Fiber Reinforced Concrete (FRC) with regards to their capabilities, limitations, recent advances and typical applications. General fiber properties that are independent of fiber material type but highly influential to the properties of composites in the fresh and hardened state are established. Fiber types by material category and their typical characteristics as well as contributions to fresh and hardened composite properties are thoroughly discussed. In addition, a short review of recent studies involving the use of hybrid fiber systems in FRC is provided.

2.1 Introduction

Concrete is a brittle material by nature and is relatively weak in tension. In order to alter this characteristic and avoid sudden brittle failure of concrete structures, reinforcement materials that are strong in tension are embedded into the concrete to support the tensile stresses that would otherwise cause the concrete to fail in a brittle manner. Since ancient times people have been putting fibers like straw or hair in mortar and brick to improve the tensile properties. These ancient and simple methods of concrete reinforcement have developed into present day methods that include continuous, aligned reinforcement in the form of steel or fiber reinforced polymer rebar, as well as different forms of textiles and fabrics that can be woven into 2 and 3 dimensional reinforcing grids that are placed in the cementitious material. The main focus of the present paper is on another method of concrete reinforcement that involves using short, discontinuous fibers distributed randomly throughout the concrete matrix during the mixing process, and the various types of fibers that have been studied as potential concrete reinforcement in discrete form. The resulting material that utilizes short, discontinuous fibers dispersed throughout the cementitious matrix can be referred to in general as Fiber Reinforced Cementitious Composites (FRCC), even though there are many names for concrete, mortar or paste that includes fibers within the composite material. The present review will focus mainly on cementitious composites that include coarse aggregate which are referred to as Fiber Reinforced Concrete (FRC).

Performance of any fiber reinforced concrete or cementitious composite is governed by the physical, mechanical and chemical properties of the fiber for any constant cementitious matrix composition. The major fiber properties that dictate performance in the fresh and hardened composite state include fiber tensile strength, elastic modulus, ultimate strain, chemical compatibility with the concrete matrix, fiber dimensions, and fiber/matrix bond properties. Speaking in terms of different fiber materials that have been subject to testing in cementitious matrices, the four main categories include metallic fibers, glass fibers, synthetic fibers and natural fibers. Select properties of these four fiber categories are reported in Table 1. Metallic fibers simply refer to fibers that are made from metals. By far the most common type of metallic fibers are steel fibers but stainless steel fibers have been developed for increased corrosion resistance as well. Glass fibers are generally defined in this review as fibers that are derived from naturally occurring minerals or rocks. The two general types of glass materials subject to use as fiber reinforcement in cementitious matrices are silica and basalt glass. Synthetic fibers are defined in this review as man-made fibers that are not metallic or glass fibers. A wide variety of synthetic fibers have been subject to adequate research and are deemed suitable for one or more type of application in FRC include but are not limited to Polypropylene (PP), Polyvinyl Alcohol (PVA), Polyolefin (PO), Carbon, Polyethylene, Polyester, Acrylic, Nylon, and Aramid. Natural fibers are fibers that occur in nature within the organic tissue of plants. Many types of natural fibers with varying properties have been the subject of FRC research.

Table 2.1 *Types of fibers used in concrete by category, with select properties*

	Metalic			Glass				Natural	
	Steel	Stainless Steel		Silica Glass	Basalt Glass	GFRP/BFRP*		(Sect. 6 for Details)	
Tensile Strength (MPa)	1700	1030		1700 - 4600	1800 - 4800	1080		70 - 2000	
Elastic Modulus (GPa)	200	200		72 - 89	72 - 110	44		1.0 - 85	
Ultimate Elongation (%)	0.5 - 3.5	0.5 - 3.5		2.0 - 3.5	2.0 - 3.5	2.0 - 3.0		2.0 - 30.0	
Water Absorption (%)	-	-		-	-	-		High	
Specific Gravity	7.84	7.8		2.6 - 2.7	2.55 - 2.8	1.9 - 2.1		1 - 1.5	
	Synthetic								
	Polypropylene	Polyolefin	Polyethylene	Polyester	PVA**	Carbon	Nylon	Acrylic	Aramid
Tensile Strength (MPa)	60 - 700	300 - 700	40 - 3000	250 - 1000	850 - 1600	1500 - 7000	300 - 950	300 - 1000	2300 - 3400
Elastic Modulus (GPa)	1.5 - 10	3.0 - 10	0.5 - 120	10 - 20	25 - 41	30 - 500	3.0 - 5.4	3.8 - 17	70 - 143
Ultimate Elongation (%)	8.0 - 15.0	5.0 - 15.0	3.0 - 80.0	10.0 - 50.0	5.0 - 7.0	0.5 - 2.5	10.0 - 20.0	7.5 - 50.0	2.0 - 4.5
Water Absorption (%)	-	-	-	0.2 - 0.6	0.1 - 1.0	-	2.5 - 5.0	1.0 - 2.5	1.2 - 4.0
Specific Gravity	0.9 - 0.95	0.9 - 0.95	0.92 - 0.98	1.32 - 1.38	1.3	1.6 - 1.9	1.13 - 1.15	0.91 - 1.2	1.39 - 1.47

* GFRP = Glass Fiber Reinforced Polymer; BFRP = Basalt Fiber Reinforced Polymer; ** PVA = Polyvinyl Alcohol

The review presented herein aims to present the capabilities, limitations and applications of different types of fibers in concrete categorized by fiber material composition. The results of different cited studies are highly dependent on not only the fiber material and volume dose, but the fiber dimensions and matrix composition used in the individual study. These parameters should be considered when comparing experimental results across studies and between fiber types.

2.2 Crack Controlling Mechanisms of FRC and Micro/Macro Fibers

The inclusion of fibers affects various fresh and hardened properties of concrete, however, the primary goal of including fibers in concrete is to prevent or control the propagation of cracks in the composite. Early age plastic shrinkage cracking can be reduced or eliminated by the inclusion of fibers at low doses. The inclusion of fibers can be beneficial for a wide range of crack control related hardened composite properties which are highly dependent on not only the fiber type and dose rate, but the dimensions of the fibers.

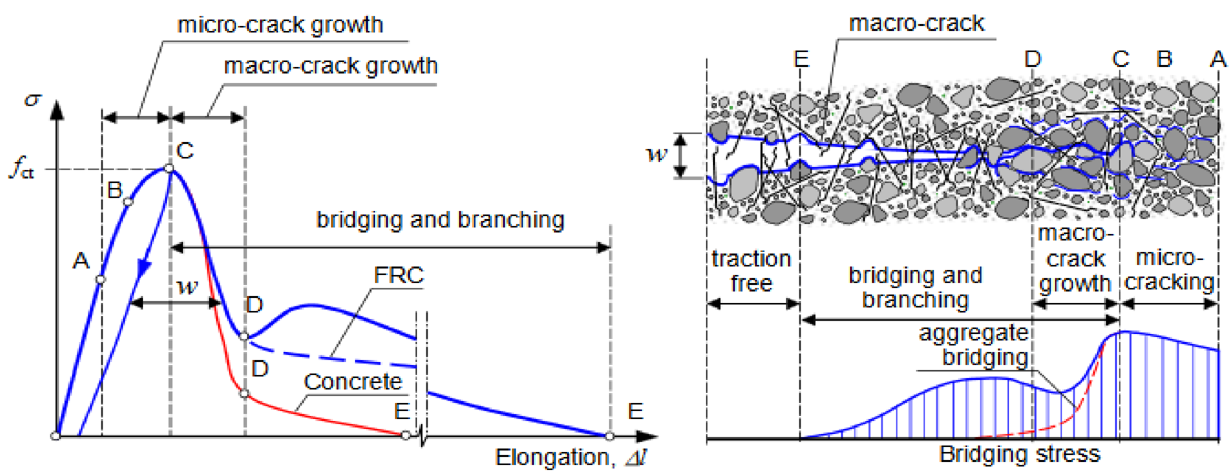


Figure 2.1 *Crack development stages in FRC and the relation to the stress strain response (Lofgren, 2005)*

Cracking in concrete is a multiscale process that starts at a micro scale when cracks begin to form under applied stress in the interfacial transition zone (ITZ) between aggregates and cement paste. These micro-cracks will spread through the paste at a micro level until they meet other micro cracks and eventually propagate into a large macro crack (Lawler, 2001). Once a macro crack has fully formed and the crack has widened past the stage of aggregate interlock, the concrete will have no load bearing capacity, and is considered to have failed. Figure 2.1 shows the different stages of crack development in FRC and their relation to the stress-strain curve as explained by Lofgren (2005). This type of multiscale mechanism will form anywhere that there is sufficient tensile stress in the concrete with no reinforcement to prevent the tensile failure as the crack widens. Because of the multiscale progression of cracks in concrete, different sizes of fibers dispersed throughout the concrete will be beneficial at different stages of crack growth. Their effects are discussed below, however it should be kept in mind that when coarse aggregate is taken out of the FRC system, the fresh properties and hardened fracture behavior of the composite change drastically due to the increased homogeneity of the matrix. The resulting fiber reinforced mortars are often referred to as high performance fiber reinforced cementitious composites (HPFRCC) and the following micro/macro fiber discussion does not necessarily apply to these materials.

Micro-fibers are low diameter, high aspect ratio (length/diameter) fibers that are most often less than 18 mm in length. Micro-fibers can be effective at arresting micro-cracks as they leave the ITZ and propagate through the cement paste by bridging the tensile stress across the micro-cracks. Due to the micro-scale reinforcement action provided by microfibers, it is generally accepted that microfibers most significantly affect strength properties of FRC prior to micro-crack coalescence and full crack formation characterized by the portion of the stress-strain curve prior to the peak stress. Ultimate strength gains in compression, flexure and tension have been reported for FRC with certain types of microfiber (Yao et al., 2003, Sorelli et al., 2005, Dopko et al., 2018), however the increases are dependent on the fiber and matrix properties. In general, the elastic modulus of the fiber should be higher than that of the concrete matrix in order to significantly improve pre-crack strength properties (Bentur & Mindess, 2006). Considering that concrete strength increases as a function of time, even low modulus microfibers can be effective at increasing strength at early ages, however for mature, and especially high strength concrete, strength increases are more often associated with high strength and modulus fibers.

Micro-fibers generally tend to have a more profound effect on the workability of concrete compared to larger (macro) fibers at equal volumetric doses due to the high surface area per unit volume that micro-fibers typically have. In order to maintain workability, sufficient paste volume is needed within the system to coat the additional surface area of the fibers, or high dosages of superplasticizers are required. This has been supported by studies which have shown that increasing the aspect ratio of fibers will decrease the workability of concrete (Johnston, 2001, Chanh, 2004, Yazici et al., 2006). More recently, Tabatabaeian et al. (2017) showed that hybrid fiber reinforced (micro polypropylene / macro steel fiber blended) self consolidating concrete (SCC) mixtures with the same total fiber volume fraction had their workability decrease proportionally to the ratio of micro fibers present in the hybrid fiber mixture (Tabatabaeian et al., 2017).

Macro-fibers are characterized by smaller aspect ratios and increased lengths compared to micro-fibers. There is no internationally accepted standard that defines the size boundaries between micro and macro fibers which creates some overlap in the definitions, however macro-fibers are rarely shorter than 18 mm and generally have diameters that are larger than 0.1 mm. Macro-fibers are effective at bridging the cracks in concrete once they have grown past the micro stage since they are large enough to provide stress transfer across crack openings when a single crack has formed from the coalescence of micro-cracks. In general, if fiber-matrix bond conditions are held constant, the higher the elastic modulus of the macro-fiber, the smaller the crack width under the same applied load and fiber dose. This feature relies upon the condition that there exists sufficient bond between the fiber and matrix to develop the strength of the fiber and utilize the high fiber tensile stiffness. Besides reported exceptions for fibers with high modulus of elasticity (Yao et al., 2003, Thomas & Ramaswamy, 2007), macro-fibers do not significantly influence the strength parameters of concrete prior to crack formation. The effectiveness of macro-fibers at bridging cracks depends on the maximum aggregate size. In general, for larger maximum size aggregate, longer fibers will be more effective at increasing post crack performance, while for smaller maximum size aggregate, shorter fibers may be equally if not more effective (Chenkui et al., 1995).

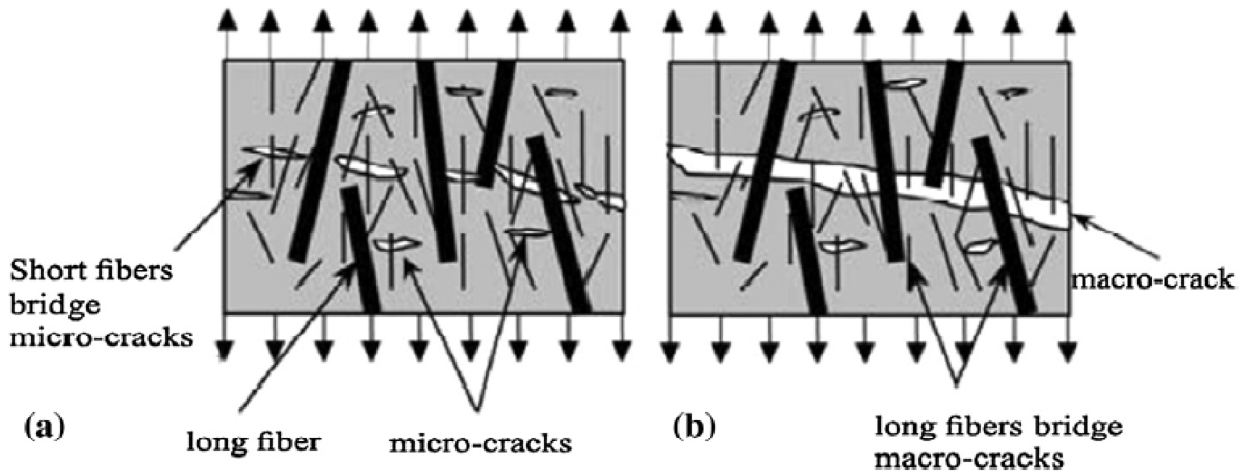


Figure 2.2 *Simplified tensile reinforcement contribution of micro and macro fibers at different stages of crack propagation (Marković, 2006)*

Due to the generality that micro-fibers are most effective at increasing performance parameters during early stages of crack formation under external loads or decreasing plastic shrinkage cracking while macro fibers are most effective for post crack ductility and macro crack control in FRC, the correct fiber geometry is of utmost importance when selecting a fiber for a specific application. A simplified visual representation of how micro and macro fibers contribute to tensile reinforcement of cementitious composites at different levels of crack propagation is shown in Figure 2.2 (Marković, 2006). It would be logical to conclude that the inclusion of micro and macro fibers in the same mixture would provide benefits associated with both fiber geometries. This theory has been subject to various recent research efforts and will be discussed in more detail in section 7 (Hybrid Fiber Systems) of this review.

2.3 Metallic Fibers

Steel is historically one of the most common fibers used in concrete. It has high elastic modulus and tensile strength as shown in Table 2.1, which are desirable fiber properties for controlling crack width as well as increasing tensile, flexural and compressive strength in concrete (Kaïkea et al., 2014, Afroughsabet et al. 2015). Increased toughness and ductility have been confirmed in steel FRC by various studies however as in all types of FRC, the fiber volume fraction, fiber dimensions and concrete mixture design govern performance (Thomas & Ramaswamy, 2007, Song & Hwang, 2004, Kim et al., 2008).

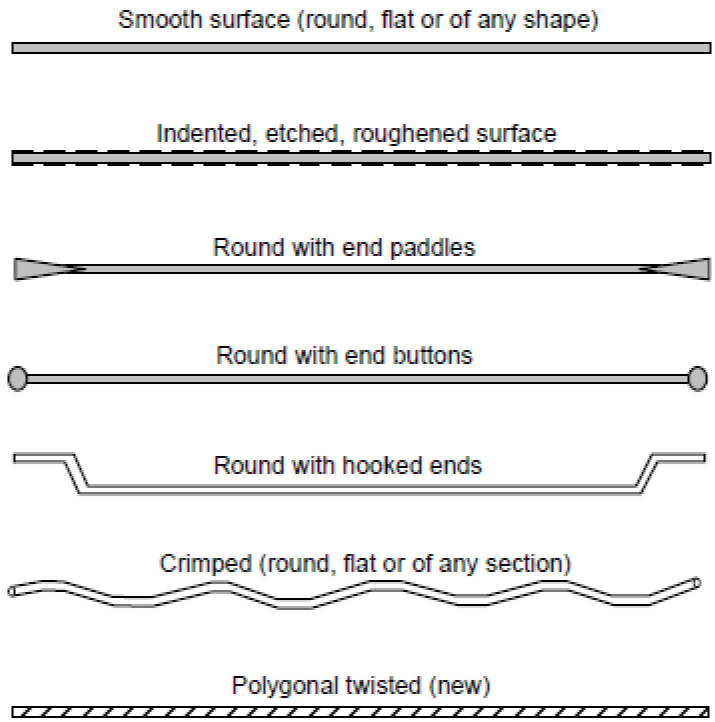


Figure 2.3 *Different geometries of steel fibers that have been subject to testing (Naaman, 2003)*

The combined malleability and tri-axial stiffness of steel makes steel concrete fibers somewhat unique in the sense that they can be molded and manipulated into many different shapes while maintaining their high stiffness. Thus, the shape of steel fibers is an important parameter governing their effects on the fresh and hardened properties of concrete. Similar to the concept of rebar development length in reinforced concrete design, the bond strength of short, discontinuous concrete fibers is a function of the strength of the concrete matrix. Due to this relation, the failure mechanism of steel fibers in normal strength concrete tends to be by pull-out, while in higher strength matrices the failure mode can shift to rupture (Yoo et al., 2015). In order to increase the bond strength of the steel fibers, without changing the mixture design to one of higher strength, it is common to deform the fibers in such a manner that the mechanical bond of the fibers is increased as shown in Figure 2.3.

Naaman (2003) suggested that altering the circular cross section to increase available surface area for matrix bonding and twisting the fiber along its length to provide mechanical anchorage resulted in optimal pull out resistance (Naaman, 2003). Kim et al. (2011) tested macro hooked end, straight and longitudinally twisted fibers in a high strength matrix under flexure and found that hooked end steel fibers provided higher strength and toughness than the straight and twisted fibers, even though the hooked end fibers had a slightly smaller aspect ratio than the other two fibers (Kim et al., 2011). Soulioti et al. (2011) found that hooked end steel fibers were more effective for increasing flexural strength and toughness of concrete than straight or wave shaped fibers of similar length and diameter (Soulioti et al., 2011). Soutsos et al. (2012) found similar results, reporting that hooked end steel fibers were more effective for increasing the flexural toughness of concrete than wave shaped or flattened end steel fibers (Soutsos et al., 2012). After comparing the performance of macro hooked end and longitudinally twisted steel fibers in mortars, Kim et al. (2008) concluded that twisted steel fibers show larger improvements in composite performance when dispersed in higher strength matrices compared to hooked end steel fibers. The twisted steel fibers showed less of an advantage over hooked end steel fibers when dispersed in lower strength matrices, highlighting the point that the concrete matrix strength is a key factor when selecting the proper fiber dimension and shape (Kim et al., 2008).

Steel fibers can drastically reduce the slump of concrete mixtures at mid to high volumes. The relatively rigid nature of the steel fibers can restrict the flow of the paste and aggregates around them as well as make them susceptible to clumping. To avoid mixing issues with steel fibers, they should be added slowly, not over-mixed, and a reasonable volume of fibers should be added to avoid choking the mixture (Bentur & Mindess, 2006). Caution should be exercised to avoid excessive deformation of the fibers as this can cause further decreased workability and reinforcing effects (Banthia, 1990). This concept can be illustrated by more recent studies which found that hooked end steel fibers (which are most aggressively deformed compared to other common steel fiber shapes) decreased workability more than wave shaped (Soulioti et al., 2011) or straight steel fibers (Sahmaran et al., 2007).

Some recent studies highlight the ability of steel fibers to markedly improve the pre and post crack performance of concrete. Afroughsabet et al. (2015) studied the mechanical properties of steel fiber reinforced concrete using macro hooked end steel fibers. The study found that increasing steel fiber volume increased the strength parameters of the concrete at the fiber volumes tested, with 1.0% fiber volume producing impressive 28 day compressive, splitting tensile, and flexural strength increases of 19%, 55% and 61% respectively over the control mixture (Afroughsabet et al., 2015). Kaïkea et al. (2014) investigated corrugated (wave shaped along their length) steel macro fibers at 1.0% and 2.0% volume fractions with different supplementary cementitious materials. The study evaluated the performance of the fibers by measuring the energy absorption capacity of the composite using the area under the crack mouth opening displacement (CMOD) curve. With 2.0% steel fiber volume fraction, the energy absorbed by the specimens during testing was 33 times higher than that of control mixtures (Kaïkea et al., 2014).

Macro steel fibers can be used as secondary reinforcement in conjunction with rebar as primary reinforcement in structural applications as they are reported to reduce crack width and spacing, increase flexural strength and stiffness, increase shear resistance and increase ductility (Lofgren, 2005). These benefits have traditionally been “pro-bono” in structural reinforced concrete due to the lack of well accepted design codes that account for the performance and serviceability benefits of random discontinuous fibers in structural concrete. This is changing, however, since the inclusion of FRC post crack residual strength contributions in the 2010 fib Model Code (fib Model Code, 2010). Macro steel fibers have been shown to enhance the load capacity and ductility of ground supported slabs at fiber volumes below 1.0% and could potentially be used as partial or full replacement of rebar or welded wire mesh in slabs on ground (Sorelli et al., 2006).

With the development of ultra-high performance concrete (UHPC), it is now possible to use micro steel fibers as the primary reinforcement in structural concrete. Ultra high performance fiber reinforced concrete (UHPFRC) utilizes very low water to cement ratios, high steel micro fiber content is typically used, aggregate gradations are optimized to achieve high particle packing density, and coarse aggregates are typically left out of the mixture to improve fresh properties, fiber reinforcing effectiveness and fracture properties. UHPC is generally understood to be a cementitious material with compressive strength of at least 135 MPa, with a discontinuous pore structure that improves durability by limiting permeability. When steel fiber is added to make UHPFRC, post crack residual strengths of over 5 MPa can be provided by the steel micro fibers. Strain hardening and multiple, tightly spaced cracks characterize UHPFRC's response to tensile stress. Cementitious composites of this nature have been patented and sold under names such as Ductal and Cemtech-multiscale (Rossi et al., 2004, Graybeal, 2006). More recent research efforts have successfully developed UHPC mixture designs using local materials in attempt to drive down the cost (Newtson et al., 2012, Berry et al., 2017, Alsalman et al., 2017). Due to the ductile failure mechanism and incredibly high strength that UHPC's can possess, it is possible to design concrete structures that have no rebar and rely solely on steel micro-fiber for tensile reinforcement and ductility. Limited case studies on structures of this type have been reported to perform well (Perry & Seibert, 2008).

A limitation of steel fibers is the issue of corrosion, which can cause the steel to degrade in strength and consequently lose reinforcing effectiveness. Because of this, steel fibers may not be the best fiber solution in situations where they would be subject to conditions that are conducive to corrosion such as outdoor or marine exposure. Kosa & Naaman, 1990 found that prolonged exposure conditions in salt solutions drastically reduced the post crack performance of steel FRC due to reduction in the fiber cross section caused by corrosion. For short term exposure to salt solution, post peak residual strengths at low flexural and tensile strains were actually higher than control samples. This suggests that low levels of corrosion increase the fiber-matrix bond strength and fiber pull-out resistance (Kosa & Naaman, 1990). This trend was repeated by Granju et al., (2004) who studied the behavior of hooked end steel FRC under marine exposure and found that small amounts of steel fiber corrosion increased the residual strength of the composite by lightly roughening the surface of the fibers and consequently increasing their pull-out resistance. When wider cracks were present, the corrosion was substantial enough to decrease the strength of the fibers and consequently decrease composite performance (Granju et al., 2004).

Marcos-Meson et al. (2018) recently completed a comprehensive review of the carbonation and aggressive chloride induced corrosion resistance of steel fiber reinforced concrete. The review highlights the discrepancies in the literature with regards to the level of corrosion and residual strength loss steel FRC can be expected to undergo in both field and lab conditions after carbonation or chloride exposure. These discrepancies can be explained by the steel fiber degradation being dependent on exposure conditions, material and geometry of the fiber, quality of the concrete matrix, and crack width, which varies across studies. It can be generalized that steel

FRC that has not cracked will not undergo significant corrosion or residual strength decreases. After cracking occurs however, there is no firm consensus in the literature about the level of fiber corrosion and strength degradations that the composite may undergo. In general, the literature suggests that crack widths under 0.2 mm show minimal negative performance effects but crack widths above 0.5 mm will likely be detrimental to performance. Low water to binder ratio and in some cases supplementary cementitious materials can help prevent performance loss from steel fiber corrosion. Cold drawn steel fibers tend to be more resistant to corrosion than mill cut or cut sheet steel fibers, additionally hooked end steel fibers show evidence of increased corrosion at the points of curvature due to surface irregularities at these points of plastic deformation (Marcos-Meson et al., 2018).

Due to the limitations of traditional carbon steel fibers, stainless steel fibers and brass coated or zinc coated (galvanized) steel fibers have been developed, and can be effective at limiting corrosion, however these fibers can be expensive (Johnston, 2001). Mangat et al. (1988) found that stainless steel fibers exposed at the concrete surface showed no signs of corrosion after 2000 cycles of marine exposure while it was concluded that low carbon steel fibers and galvanized steel fibers are prone to corrosion in the same environment (Mangat et al., 1988). O’Neil et al. (1999) tested chopped steel, brass coated steel and stainless steel fibers under marine exposure conditions in the un-cracked state and concluded that the chopped and brass coated steel fibers are more effective for providing higher flexural strength, toughness, modulus of elasticity and indirect tensile strength compared to stainless steel fibers. The study also concluded that the influence of seawater on the steel FRC is limited to a few millimeters below the concrete surface in the un-cracked state (O’Neil et al., 1999). More recently, Sun et al. (2011) found that steel fibers coated with a zinc-phosphate compound could retain an average 96% of flexural toughness after simulated seawater exposure

(30 cycles of 12 hours in 5% NaCl solution) compared to a 74% retention for non-coated fibers. It can be agreed upon from the literature that stainless steel or brass/zinc coated steel fibers can drastically reduce steel fiber corrosion under chloride and carbonation exposure (Marcos-Meson et al., 2018)

Steel fibers have a density which is much higher than that of any other type of fiber used for concrete reinforcement, and even much higher than that of the concrete matrix. Because of this, adding steel fibers will increase the unit weight of the concrete which can be a drawback in applications where it is desirable to limit the weight of construction materials.

The cost of steel fibers is in general below that of other high strength synthetic fibers on a weight basis, however due to the relatively high density of steel fibers, the same volume fraction addition of steel fibers and synthetic fibers will result in a much higher weight of steel fibers to be added. Since fibers are sold by weight, this means that steel fibers will cost more at the same volume fraction if the price point of the fibers are equal. Steel fibers can be purchased from nearly all North American concrete fiber distributors, however low cost, corrosion free, low density, high tenacity synthetic concrete fibers are becoming more popular and taking some of the market share from steel concrete fibers.

2.4 Synthetic Fibers

Synthetic fibers can be described as man-made fibers that are not metallic or glass. Many types of synthetic fiber materials have been the subject of testing in FRC composites with varying results due to the diversity in chemical, physical and dimensional properties that synthetic fibers can provide. The synthetic fibers discussed in this review i.e. Polypropylene (PP), Polyvinyl Alcohol (PVA), Polyolefin (PO), Carbon, Polyethylene (PE), Polyester, Acrylic, Nylon and

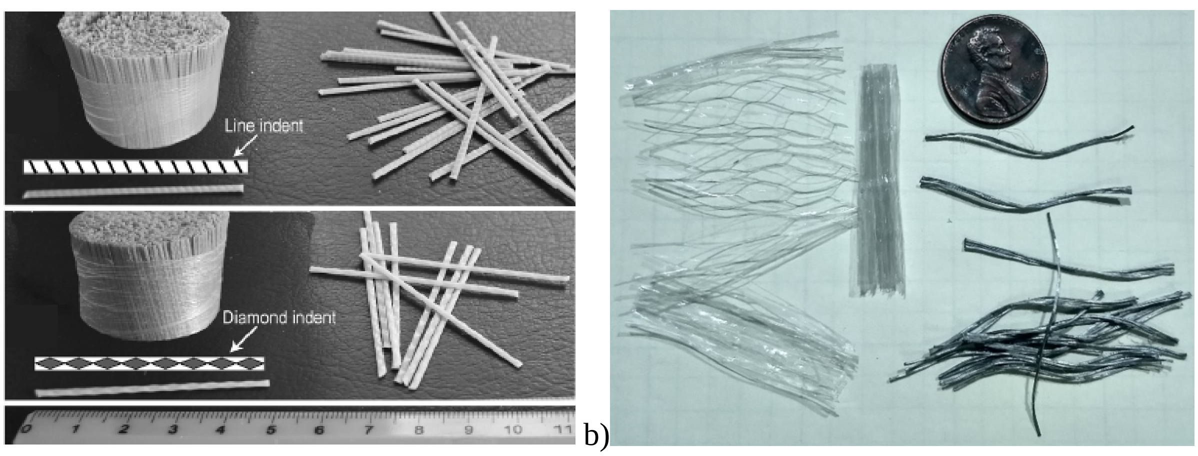
Aramid, have been subject to adequate research to warrant their inclusion. Table 2.1 shows the typical range of selected properties of the discussed synthetic fibers.

2.4.1 Polypropylene

Polypropylene (PP) is a common type of concrete fiber due to its chemical stability in the alkalinity of concrete, availability and low cost. The characteristics and behavior of PP fiber as short, random discontinuous reinforcement in various concrete mixtures has been well explored (Singh et al., 2004, Pakravan et al., 2010, Alhozaimy et al., 1996, Toutanji et al., 1998). In contrast to steel fibers, PP fibers have relatively low tensile strengths and modulus of elasticity (Table 2.1). Although new types of high tenacity PP fibers have been developed with much higher strength and elastic modulus compared to traditional PP fibers, they are still low in strength and elastic modulus compared to other high strength fibers. Despite PP's lack of strength, it is a highly ductile fiber and can therefore increase the toughness and impact resistance of concrete, especially at high strains. The hydrophobic nature and chemical stability of PP also results in a weak fiber-matrix bond strength.

There are essentially two common types of PP fibers that are manufactured for concrete. The first type, called fibrillated fibers, are most common for micro PP fibers, although macro versions can be made. In order to increase the fiber-matrix bond strength, the fibrillated PP fiber's mechanical bond is improved by splitting a PP film into fibrillated bundles that open during mixing (Figure 2.4b). Fibrillated PP microfibers have low diameter and resulting high aspect ratio after opening, making them effective for controlling plastic shrinkage cracking in fresh concrete at low volume doses, one of the most common concrete applications for PP fiber (Bayasi & Zeng, 1993).

The second type are monofilament PP fibers which are most common in macro fiber form, although micro versions are available. Monofilament PP macro-fibers can have their mechanical bond improved by a number of shape variations or modifications. Oh et al., 2007 tested straight, crimped, hooked, button end, twisted, sinusoidal and partially sinusoidal shaped synthetic macro fibers for their bond strength and concluded that crimped or sinusoidal fibers showed the highest increase in mechanical bond properties compared to straight monofilament fibers (Oh et al., 2007). The exact material that the fibers were produced from in that study is unclear, however it is likely that the fibers were made from a PP, PO, PP+PO or another polymeric resin combination. More common ways that monofilament PP fibers can have their fiber-matrix bond strength increased is by twisting the fibers along their longitudinal axis, or indenting their surface (Figure 2.4a). Yin et al. (2015) concluded that diamond surface indentations were more effective for increasing the mechanical bond of macro PP fibers than line indentations (Yin et al., 2015).



a) b)

Figure 2.4 *a) Surface indented PP fibers (Yin et al., 2015) b) Fibrillated PP (left); Twisted PP (right)*

Discrepancies exist in the literature as to whether PP fiber can affect the strength parameters of concrete prior to crack formation. Hsie et al. (2008) found that the additions of monofilament PP fibers at volumes below 1.0% could increase the strength properties of the composite. Hasan et al. (2011) found that the compressive strength of concrete was not affected by the addition of macro PP fibers, however the tensile strength could be significantly improved at volumes below 0.55%. Choi et al. (2005) found similar results for volume additions up to 1.5%, indicating that compressive strength is not affected by macro PP fibers but splitting tensile strength can be significantly improved. Soroushian et al. (2003) found that low volumes of macro PP fibers had negligible impact on the flexural strength of concrete. These discrepancies regarding the ability of PP fiber to increase pre-crack strength parameters can be explained by the variation in fiber dose, geometry and mechanical properties as well as matrix property variations across different studies.

Numerous studies have reported marked increases in post crack residual strength and toughness that macro PP fiber addition can provide to concrete (Barr & Newman, 1985, Fraternali et al., 2011, Cengiz et al., 2004, Hsie et al., 2008, Dopko et al., 2018). In general higher PP macro fiber content leads to increased post crack performance, however due to the low stiffness of PP, residual strengths tend to be more positively influenced at larger deflections or wider crack openings. PP fibers tend to fail by pull out due to their weak fiber-matrix bond strength, however if matrix strength is increased sufficiently, and/or the fibers have sufficient mechanical anchorage from geometric modifications, PP fibers can fail by rupture. Based on the reviewed material, it can be generalized that although there is some evidence that pre-crack strength properties can be modestly increased by PP fiber additions, the main advantage of adding macro PP fiber to concrete is to provide post crack residual strength and toughness.

Table 2.2 *Increases in fiber-matrix bond characterized by pullout load and post crack performance characterized by 3 common ASTM methods (Attiogbe et al., 2014).*

Polypropylene fiber	ASTM C1399/C1399M average residual strength, psi (MPa)	ASTM C1609/C1609M equivalent flexural strength ratio, %	ASTM C1550 energy absorption, in.-lbf (J)	Pullout load, lbf (N)
Dosage, lb/yd^3 (kg/m^3)	5 (3)	5 (3)	9 (5.3)	Single fiber
Reference	176 (1.2)	27	3248 (367)	14.4 (64)
Chemical-bond	240 (1.7)	36	4283 (484)	20.9 (93)
Performance improvement, %	37	33	32	45

Although high tenacity PP fibers can be designed to develop sufficient mechanical bond to prevent or delay pull-out, in turn providing significant post crack residual strength and toughness, fiber-matrix bond has been a limiting factor to the reinforcing effectiveness of PP. Recently a new proprietary type of PP fiber has been developed that has the ability to bond with the concrete matrix chemically. When this new type of macro PP fiber was compared to a traditional type of macro PP fiber, both in monofilament form, it was found that the new chemically bonding PP fiber improved residual strength, equivalent flexural strength ratio, energy absorption, and fiber pull-out load by over 30% in all cases as shown in Table 2.2. (Attiogbe et al., 2014).

It is possible to produce PP concrete fibers using recycled material, which is an advantage over most concrete fibers. Studies have found that recycled PP fibers can provide similar mechanical properties to FRC and avert degradation in the cement chemistry as effectively as virgin polymer PP fibers (Yin et al., 2015, Yin et al. 2016).

Woven PP fabrics can be used to make textile concrete by simultaneously laying up woven PP sheets and mortar. This type of textile concrete can possess impressive energy absorption, ductility and crack control. PP textile concrete members are typically thin sheet components that perform well in flexure and tension, with the ability to exhibit strain hardening and micro-cracking at very high strains. (Mumenya, 2011, Swamy & Hussin, 1989). This is due to the ability to achieve very high fiber contents and preferential fiber orientation in textile concrete compared to random discontinuous FRC cast using conventional mixing techniques. PP textile concrete has been mainly limited to thin sheet, non-structural applications due to the constraints associated with the casting technique.

The hydrophobic nature and low density of PP fibers can cause mixing problems at high volumes. Reports indicate that the fibers tend to form undispersed clumps and significantly reduce slump at volumes above 1.0% (Mohod 2015), however this feature is highly dependent on fiber dimensions and mixture design. Dopko et al. (2018) also reported that PP macro fiber additions above 1.0% fiber volume significantly reduced the workability of the mixture (Dopko et al., 2018).

PP fibers have a relatively low melting point in comparison to most other concrete fibers and should not be used in high temperature applications such as autoclave curing (Mai et al., 1980). The low melting point of PP fibers gives rise to applications for spalling prevention during fires in concrete structures. As the fibers reach their melting point during a fire, they provide escape routes for highly compressed gas caused from the vaporization of moisture inside the concrete. (Lee et al., 2012).

PP is one of the most cost effective concrete fibers. This feature, coupled with the excellent chemical stability in the cement chemistry, reasonable mechanical properties and widespread availability has made PP one of the most popular synthetic concrete fibers. The most common applications for PP fibers in concrete are fibrillated microfibers primarily for plastic shrinkage crack control and monofilament macro fibers primarily for controlling cracks caused by applied loads, temperature gradient loads or drying shrinkage. Almost all North American concrete fiber suppliers sell multiple types of PP fiber.

2.4.2 Nylon

Nylon is a synthetic fiber that is common in many different applications such as clothing, apparel, furniture, textiles and commercial applications. Nylon can have a range of strength properties that are dependent on the base polymer, manufacturing techniques and additives used to make it (ACI Report 544.1R-96, 2009). Although chemically different, nylon and polypropylene fibers produce similar benefits when used in FRC because in general they have similar fiber/matrix bond strengths, tensile strengths, and elastic moduli. Due to their similar benefits in FRC, nylon and PP have been compared for their reinforcing benefits in concrete.

Wang et al. (1987) found that the pull-out from the concrete matrix behavior of nylon and PP are very similar. Nylon does not form any chemical bond with the concrete matrix, however as the fibers are pulled out of the matrix, the pull-out load increases. By examining the surface of the fibers during pull-out, it was deduced that the pull-out load increases during the pull-out process because the concrete matrix scars the outside of the fiber, effectively increasing the friction between the fiber and matrix, increasing the pull-out load. This was true for PP fibers as well and supports the idea that the bond between nylon and the cement matrix is purely mechanical (Wang et al., 1987). More recently, this type of pull out failure was documented by Khan et al. (2016), when 50 mm long nylon fibers were tested in a normal strength matrix. Under flexural action, the study found that about 70% of the nylon fibers failed by pull-out, while the other 30% failed by rupture. When tested under compression, all of the nylon fibers failed by pull-out (Khan et al., 2016).

Nylon fibers are hydrophilic and can absorb a small amount of water during mixing (ACI Report 544.1R-96, 2009). This feature can be beneficial to the dispersion of nylon fibers during mixing due to their affinity for the mixing water (Song et al., 2005), however at higher volume doses the water absorption capacity of the fibers may negatively affect the mixture's workability due to excess absorption of mixing water. Yap et al. (2013) noticed that the workability of nylon FRC was less than that of PP FRC at the same fiber content in light weight concrete. This could have been due to the fact that fiber volumes up to 0.75% were tested in this study and the nylon fibers absorbed a significant enough amount of water to decrease the workability of the mixture. Regardless of the inferior mixing capabilities of nylon fibers at these volumes, the nylon FRC outperformed the PP FRC in compressive and tensile strength parameters (Yap et al., 2013). Khan et al., (2016) reported that when dispersed at fiber volumes near 1.5%, 50 mm long nylon fibers reduced the slump by almost 69% compared to the control mixture (Khan et al., 2016). When dispersed in low volumes, nylon micro fibers are reported to have minimal effects on the pre-crack strength parameters of FRC, but a more ductile failure mode can be achieved (Song et al., 2005, Lee et al., 2012, Ozger et al., 2013, Oh et al., 2014).

Ozsar et al. (2017) investigated the use of both macro and micro monofilament nylon fibers in two different strength matrices. The study found that micro nylon fibers increased the compressive strength of the composite and were most effective for decreasing plastic shrinkage cracking, while the macro nylon fibers increased the fracture energy and post crack performance. These results are expected based on the previously discussed intrinsic properties of micro and macro fibers in FRC. The study found that microfibers were more effective for increasing splitting tensile strength in mixtures with lower water to cement ratios but were less effective in mixtures with higher water to cement ratios. This trend was reversed for macro fibers (Ozsar et al., 2017).

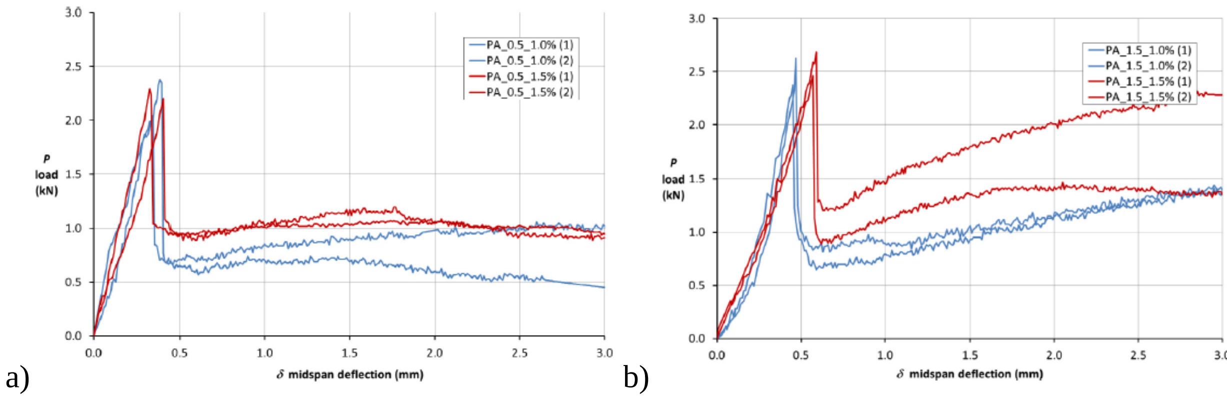


Figure 2.5 *Load vs. mid-span deflection for recycled nylon FRC a) 0.5 inch length b) 1.5 inch length (Spadea et al., 2015)*

It is also possible to use recycled nylon fibers in FRC, which has been highlighted in some recent studies. Spadea et al. (2015) investigated compressive and flexural properties of fiber reinforced mortars made with macro nylon fibers produced from recycled fishing nets. Different fiber lengths were tested at relatively high (1.0% and 1.5%) volumes. It was found that for all fiber lengths, higher volumes produced higher flexural toughness and longer fibers were more effective for increasing residual strengths, especially at larger deflections (Figure 2.5). Compressive strengths decreased roughly 25% on average and flexural first crack strengths increased by roughly 27% on average compared to the control mortar for the recycled nylon fiber composites tested (Spadea et al., 2015). Similarly, Orasutthikul et al. (2017) observed reduced compressive strength and increased flexural strength when testing recycled nylon fibers in mortar at volumes up to 2.0%. They confirmed that sufficient fiber length is important for nylon fibers, in order to develop a fiber-matrix bond that can provide pull-out resistance and associated residual strength. Nylon fibers with knotted ends were also tested in this study, however the geometry change did not effectively increase the toughness of the composite (Orasutthikul et al., 2017).

As previously mentioned, nylon fibers may absorb mixing water and in turn reduce workability compared to other fibers. These qualities may somewhat limit nylon fibers to applications with relatively low fiber volumes, especially if micro fibers are used. Another limitation of nylon fibers is that they provide very similar advantages to PP fibers in concrete, but in general are more expensive. Recent interest in recycled nylon fibers could help drive the cost of nylon concrete fibers down. Nylon fibers can readily be purchased from most concrete fiber distributors and are commonly used for thermal and plastic shrinkage crack control at low volumes.

2.4.3 Polyvinyl Alcohol

Polyvinyl Alcohol (PVA) is a relatively high strength synthetic fiber that was originally developed for the replacement of asbestos in asbestos cement (Stundinka, 1989, Bentur & Mindess, 2006). The use of PVA has been expanded to many other FRC and FRCC applications due to its attractive mechanical properties and ability to bond chemically with the cement matrix. PVA is hydrophilic, has a non-circular cross section, and forms hydrogen bonds with the cement matrix. These characteristics give PVA fibers the ability to form a strong bond with the cement matrix (Zheng & Feldman, 1995).

Although PVA is hydrophilic, it has very low water absorption. PVA is also very compatible with the chemical environment of the cement matrix and has been found to retain nearly all of its strength after accelerated aging tests equivalent to 100 years (Ogawa & Hoshiro, 2011).

Due to the fibers ability to bond chemically with cement, the physical shape of PVA fibers is not typically altered to increase mechanical bond since sufficient bond can usually be developed to utilize the fibers strength potential without deforming the fiber. Due to this feature, PVA fibers are manufactured in monofilament form for both macro and micro fibers. PVA fibers tend to fail by rupture rather than pull-out much more readily compared to other fibers due to a slip-hardening response during pullout caused by their strong fiber-matrix bond properties (Betterman et al., 1995, Hamoush et al., 2010). PVA fibers have tensile strengths in the same range as steel fibers, however the elastic modulus of PVA is less than 25% of steel as is shown in Table 2.1. The result is that PVA fibers have the ability to modestly increase flexural and tensile strengths of hardened concrete but more effectively increase the toughness and ductility (Shafiq et al., 2016).

Micro PVA fibers are utilized in a novel cementitious material referred to as Engineered Cementitious Composite (ECC). ECC lacks coarse aggregate, typically utilizes high fly ash content, and most often 2% PVA fibers by volume, although other fibers like high strength polyethylene have been used to produce ECC type materials in the lab (Ahmed et al., 2007). PVA-ECC has been reported to achieve tensile strains up to 5% and post crack tensile strengths up to 4.5 MPa, accompanied by strain hardening behavior and multiple micro-cracks with no wide cracks forming, as shown in Figure 2.6 (Li, 2008). PVA-ECC is an attractive material in high performance applications because of its impressive ductility and cracking properties coupled with the ability to produce it using conventional mixing techniques. PVA-ECC has even been successfully produced and placed using large volume batches in the field (Li et al., 2005). Different types of PVA-ECC have been developed for special applications such as lightweight ECC (Arisoy & Wu, 2008) and high early strength ECC (Wang & Li, 2006). Some PVA-ECC utilizes a fiber surface coating that decreases the matrix bond strength in order to shift the fiber failure mechanism from rupture to pull-out, which can increase ductility (Li, 2003).

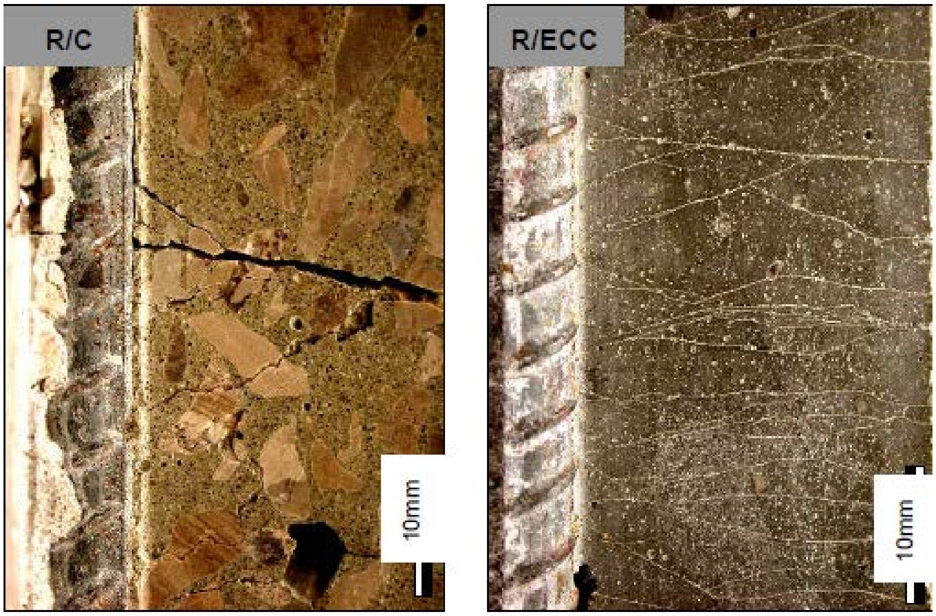


Figure 2.6 *Cracking pattern under tensile load for reinforced concrete (left) and reinforced ECC (Right) (Li, 2003)*

When PVA macro fibers are used in concrete, there is some evidence that workability issues can arise for high fiber volume mixtures. Shafiq et al. (2016) reported the need for increased water to cement ratios and sufficient doses of superplasticizer to achieve target slump for PVA macro fiber mixtures, however this study was able to achieve 3.0% fiber volume, indicating reasonable workability characteristics (Shafiq et al., 2016). Dopko et al. (2018) reported difficulties when mixing macro PVA fibers in concrete at 1.0% volume and over, reporting that the fibers had a tendency to re-aggregate and form clumps once a critical volume was reached. This study also reported that PVA fibers showed decreased workability and dispersion at the same fiber volume of PP fibers, even though the PP fibers had a higher aspect ratio than the PVA fibers tested (Dopko et al., 2018).

Macro PVA fibers have also been reported to improve the toughness and post crack performance of FRC. Shafiq et al. (2016) reported that macro PVA fibers provided no substantial improvement to the flexural strength of concrete, however the fibers provided significant post crack residual strengths (Shafiq et al., 2016). Dopko et al. (2018) reported similar results, showing that macro PVA fibers had no significant contribution to flexural strength but post crack residual strength and toughness increased nearly linearly with increasing fiber volumes between 0.5% and 1.5% (Dopko et al., 2018).

Orasutthikul et al. (2017) tested two different sizes of macro PVA fiber dispersed in fiber reinforced mortars at 1.0% and 1.5% volume under compression and flexure. The study found that for both sizes of PVA fiber, compressive strengths were not significantly affected but flexural strengths were increased. The larger PVA fiber provided higher flexural post crack residual strength and toughness compared to the shorter fiber at both volumes tested (Orasutthikul et al., 2017).

Both macro and micro PVA fibers can also be effective in controlling drying shrinkage cracks in concrete. It was found that PVA fibers in concrete at relatively low volumes (below 0.5%) decreased shrinkage crack widths in concrete by 90% for micro fibers and 70% for macro fibers. The presence of PVA fibers did not affect the restrained drying shrinkage stress development rate, however they controlled the crack widths once cracking was initiated. This result indicates that pre-crack strength was not greatly influenced but residual strength was positively affected by the fibers (Passuello et al., 2009).

Despite the reported excellent resistance to acid and alkali, Rouque et al. (2009) reported that PVA fibers can show degradation in sea water environments, especially after repeated wet and dry cycles (Rouque et al., 2009). Additionally, it has been reported that the failure response of the PVA fibers will shift from ductile towards brittle as the fiber matrix bond increases with time and fiber failure mode shifts from pull-out to rupture, however this feature is highly dependent on matrix properties (Li et al., 2004).

PVA fibers are less common in practice since they are more expensive than most other concrete fibers. Due to the lack of general use of PVA fibers in common fiber concrete applications like plastic shrinkage and thermal crack control, they are not as readily available for purchase as other less expensive synthetic fibers, however they can be purchased from select vendors.

2.4.4 Polyolefin

Polyolefin is a type of polymer fiber formed by the polymerization of olefin monomer units that in true definition encompasses polypropylene and polyethylene as subgroups (Kaminsky, 2008). For the purpose of this review, PO fiber will be discussed separately due to the presence of a distinction between polyolefin and other polymeric fibers in the FRC literature. PO concrete fibers share similar properties with high tenacity PP fibers as shown in Table 2.1. Due to the fiber similarities between PO and PP, characterized by low tensile strength, low elastic modulus and high ultimate strain, the performance of FRC made with these fibers tends to be similar. Accordingly, like PP FRC, crack widths tend to be larger, strength tends to be lower and strain capacity tends to be larger in PO FRC than FRC made with higher modulus fibers. It is also common for blended PP/PO copolymer resins to be manufactured into concrete macro fibers.

PO is very compatible and does not degrade in the chemistry of the cement environment. The PO fiber-matrix bond is mechanical in nature (Yan et al., 1998). Depending on the manufacturing technique, macro PO fibers can be made with deformations to enhance mechanical bond (Bentur & Mindess, 2006). It has also been suggested that since PO fibers have a low superficial hardness, their mechanical bond to the cement paste can be increased because of micro-scale surface imperfections that form as a result of damage during mixing. It was also found that the fiber-matrix bond properties of PO fibers increase with cement hydration time (Tagnit-Hamou et al., 2005).

PO micro fibers are not well represented in the literature or concrete fiber market, likely due to lack of need for them in practice because of the popularity and abundance of PP micro fibers. On the other hand, macro PO fibers are typically used to increase post crack residual strength in concrete. They can improve post crack ductility and limit crack growth but due to their low modulus, they are not typically as effective for low deflection or small crack width residual strengths as other fibers with higher elastic moduli (Alberti et al., 2014).

Ramakrishnan (1999), described the use of macro PO fibers in bridge decks and barrier rails. It was reported that the addition of fibers at around 1.5% volume not only improved the impact resistance and toughness of the concrete, but provided a synergistic effect with the rebar, shifting the cracking pattern from a lower number of wider cracks to a larger number of narrower cracks which would effectively limit the ingress of corrosive material through the bridge deck concrete and limit rebar corrosion (Ramakrishnan, 1999). Suitable performance has been reported by Alberti et al. (2014) with PO reinforced SCC. Macro PO fibers 50 mm in length were reported to mix well in the SCC at volumes up to around 1.0%, however this study utilized a high water to cement ratio of 0.5 to improve workability. For lower fiber volumes only tensile strength was slightly increased while for higher fiber contents, compressive strength decreased slightly and tensile strength increased substantially. For all fiber contents tested, the toughness and ductility was increased, with high fiber volume mixtures providing high residual strengths at large deflections. It should be noted that a fiber-matrix bond improving admixture was used in this study for high volume fiber mixtures (Alberti et al., 2014).

Han et al. (2012) found silica fume efficient in improving PO fiber-matrix bond properties. Relatively low modulus PO fibers were found to be most effective when used with silica fume in concrete when 25 mm fibers were used in place of 50 mm fibers for improving strength parameters, ductility and absorption. It was found through investigations with a scanning electron microscope that the silica fume improved the bond between the PO fibers and concrete matrix (Han et al., 2012). Another study showed that PO fibers of different length and aspect ratio are effective in controlling plastic shrinkage and thermal cracking in concrete overlays. Shorter fibers proved to be most effective for this application at the same volume dose (Banthia & Yan, 2000).

Alani & Beckett (2013) investigated the performance of PO fibers compared to the performance of hooked end steel fibers for slab on ground reinforcement. They concluded that surface embossed PO macro fibers could provide similar benefits to steel fibers as the primary reinforcement in ground supported slabs. The volumetric dose corresponding to equivalent performance of the PO fibers was about 1/3 higher than that of steel fibers, however the study showed that high tenacity macro synthetic fibers have potential to be used as the sole reinforcement in certain ground slab applications (Alani & Beckett, 2013). Similarly, Alberti et al. (2017) described a case study in which the conventional reinforcing bars in a concrete water pipeline casing were completely replaced by 5 kg/m^3 PO macro fibers. This was achievable due to the fact that only small tensile stresses were anticipated in the concrete. By eliminating the conventional rebar, construction cost and time of construction were greatly reduced for the project (Alberti et al., 2017).

The same limitations in the fresh state apply to PO fibers as the previously discussed limitations for PP fibers. PO fibers with surface indentations may further decrease the workability compared to smooth fibers due to the increased surface area per fiber. Several studies have shown that PO can be used in SCC mixtures (Alberti et al., 2014, Alberti et al., 2014). No detrimental effects to workability have been reported in the literature for PO fibers, although workability decreases can be anticipated as for any fiber addition.

The main limitation of PO fibers as concrete reinforcement is their relatively low elastic modulus, similar to PP fibers, causing relatively low residual strengths at small crack widths. In addition, low fiber-matrix bond strength is expected, however fiber geometric modifications can help develop sufficient mechanical bond to achieve acceptable residual strengths (Oh et al, 2007). Most concrete fiber distributors sell some form of PO fiber, since they are commonly used and work well for crack control. PO is relatively inexpensive, as it is in the same price range as PP, making it one of the least expensive synthetic concrete fibers. Products that combine polymeric resins like PP and PO resins to make macro fibers are very common. Each manufacturer has their own proprietary formula for the resins of these copolymer fibers and their properties tend to be similar.

2.4.5 Carbon

Carbon fiber has historically been one of the most popular types of fiber for reinforcing brittle matrix composites to improve tensile properties (Drechsler et al., 2009). As expected, the reinforcing effectiveness of carbon fiber reinforcement in other types of matrices has sparked interest in using carbon fiber in cement based composites.

Carbon fibers can have a wide range of mechanical properties which depend on the material and processes that were used to make the fibers. Polyacrylonitrile (PAN) based carbon fibers have very high tensile strength and elastic modulus, up to double that of steel, while pitch carbon fibers are made from petroleum and coal tar pitch and have lower tensile strength and elastic modulus. The weaker, pitch carbon fibers exhibit a wide range of tensile strengths and elastic modulus, depending on the nature of the pitch that was used to make them (Johnston, 2001). The properties of the fibers can vary considerably depending on the manufacturing process as well. Both types of carbon fiber are made from varying degrees of heat treatment, stretching and oxidation (Bentur & Mindess, 2006).

Carbon fibers are chemically inert and as a result do not undergo strength deterioration in the chemistry of the cement environment (Bentur & Mindess, 2006, Ali et al., 1972, Chand, 2000, Girgle et al., 2016). Since carbon is chemically inert, carbon fibers can only form mechanical or frictional bond with the cement matrix. The fiber failure mode within the composite depends on the mechanical properties of the fiber since higher modulus fibers would tend to pull out rather than rupture, however this depends on the matrix strength as well as the dimensions of the fiber and associated surface area available to contact the cement matrix. Pitch carbon fibers in mortar were found to have sufficient strength to fail by pull-out unless latex was used to enhance the fiber-matrix bond, in which case failure mode shifted to fiber rupture (Larson et al., 1990). Carbon fiber can substantially improve the mechanical properties of cement based composites if a sufficient volume of fibers can be achieved. The nature of the improvements of the mechanical properties of the composites that can be expected when carbon fibers are used in cement, is proportional to the modulus and strength of the fibers used. Stiffer and stronger fibers will more effectively improve strength parameters while weaker fibers are more likely to improve toughness.

Macro carbon fibers are uncommon since during mixing carbon fibers tend to break into shorter lengths due to their brittle nature (Nishioka et al., 1986). The presence of coarse aggregates will increase the level of carbon fiber damage accrued during mixing, however mixing damage can be lessened by using appropriate mixing procedure and additives like methyl cellulose and superplasticizer to disperse the fibers with minimal mixing (Banthia et al., 1994). The reported upper limit for conventional mixing of carbon fiber reinforced cement is about 1% by volume due to the fibers high aspect ratio and specific surface (Jonhston 2001), although higher volumes may be achieved with modified mixing techniques and admixtures (Akihama et al., 1984). Dopko et al. (2018) reported adequate workability and dispersion of carbon microfiber FRC mixtures containing up to 0.5% fiber volume by utilizing reasonable additions of superplasticizer and a modified mixing procedure to increase the mixing energy using a gravity based drum mixer (Dopko et al., 2018).

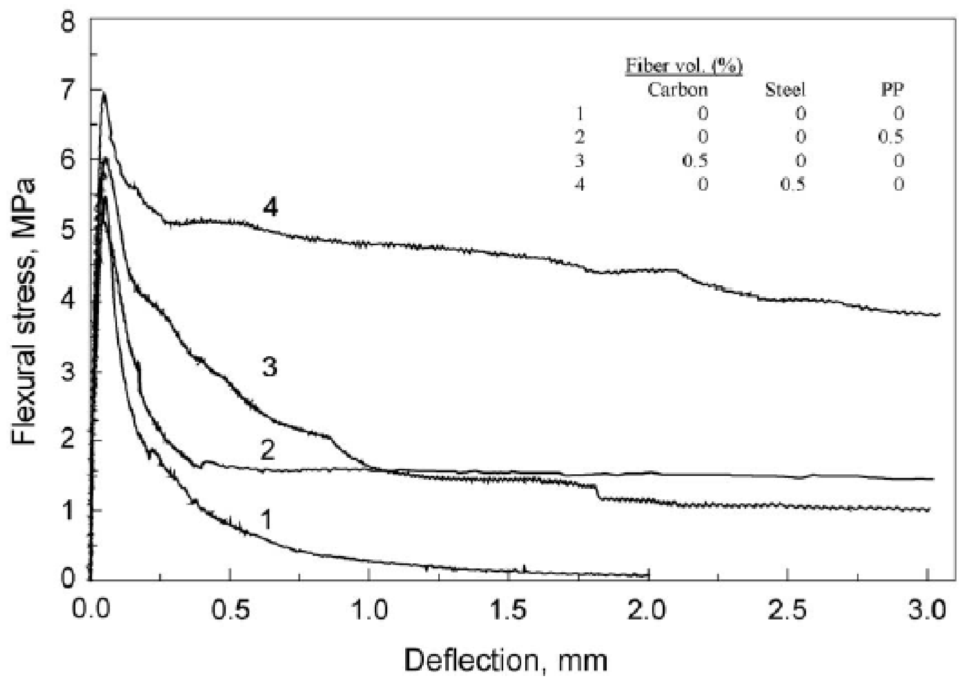


Figure 2.7 *Flexural response of micro carbon, macro steel and micro PP FRC at 0.5% fiber volume (Yao et al., 2003)*

Due to the impracticality of carbon macro fibers, their use is absent in the literature, however carbon microfibers have been the focus of several studies involving carbon microfiber reinforced cementitious composites lacking coarse aggregates. Different studies have reported substantial increases in the tensile and flexural strengths and controlling the shrinkage cracking of cementitious composites reinforced with varying volumes of carbon microfibers. In general, the higher the fiber volume, the higher the expected performance (Park et al., 1991, Toutanji et al., 1993). Low modulus, pitch based carbon microfiber cementitious composites have been shown to have strain hardening and micro-cracking capabilities at volumes between 1% & 3% (Akihama et al., 1984).

Similar benefits have been reported in limited studies for carbon microfiber in concrete. Yao et al. (2003) tested 0.5% volume high strength and elastic modulus micro carbon FRC and found that the fiber addition increased compressive strength, splitting tensile strength and modulus of rupture by 14%, 19% and 9% respectively. The carbon fiber also modestly increased the residual strength of the concrete, especially at low deflections as shown in Figure 2.7. (Yao et al., 2003). Dopko et al. (2018) tested varying volumes of carbon microfiber, accelerating admixture, and shrinkage reducing admixture for their effect on compressive strength, splitting tensile strength, and restrained shrinkage behaviors. The study found that increasing carbon microfiber volume generally increased the 24 hour compressive strength (Figure 2.8) and splitting tensile strength of the composite. The presence of 0.3% carbon microfiber also increased the 7 day compressive and splitting tensile strength by an average of roughly 9.6% and 22.8% respectively. The study also showed that carbon microfiber can substantially reduce the restrained shrinkage cracking potential of concrete (Dopko et al., 2018).

Carbon fibers have the ability to conduct electricity, allowing them to be used in cement matrix composites for deicing, electromagnetic shielding and strain sensing (Wen & Chung, 2005). This gives rise to the use of carbon cement composites for “smart pavement” applications such as weigh-in-motion stations (Shi & Chung, 1999) and heated pavements, which could be a large benefit to the aviation industry in keeping runways clear of snow and ice without the use of chemicals which can damage airplanes and the environment (Sassani et al., 2018).

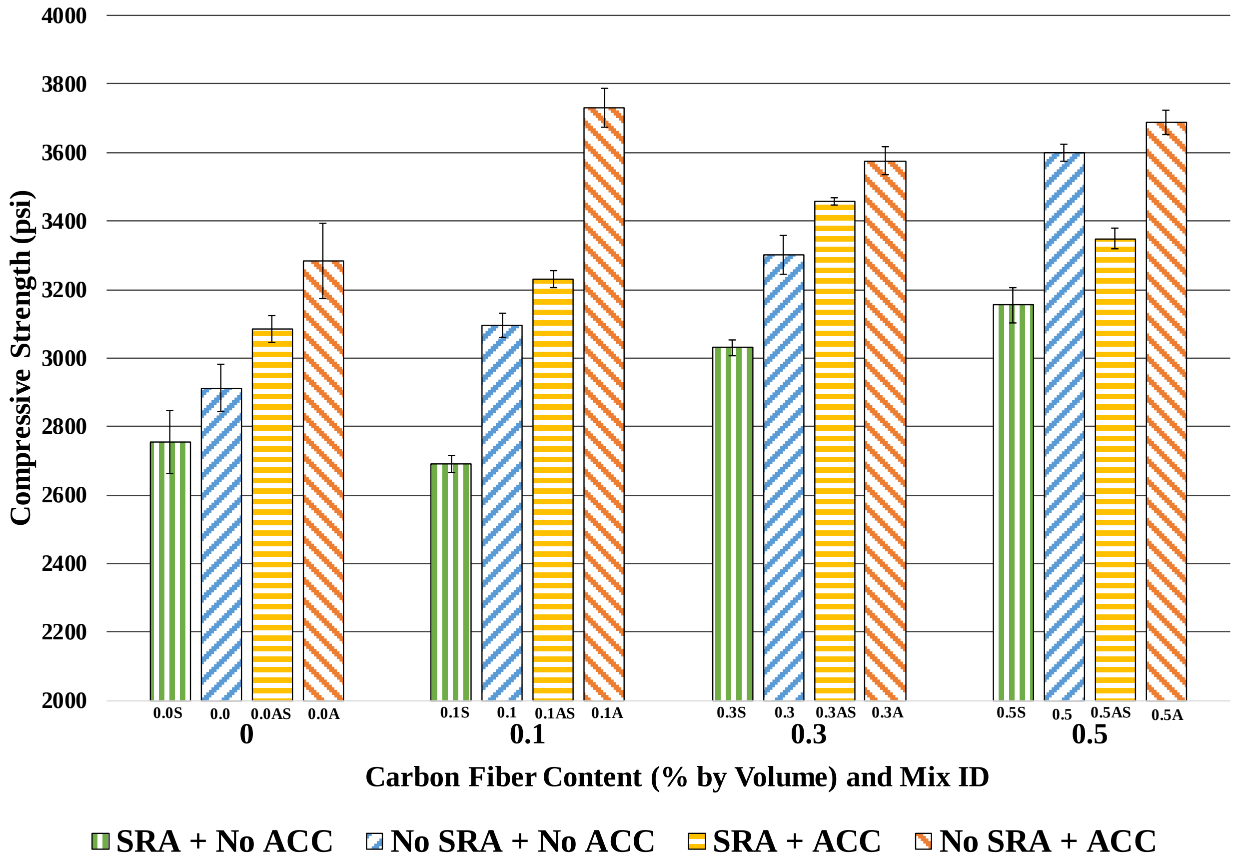


Figure 2.8 *24 hour compressive strength of concrete containing 0.0% - 0.5% carbon microfiber volumes and different combinations of accelerating admixture (ACC) and shrinkage reducing admixture (SRA) (Dopko et al., 2018)*

Due to limitations during mixing with conventional methods, especially with mixtures containing coarse aggregate, combined with the high price of most carbon fiber, other concrete fibers are most often more effective for common concrete applications generally associated with synthetic fiber. Since carbon could be considered an expensive specialty fiber, their availability is somewhat limited to select vendors.

2.4.6 Polyethylene

Polyethylene (PE) is one of the most produced plastics and is common for use in packaging. PE fiber can be produced with a wide range of mechanical properties. Historically, polyethylene has been characterized by low strength and elastic modulus, similar to PP or PO fibers, however the development of ultra-high density polyethylene has greatly increased the strength and stiffness potential of polyethylene fiber. Essentially, the higher the fiber density and molecular weight, the higher the strength and stiffness potential. These material properties depend on the degree of molecular alignment achieved by advanced production processes involving heat pressure and catalysts (Lepoutre, 2013). Due to the diversity in strength and stiffness parameters coupled with strong chemical stability, PE is used for a variety of applications including packaging, fabrics, ropes and yarns.

Different researchers have explored the use of high strength and stiffness polyethylene in cement based composites in a variety of studies due to its attractive mechanical properties and associated reinforcing potential, especially in high performance mortars. There is a lack of current literature describing low strength and stiffness polyethylene FRC, likely due to poor mechanical properties coupled with the abundance, low cost and availability of other polymeric low strength concrete fibers.

Polyethylene (PE) macro fibers with lower strength and modulus, similar to that of PP or PO have been reported to mix sufficiently into a normal FRC matrix at volumes up to 4%. This is a relatively high fiber volume and it should be noted that a high water to cement ratio was utilized in this study to help with mixing. These PE fibers were described as monofilament with wart like deformations on their surface to increase their mechanical bond with the cement matrix. The study showed that post-crack flexural ductility was greatly improved, especially at larger deflections, which is expected for a low modulus macro fiber (Kobayashi & Cho, 1981).

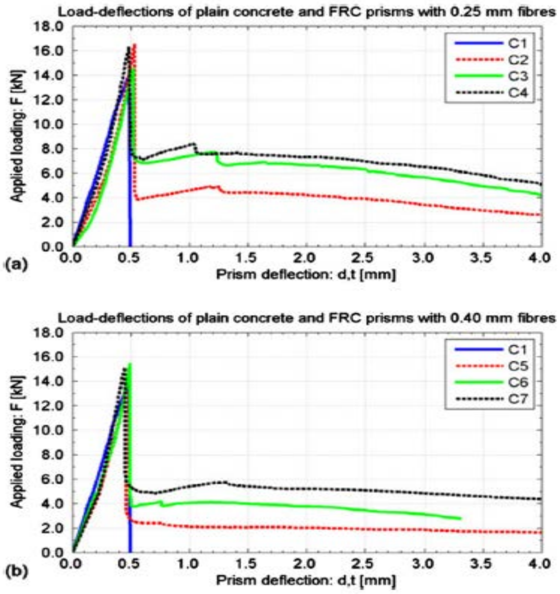


Table 3
Fibre reinforced concrete (FRC) mixes.

Concrete Series	Label	Fibres %	Slump [mm]	Air %
Plain concrete				
	C1	–	65	3.2
FRC (fibres: $Ø_1 = 0.25\ mm, L_1 = 23\ mm$*)*				
	C2	0.40	36	3.4
$(r_{a1} = 92)$	C3	0.75	22	3.3
	C4	1.25	17	3.4
FRC (fibres: $Ø_2 = 0.40\ mm, L_2 = 30\ mm$*)*				
$(r_{a2} = 75)$	C5	0.40	33	3.2
	C6	0.75	18	3.4
	C7	1.25	13	3.3

Figure 2.9 *Recycled PE flexural load-deflection curves (left) and mixture ID's for specimens tested (right) (Pešić et al., 2016)*

The possibility of using recycled polyethylene fibers for concrete reinforcement has also been investigated. Recently Pešić et al. (2016) investigated FRC incorporating PE fibers made from recycled consumer products like home appliances. The fibers investigated had relatively low strength and modulus, even compared to other polymeric macro fibers due to a strength reduction caused by the recycling process. The study found that composite strength parameters were not significantly influenced by the addition of fibers compared to the control mixture, however reasonable flexural toughness and residual strengths were provided by the fibers at increasing values with fiber content as shown in Figure 2.9. Plastic shrinkage cracking and water permeability were both significantly decreased by the presence of fibers even at low volumes (Pesic et al., 2016).

High Strength Polyethylene (HSPE) is made from gel-spinning ultra-high molecular weight PE. The tensile strength and modulus of elasticity of HSPE are higher than other polymeric fibers as shown in Table 2.1. HSPE is chemically inert, giving it high stability and degradation resistance in the concrete environment. HSPE also has a low coefficient of friction which causes it to form a weak bond with other materials (Marissen, 2011). Due to these properties, HSPE can only form a mechanical bond with the cement matrix, however it has been shown that surface treatments can increase the bond strength. Wu & Li (1999) studied the effect of surface treatment on the bond strength of HSPE fibers and concluded that the fibers could form roughly a 1 MPa bond with the cement matrix due to the surface finish applied to the fibers by the manufacturer to increase the friction coefficient of the fiber surface. In that same study it was found that plasma treatment of the fibers could increase their fiber-matrix bond strength considerably (Wu & Li, 1999). More recently, He et al. (2017) showed that coating HSPE fibers with carbon nanofiber can increase the frictional bond strength of the fibers by 22%.

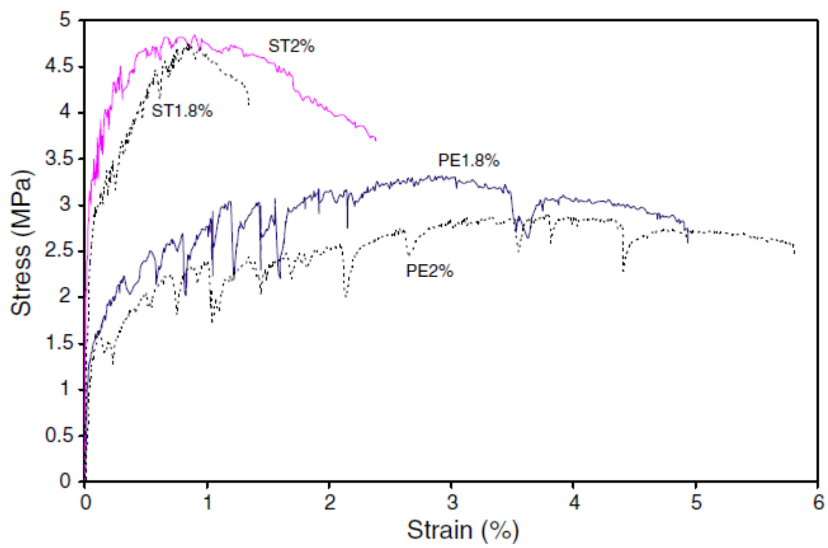


Figure 2.10 *Direct tensile response of HSPE and steel mono-fiber cement mixtures (Ahmed & Maalej, 2009)*

HSPE fibers represented in FRC literature can be classified as microfibers due to their low diameter and resulting high aspect ratio. HSPE macro fibers are not represented in the FRC literature, likely due to the high cost of HSPE fibers with larger diameters. HSPE microfibers have shown the ability to produce cementitious composites that exhibit strain hardening and micro cracking when sufficient fiber volume is used, similar to PVA-ECC, which has led to a number of research studies describing the performance of these types of HSPE cementitious composites.

Ahmed et al. (2007) investigated the use of HSPE microfiber in mortar to achieve increased strength and ductility in the composite. Very high ductility and toughness was achieved through strain hardening and micro-cracking when using the HSPE fibers alone in the mortar with 50% fly ash binder at 2.5% fiber volume. This study also showed evidence that HSPE fibers mix reasonably well with cement based composites lacking coarse aggregate (Ahmed et al., 2007). In similar research, Ahmed & Maalej, (2009) studied two different lengths of HSPE fibers for their contribution to tensile ductility of cement paste. The study found that 18 mm HSPE fibers were more effective at increasing the tensile ductility and toughness of the hardened composites, especially at larger deflections, than 12 mm HSPE fibers. This is likely due to the low fiber-matrix bond strength of the fibers, giving the longer fibers the advantage of increased bonding surface area per fiber cross sectional area. Additionally, the study confirmed that HSPE fiber reinforced paste mixtures can show strain hardening and multiple cracking behavior with higher ductility and lower strength than steel fiber reinforced paste mixtures (Figure 2.10) (Ahmed & Maalej, 2009). More recently, Curosu et al. (2017) showed that 2% HSPE microfibers were effective at producing high ductility mortars that showed strain hardening and micro-cracking in tension. Strength parameters were not significantly affected, however ultimate tensile strains of 3.9% were achieved, accompanied by average crack width and spacing of 35 micrometers and 2.3 mm respectively (Curosu et al., 2017).

Recent research by Choi et al. (2016, 2016) investigated the use of HSPE microfibers in alkali activated binder paste mixtures. It was found that the alkali activated binders lowered the strength properties of the composites compared to Portland cement binders, however incredible ductility values of 7.5% tensile strain with improved cracking patterns could be achieved with the alkali activated binder and 1.75% HSPE microfiber volume (Choi et al., 2016, Choi et al., 2016).

HSPE fibers have shown adequate reinforcing effect in concrete in limited studies. It has been shown to provide better flexural strength and comparable impact resistance when compared to fibrillated polypropylene fibers at low volumes in concrete mixtures (Soroushian et al., 1992). More recently, Yamaguchi et al. (2011) explored high volumes of HSPE fiber for their contributions to compressive, splitting tensile, and flexural strength as well as toughness and resistance to contact detonation. Very high fiber volumes of 2.0% and 4.0% were reported, even though a high aspect ratio HSPE fiber was used. These volumes were accompanied by reasonable slump values achieved by large superplasticizer doses and the use of a high shear forced double axis mixer. As expected with such large high performance fiber volumes, increases in all strength parameters were reported and toughness values were markedly increased with the both fiber contents. The fibers also greatly improved the blast resistance of the composites (Yamaguchi et al., 2011). Besides these studies, there is a lack of existing literature describing HSPE cementitious composites containing coarse aggregate.

The fiber-matrix bond strength of HSPE fibers is the main limitation to their reinforcing effect due to the fact that a very strong bond and/or very high aspect ratio would be needed in order to utilize the full tensile strength and stiffness of the fibers. HSPE is typically a high performance product so it is expensive to buy directly from the manufacturer. It is typically produced in spools to be used for weaving high performance fabrics and ropes, however at the time of this review, waste HSPE fibers can be obtained from a third party distributor for a very low price with 19 mm length and high aspect ratio. Due to the lack of practicality for macro polyethylene or macro HSPE fiber caused by the previously mentioned limitations, these fibers are somewhat limited in normal concrete applications.

2.4.7 Polyester

Polyester fibers generally fall under two categories, Polyethylene Terephthalate (PET) and Poly-1, 4-Cyclohexylene-Dimethylene Terephthalate (PCDT), each are made using different processes and have different chemical and mechanical properties. PET generally has higher strength and stiffness than PCDT, which is generally more ductile and resilient.

With reference to use as concrete fibers, PET has been subject to adequate research to warrant inclusion in this review, mostly as a recycled fiber from consumer products. Henceforth, the polyester fibers mentioned in this review are of the PET variety, and the terms PET and polyester will be synonymous. It should be noted that although polyethylene and polyethylene terephthalate share the polyethylene name, the materials are chemically completely different, since PET is a polyester, not a type of polyethylene. PET is a common plastic material used for making bottles or containers.

PET fibers can have variable chemical and mechanical properties depending on their manufacturing techniques. PET is thermally sensitive and breaks down at high temperatures (above 280 ºC). Additionally the fiber-matrix bond properties of polyester are reported to be only mechanical in nature, similar to other polymeric fibers (ACI 544.1R-96, 2009). Although the majority of studies incorporate 1.0% PET fiber volume or lower, PET macro fibers are reported to mix well in concrete at volumes up to 1.5% (Ochi et al., 2007, Borg et al., 2016). It should be noted that these studies utilized water to cement ratios equal to or above 0.55 which are conducive to more workable mixtures. Research has shown that polyester fibers are capable of improving the mechanical properties of concrete in laboratory testing.

The bulk of research that has been conducted on PET fibers involves monofilament macro fibers that are made from recycled plastics, however limited research has investigated virgin PET fibers. Patel et al. (1989) investigated 20 mm long polyester fibers with high aspect ratio at volumes up to 1.0%. The exact chemical composition, mechanical properties or source of these fibers was not revealed, however the authors found that the addition of these virgin polyester fibers at 1.0% volume increased the compressive, flexural, split tensile and impact strength of the hardened composite by 5%, 7%, 27% and 100% respectively (Patel et al., 1989). Sivakumar & Santhanam (2007) investigated virgin polyester microfibers dispersed at 0.5% volume in a high strength concrete matrix and found that compressive strength was not significantly affected by polyester fiber addition but elastic modulus, splitting tensile and flexural strength as well as flexural toughness were increased (Sivakumar & Santhanam, 2007).

Recent work involving polyester fibers in concrete focuses on PET macro fibers made from recycled bottles which are either cut into strips directly from waste bottles, or melted from processed bottle chips then extruded, cut and often embossed to the desired dimensions and texture. Kim et al. (2010) compared the performance of recycled PET fibers made from extruding shredded bottles with virgin PP fibers. Both fibers were 50 mm long with similar aspect ratios but the PET fibers were surface embossed while the PP fibers were crimped. Compressive strength and elastic modulus was slightly decreased, while time to crack formation under restrained drying shrinkage was increased with increasing fiber volume fractions. This study also tested beams containing tensile and compressive longitudinal rebar as well as shear stirrups with FRC mixes to investigate the fiber contribution to full scale structures. The authors found that impressive ductility increases could be achieved compared to the reference beam with no fiber. Ultimate strengths were also increased for all fiber additions (Figure 2.11). The increase in performance was relatively consistent for both PET and PP fibers through the fiber dosage range used in the study (Kim et al., 2010).

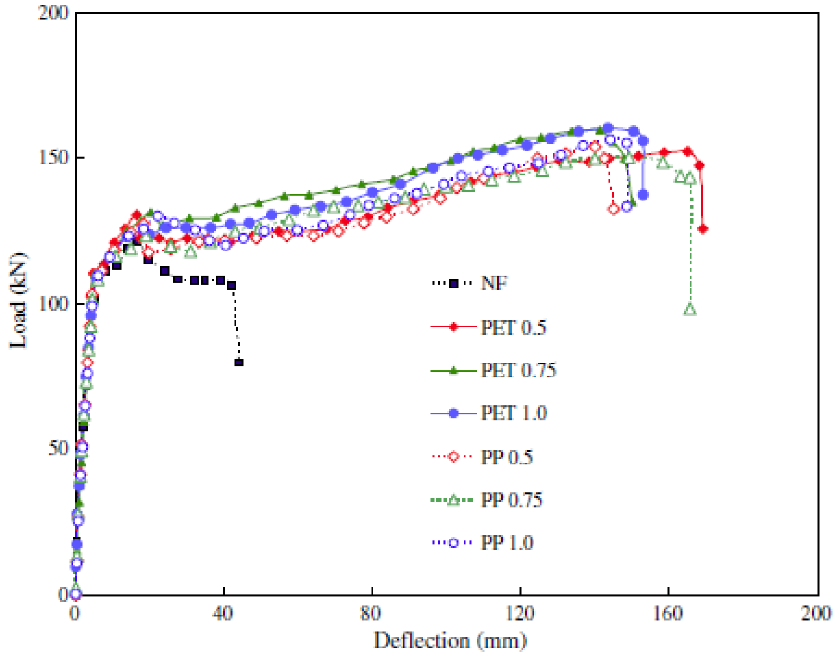


Figure 2.11 *Load-deflection response of reinforced concrete beams cast with PET and PP FRC at 0.5%, 0.75% and 1.0% fiber volume (Kim et al., 2010)*

Fraternali et al. (2011) studied FRC containing a constant 1.0% fiber volume made with recycled PET macro fibers that were extruded from resins obtained from melting recycled bottle flakes. Three different PET fibers were obtained each with different geometries and parent resins giving them different mechanical properties. These three fibers were compared with virgin PP macro fibers with embossed surface texture. The authors found that PET fibers with a straight cross section were able to provide a larger increase to compressive strength than the embossed PP fibers tested. Additionally, pre-crack flexural strength was increased for all PET fibers tested. The addition of PET fibers increased the flexural ductility by significant margins for all fibers. The fiber that had the highest tensile strength showed the best performance for composite strength and ductility parameters. Thermal conductivity was significantly decreased by the presence of PET fibers. When comparing the PET fibers to the PP fibers tested, the study showed that similar properties could be obtained in the hardened composite (Fraternali et al., 2011).

Fraternali et al. (2013) also investigated 1.0% volume of macro recycled PET fibers from bottles that were hand cut to three different lengths (11.3mm, 22.6mm and 35.0mm) for their flexural contributions to FRC. The study found that 28 day flexural strengths were decreased by the presence of shorter PET fibers but not significantly affected by longer PET fibers. Additionally, flexural toughness was increased with increasing fiber length, with relatively high flexural toughness produced by the 35mm fiber mixture (Fraternali et al. 2013).

In a similar study, Borg et al. (2016) investigated 0.5%, 1.0% and 1.5% volume of recycled PET fiber FRC made with fibers that were hand cut from waste bottles to lengths of 30 mm and 50 mm. Fibers of both lengths were either deformed or straight, making for a total of 4 different fiber geometries. The authors found that the compressive strength was reduced when PET fibers were present in the mixture for all cases, with the largest reductions occurring for long fibers mixed at higher volumes. With regards to flexural properties, the pre-crack strength of the composites containing PET fibers was slightly increased compared to the control mixture. The largest contribution of the fibers was to toughness, in which case the deformed, longer fibers performed best due to increased fiber matrix bond strength. Toughness of the composites increased with increasing fiber volume. This study also found that recycled PET fibers could effectively reduce plastic shrinkage cracking under accelerated drying conditions as well as reduce and delay crack width opening under restrained drying shrinkage (Borg et al., 2016).

The main concern involved with polyester fibers in cement based composites is uncertainty with regards to their stability in the highly alkaline environment of cement. The majority of studies have reported some level of degradation with prolonged exposure to acid and alkali. Won et al. (2009) studied recycled PET FRC for freeze-thaw resistance, as well as strength retention after exposure to alkali and acidic solutions. The study found that the composites had good frost resistance, however the authors concluded that if PET fibers are exposed to an alkaline environment, poor performance can be expected. Additionally, the authors found that exposure to acid not only reduced the strength of the PET fiber, but the physical and mechanical properties of the concrete matrix were significantly deteriorated as well (Won et al., 2009). These conclusions were supported by Fraternali et al. (2014), who found that after 12 months in an aggressive seawater exposure, toughness of recycled PET FRC composites was decreased by over 50% (Fraternali et al., 2014). Additionally, Silva et al. (2005) showed that PET FRC composites displayed decreased toughness parameters over time. The authors used Scanning Electron Microscopy (SEM) to identify that under prolonged exposure in an alkaline conditions fiber degradation characterized by surface irregularities (Figure 2.12) and in some regions, complete degradation of the fibers was evident (Silva et al., 2005).

Contrary to studies that confirmed degradation of PET fibers over time in alkaline environments, Ochi et al. (2007) concluded that recycled PET fibers underwent negligible degradation after 120 hours in an alkaline environment at 60 ºC, quantified through direct tensile tests on individual fibers. The authors reported that the PET fibers showed better alkali resistance than PP or PVA fibers (Ochi et al. (2007). Under the same testing conditions, Fraternali et al. (2013) reported an 87% strength retention for recycled PET fibers (Fraternali et al., 2013). These conclusions should be accepted cautiously, since the testing regime only subjected the fibers to

120 hours of alkaline exposure, which may not have been long enough to allow sufficient exposure to relate the results to long term durability. Regardless, there is sufficient evidence in literature to conclude that PET fibers will undergo some level of degradation in the cement environment, which is a major limitation to the fibers reinforcing potential.

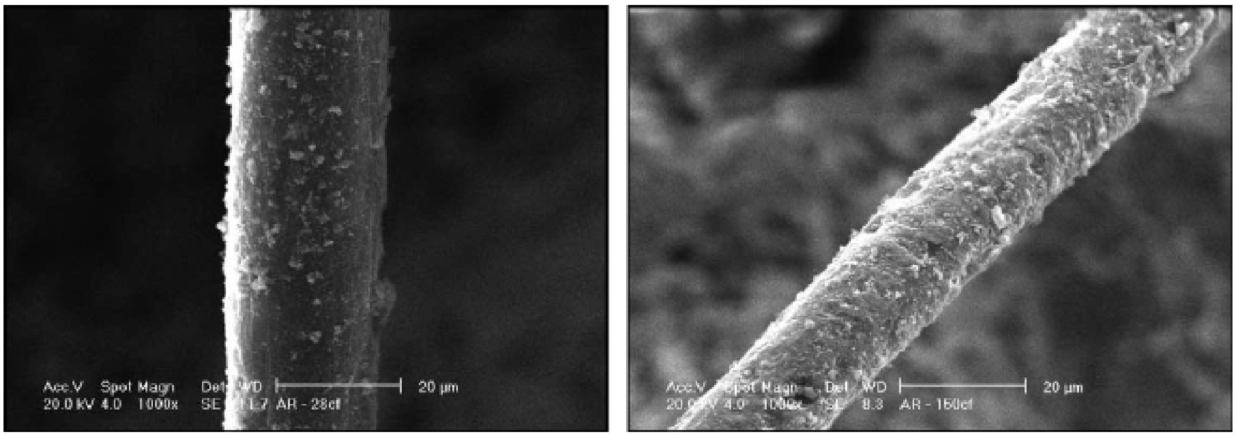


Figure 2.12 *SEM of recycled PET fibers after 42 days (left) and 164 days (right) of exposure in cement mortar (Silva et al., 2005)*

The use of PET fibers in FRC is bound to laboratory testing and research at the time of this review. It is expected that as production technology and the associated quality of recycled PET fibers increases in the future, these fibers may gain traction in the concrete fiber industry due to their economic and environmental benefits over traditional synthetic fibers.

2.4.8 Acrylic

Acrylic is a polymer that contains at least 85% acrylonitrile by weight (Zheng & Feldman, 1995). The name “Acrylic” is short form for, and essentially interchangeable with Polyacrylonitrile (PAN). As previously mentioned, PAN fiber is also the precursor material used to manufacture PAN based carbon fiber.

Early forms of acrylic fibers traditionally used in the textile industry exhibit low strength and elastic modulus as well as poor resistance to acids and alkali which limited their applications in cement and concrete (Bentur & Mindess, 2006). Acrylic fibers with much higher tensile strengths and elastic modulus were developed in the 1980's as a solution to replace carcinogenic asbestos in asbestos cement (ACI 544.1R-96, 2009), and have been used successfully as small diameter short cut fibers at high volumes for asbestos replacement in hollow circular and sheet cement products made with the Hatschek process. These fibers have shown little to no sensitivity to the alkalinity of concrete. Some research has reported small long term sensitivity to alkali environments, especially at higher temperatures (Wang et al., 1987) while others have reported that acrylic fibers are not sensitive to chemical degradation (Amat et al., 1994, Jamshidi & Karimi, 2010).

Typical ranges of acrylic fiber properties can be found in Table 2.1. As can be seen, there are a wide range of strength and stiffness parameters that PAN fibers can possess. Due to this variation, the properties of PAN FRC can vary substantially as well. The research pertaining to the performance of PAN fibers in cementitious composites containing coarse aggregate is limited, however, there is more evidence in the literature for acrylic fibers in paste or mortar, likely due to the fact that PAN fibers are predominantly micro in form. The present author has found no record of PAN macro concrete fibers in the literature, with the largest reported PAN fiber diameter being 0.1 mm (Hahne et al., 1987).

Although somewhat dated, Hahne et al. (1987) studied the performance of FRC made with high strength PAN fiber. They studied high strength acrylic fibers of different length (6 mm – 24 mm) and diameter (18-104 micrometers) as well as strength (up to 1000 MPa) and elastic modulus (up to 19.5 GPa) for their fiber-matrix bond strength as well as their effects on workability, drying shrinkage, compressive and flexural strength and ductility. The study found that acrylic fibers form a good bond with the cement matrix due to their irregular cross sectional shape. Fiber volumes up to 2.5% were investigated and it was reported that the water to cement ratio had to be increased substantially and superplasticizers were needed to accommodate the fiber addition, especially with low diameter fibers. The addition of PAN fibers drastically diminished drying shrinkage cracking, especially at higher volumes. Compressive strengths were not significantly affected or slightly decreased, however flexural strength and post crack residual strengths were increased, especially at low deflections. Generally speaking, increasing fiber length increased performance. (Hahne et al., 1987). The acrylic fibers studied by Hahne et al. (1987) had significantly higher mechanical properties than other acrylic fibers found in the FRC literature.

Limited recent studies have explored acrylic fibers of lower strength and elastic modulus in FRC. Fan et al. (2015) investigated the additions of PAN microfibers to concrete. Fiber volumes between 0.5% and 2.0% were tested. The authors concluded that 1.0% volume of PAN fibers was optimal for controlling plastic shrinkage, reducing chloride penetration, decreasing permeability as well as increasing impact toughness and abrasion resistance. High fiber volumes were accommodated by including relatively high amounts of polycarboxylate superplasticizer (Fan et al., 2015). Mo et al. (2015) investigated low volumes (below 0.2%) of acrylic microfibers in lightweight oil palm shell concrete containing ground granulated blast furnace slag. The study found that the presence of low volumes of PAN fibers significantly reduced the workability of the mixtures. The fibers also reduced drying shrinkage strain and slightly increased flexural and tensile strengths. Post crack parameters were not studied in this effort but it was found that the acrylic fibers were effective for preserving the composite strength after heat exposure due to the melting of the fibers, allowing entrapped gas to escape the concrete, similar to the phenomenon previously mentioned for low volume PP microfiber concrete (Mo et al., 2015).

Studies involving PAN fibers in pastes and mortars are better represented in the literature. Ward et al. (1990) investigated low strength acrylic micro fibers at volumes between 1.0% and 3.0% in mortar for their effects on compressive, flexural, direct tensile and splitting tensile strength as well as their effectiveness as beam shear reinforcement and contribution to fracture energy evaluated by notched beam specimens. The authors found that pre-crack strength parameters were all increased, besides compressive strength, which was slightly decreased. High fiber volumes were difficult to mix and extra compaction effort had to be applied to consolidate these specimens sufficiently. Shear strength was modestly increased by the inclusion of the acrylic fibers. Increases in fracture energy were achieved, characterized by a tension softening response and low residual strengths at high deflections, likely due to the very short length of the micro fibers used in the study (Ward et al., 1990).

Jamshidi & Karimi, (2010) studied the chemical durability after alkali aging of acrylic fibers and flexural strength of thin sheet cement paste composites reinforced with acrylic fibers. The study compared the durability and flexural performance of PAN fibers to that of nylon and PP under the same conditions. The authors concluded that the PAN fibers had high chemical stability and almost no strength loss was reported when exposed to alkali solution for 28 days. After SEM inspection, it was shown that nylon and acrylic form a stronger bond with the cement matrix characterized by cement hydration products formed on the nylon and acrylic fiber surface, but not on PP (Figure 2.13). Flexural strength and ductility parameters were slightly improved, however very short (3-4 mm) micro fibers were used in this study and such fiber lengths are not conducive to high ductility even in paste or mortar composites (Jamshidi & Karimi, 2010).

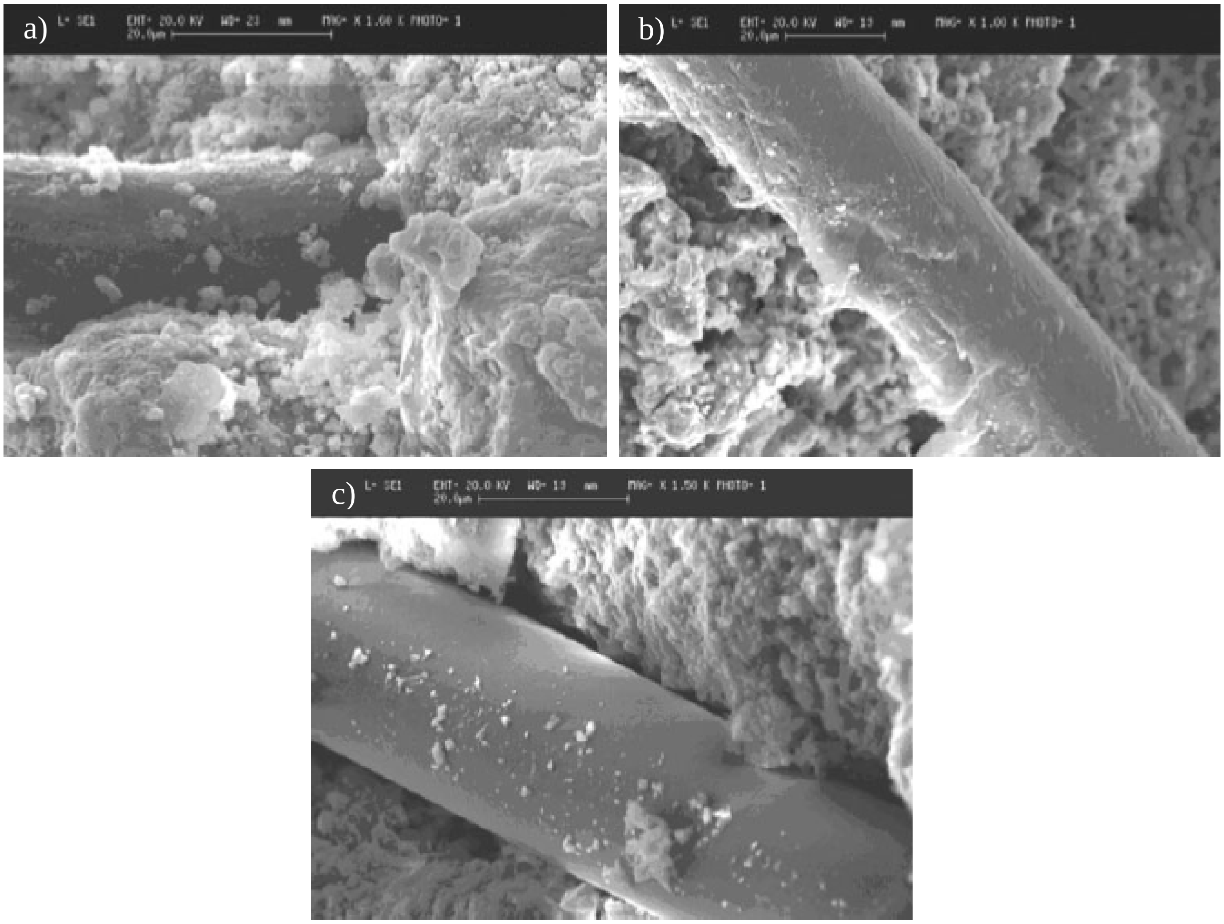


Figure 2.13 *SEM images of a) nylon b) acrylic and c) polypropylene fiber surface (Jamshidi & Karimi, 2010)*

Pereira-de-Oliveira et al. (2012) investigated the influence of adding up to 1.0% volume of micro PAN fibers with different aspect ratios to mortar. It was found that workability of PAN fiber mortars was decreased as fiber volume and aspect ratio were increased. The authors concluded that compressive strengths were not affected by fiber addition but flexural strengths actually decreased. The decrease in flexural strength was attributed to poor fiber dispersion, which was improved by dry mixing the fibers prior to water addition during mixing. Plastic shrinkage cracking was drastically decreased by the addition of PAN fibers, even at volumes as low as 0.1%. The PAN fiber mortars were compared to glass and PP fiber mortars under the same testing conditions. The authors concluded that the PAN fibers could provide similar performance enhancements to mortar as glass or PP fibers (Pereira-de-Oliveira et al., 2012).

Halvaei et al. (2015) studied and compared the bond properties and flexural behavior of acrylic and nylon fibers in mortars. The study found that the fiber-matrix bond strength of the acrylic fibers was over 30% higher than that of nylon fibers, evaluated by single fiber pull-out tests. The increased bond strength resulted in the acrylic fibers to fail by rupture, causing the single fiber pull-out energy of acrylic fibers to be much lower than that of nylon fibers, since the nylon fibers pulled out of the matrix completely through the failure process, thereby absorbing significant energy compared to the acrylic fibers. The acrylic fiber provided increases to flexural strength of the composite, as well as significant residual strengths and toughness, mainly at lower deflection values due to the fibers rupturing before larger deflections could be achieved (Halvaei et al., 2015).

PAN micro fibers appear to be an effective solution as concrete fibers in the sense that they can provide similar benefits as other low strength and modulus synthetic fibers. Compared to other common synthetic fibers, the literature suggests that acrylic will more negatively affect workability, but can provide increased fiber-matrix bond strength along with significant residual strengths at small crack openings. The limited general use of PAN fibers in concrete containing coarse aggregate is likely due to the fact that other less expensive synthetic fibers can generally provide similar benefits, coupled with the absence of acrylic macro fiber production. Acrylic microfibers have reasonable availability, as they are offered through select concrete fiber vendors at a price that is in general higher than other low strength and modulus synthetic microfibers.

2.4.9 Aramid

Aromatic Polyamide, also known in short form as Aramid, is a fiber that has many high performance applications due to its high strength and elastic modulus relative to most other synthetic fibers. Common applications of aramid include bullet proof vests, high strength ropes and yarns and other applications where a high strength to weight ratio fiber is desirable. Aramid fibers are 2.5 times as strong as glass and 5 times as strong as steel per unit weight (ACI Report 544.1R-96, 2009). These attractive qualities have drawn attention to Aramid fibers for applications as reinforcement in cementitious matrices. The two most common types of aramid fibers are marketed under the trade names Kevlar and Technora. These two fibers possess different properties, mainly to do with their chemical durability, due to the differences in their production methods. Kevlar is produced by dry and wet spinning of a sulfuric acid solution of aromatic polyamide, while Technora fiber production does not utilize acid spinning (Uomoto et al., 1999).

One of the earliest studies regarding aramid fiber reinforced cement based composites was carried out by Konczalski et al. (1982). This study used long Kevlar fibers aligned in the direction of loading cast in cement paste. Impressive tensile strain hardening and micro-cracking properties were achieved with fiber volumes around 2.0%. This study showed that aramid fibers have good potential as concrete reinforcement due to their high strength, elastic modulus and sufficient bond to the concrete matrix. (Konczalski et al., 1982).

Wang et al. (1990) studied Kevlar and Technora micro fibers dispersed in mortar at 1.0%, 2.0% and 3.0% volume for their effect on workability, tensile strength, drying shrinkage as well as tensile post crack residual strength and fracture energy under monotonic and cyclic loads. The aramid fibers were reported to mix well in the mortar mixture up to 2.0% volume if sufficient superplasticizer was added, however the 3.0% volume aramid fiber mixture was not workable. The addition of aramid fibers markedly improved tensile strengths by 40%-90%. Tensile post crack residual strengths and fracture energy (toughness) were greatly increased as well. Residual strengths were most positively affected by aramid fibers at low crack openings. The study also found that the cyclic tensile loading response of aramid fiber mortars after cracking was similar to the monotonic loading response, showing good cyclic load resistance (Wang et al., 1990).

Nanni (1992) investigated different volumes of aramid fiber reinforced polymer (AFRP) macro fibers dispersed in concrete. AFRP fibers include hundreds of aramid microfibers bound together by impregnation with resin to form a single macro fiber. The study compared the AFRP fiber concrete performance to that of steel and PP fiber concrete. The results indicated that AFRP fibers did not significantly affect the pre-crack flexural or split tensile strength of the composites, however large increases in post crack residual strength and toughness could be achieved with increasing AFRP fiber content. The study concluded that the AFRP fibers could far out-perform PP fibers and showed similar benefits as steel fiber in concrete (Nanni, 1992). Based on the findings from the literature, this type of AFRP fiber was not studied again for almost 20 years after the Nanni (1992) study.

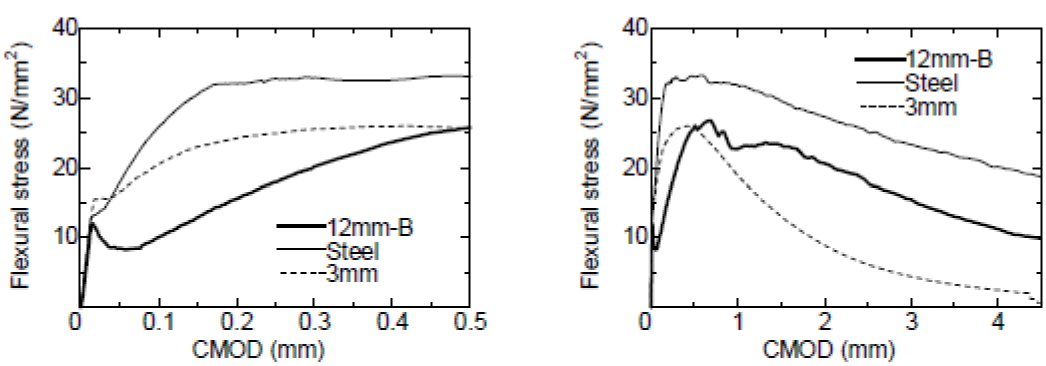


Figure 2.14 *Flexural stress vs crack mouth opening displacement (CMOD) for 3.0% vol. aramid micro fiber, 1.75% vol. AFRP macro fiber (12mm-B) and 2.0% steel fiber (Uchida et al., 2010)*

Uchida et al. (2010) investigated different types and geometries of aramid fiber dispersed in mortar at volumes between 0.5% and 3.0%. Monofilament aramid fibers with two different diameters of 12 and 45 micrometers as well as lengths of 3, 6, 8 and 12 mm were tested for their effects on fresh properties, as well as compressive strength and flexural behavior. This study also tested a type of macro AFRP fiber. The authors found that workability was decreased as fiber length and volume increased. The workability of the macro AFRP fibers was better than that of the filament strand fibers due to the decreased surface area per volume of fibers, however the AFRP composite workability was less than that of steel fiber composite. The compressive strengths of the composites was not influenced significantly, however the shorter aramid micro fibers showed somewhat higher compressive strength than the longer fibers. The results of the flexural testing for the maximum fiber volumes of the 3 mm long micro aramid (3.0% volume), 12mm long macro AFRP (1.75% volume) and 12mm long steel fibers (2.0% volume) is shown in Figure 2.14. The flexural stress vs CMOD curves for the different fibers shows that the AFRP macro fibers can provide high residual strengths throughout crack opening and the aramid micro fibers can increase residual strengths at low deflections and increase the pre crack strength (Uchida et al., 2010).

Zhang et al. (2017) investigated aramid microfiber at volumes up to 1.5% in concrete. The studies found that 0.5% fiber volume was able to slightly increase the compressive strength and elastic modulus of the composite, however 1.0% and 1.5% fiber volume mixtures showed decreased compressive strength and elastic modulus. The study also found that carbonation depth was slightly decreased at all fiber volumes tested (Zhang et al., 2017).

Recent studies by Chan et al. (2016), Abeysinghe et al. (2017) and Zhao et al. (2018) have described the use of a “twisted” macro Technora aramid fiber having 0.5 mm diameter and cut lengths of 30-40 mm. The appearance of these fibers is similar to that of the AFRP fibers studied by Uchida et al. (2010), however it is unclear from the descriptions in the literature if these fibers are resin impregnated AFRP. Regardless of the material, these studies found positive results with these aramid macro fibers, but they did not test the typical post crack responses that one would expect from macro fibers in concrete. Chan et al. (2016) tested 30 mm and 40 mm long Technora aramid macro fibers dispersed in concrete at 1.0% volume for their effects on the flexural response of steel reinforced concrete (RC) beams. The fibers did not significantly impact compressive strength, but the peak flexural load and toughness in the RC beams was found to increase by about 9% and 15% respectively. Fiber length did not show significant improvements to flexural results, however when compared to hooked end steel fibers, crack widths in the beams were smaller for aramid fibers up to the flexural steel rebar yield load (Chan et al., 2016). Abeysinghe et al. (2017) tested the same type of Techora fiber cut at 40 mm length for contributions to blast resistance in concrete panels. 1.0% volume of fibers was found to reduce crack widths and eliminate spalling from blast exposure (Abeysinghe et al., 2017). Zhao et al. (2018) investigated 30 mm long Technora aramid macro fibers for their effects on plastic shrinkage cracking and restrained drying shrinkage in concrete at volumes between 0.2% and 1.2%. The presence of 0.4% volume of fibers and over eliminated plastic shrinkage cracking, while the presence of 0.8% volume of fibers and over could decrease drying shrinkage strain by about 15% (Zhao et al., 2018).

Kim et al. (2018) described the use of a different type of aramid macro fiber produced using the air-textured yarn (ATY) method. These fibers consisted of 0.4 mm diameter bundles of 30 mm long aramid strands, not bound together by any resin. This is the only documentation the present author could locate describing macro aramid fibers of this type. The study tested the direct tensile behavior of mortars reinforced with 1.0% and 1.5% volume of the macro fiber and found that pseudo strain hardening and micro cracking accompanied by over 0.5% tensile strain could be achieved at 1.5% fiber volume (Kim et al., 2018).

A limitation of Aramid for use as concrete reinforcing fibers is the lack of clarity in the literature about the level of strength degradation the fibers will experience in the chemistry of the concrete environment (Johnston, 2001). Research by Uomoto et al. (1999) found that the sensitivity of aramid fibers to chemical deterioration has a correlation to the way the fibers are manufactured. The study found that aramid fibers that were acid spun (Kevlar) underwent degradation at high temperatures (80ºC) in acid, alkali and distilled water solutions. Aramid fibers that were not acid spun (Technora) had much better chemical durability in acid, alkali and especially distilled water solutions. Degradation of the Technora aramid was only an issue at high temperatures, however such temperatures would not be expected to be encountered in most concrete applications (Uomoto et al., 1999). Uomoto et al. (2002) reported that aramid fiber was capable of retaining 92%, 60%-85% and 45% of its strength after long term aging in an alkali, acidic and ultraviolet exposure environments respectively, showing good long term resistance to the chemistry of the alkali rich cement environment. Additionally, AFRP showed increased alkali resistance compared to monofilament aramid fibers. (Uomoto et al., 2002). Derombise et al. (2009) studied the alkali resistance of Technora aramid fibers and reported that although small amounts of chain degradation and finish rearrangements were noticed after alkali exposures, the fibers retain nearly all of their mechanical properties (Derombise et al., 2009). It can be deduced from these studies that aramid can be sensitive to alkali degradation, however if the fibers are not acid spun and high temperatures are not anticipated through the service life of the concrete, alkali degradation of the fibers in concrete will likely not be an issue.

The main limitation of aramid fibers for concrete reinforcement is their cost. Since aramid fibers are relatively expensive and may not provide enough additional benefit over other common concrete fibers, their applications seem to be limited. Recent works describing aramid macro fiber FRC shows promising reinforcing potential, however the literature is not descriptive of their post crack performance. Kevlar and Technora fibers can be readily purchased, however their presence seems to be sparse in the concrete fiber market.

2.5 Glass Based Fibers

For the sake of organization and simplicity in this review, glass fibers will be described very generally as fibers that are derived from naturally occurring minerals or rocks. By this definition, glass fibers are somewhere in between natural and synthetic fibers. Glass fibers are manufactured by extruding melted parent material into filament form. During the extrusion process the filaments are coated with a material called sizing, which provides the fibers with the desired surface texture and interfacial properties for the matrix within which they will be used. With regards to glass fibers used in concrete, individual sizing coated glass filaments are typically gathered into strands of around 200 filaments and cut to desired length. Depending on the production process and intended use, glass strands can be made to disperse back into their filament (micro fiber) form when in contact with water or they can be manufactured to stay in integral strand (macro fiber) form. Un-chopped strands can also be woven into rovings or textiles (ASTM C1666, 2015). Another type of macro glass fiber has recently been developed by impregnating glass strands with an alkali resistant polymer resin. This type of resin impregnated fiber follows the same concept as glass fiber reinforced polymer (GFRP) rebar, only on a smaller scale.

The two main types of glass based fibers that have been subject to adequate research as reinforcement in cement based composites include silica glass and basalt glass. Due to the chemical similarity of their parent materials, the final fiber products are also chemically similar. Basalt and silica glass contain high amounts of silicon dioxide (typically 40% to 70%) depending on the composition of the parent material. The main difference between basalt and silica glass fibers is that basalt glass fibers tend to have significant levels of iron, potassium, magnesium and sodium oxides while silica glass fibers typically have low levels of these oxides but can contain significant levels of boron oxides (Deák & Czigány, 2009).

Although their production methods are similar, typically the production of silica glass fibers involves the use of additives to improve the physical properties of the fiber. Basalt glass fiber production does not typically require additives, however this results in less consistent fiber properties in the finished product. On the other hand, basalt fiber production is usually a simpler process since additives are not usually necessary which typically makes basalt glass fiber less expensive than silica glass fiber. (Fiore et al., 2015). Generally, basalt glass fiber has higher strength and elastic modulus than silica glass fiber as shown in Table 2.1, however these features are highly dependent on the parent material and manufacturing conditions.

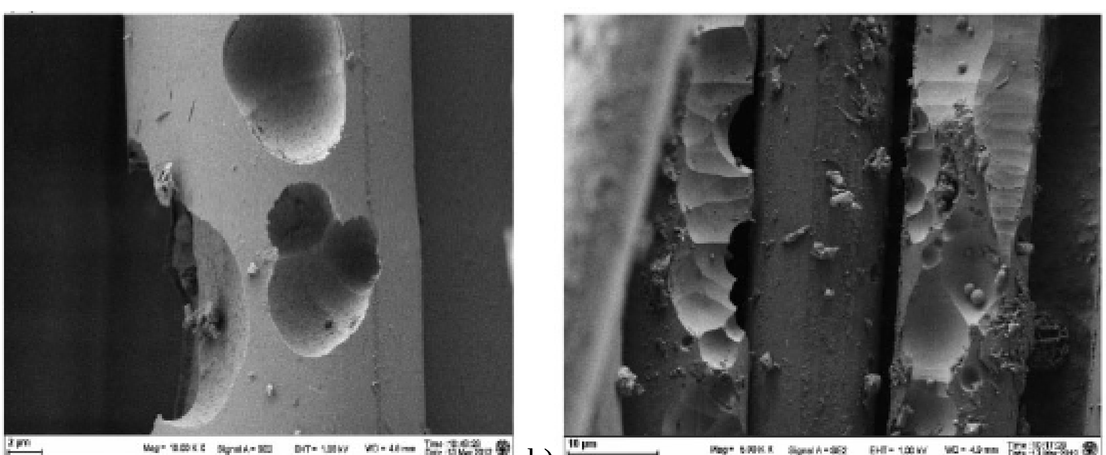
a) b)


Figure 2.15 *SEM images of glass fibers after alkali exposure a) Silica (E) glass b) Basalt glass (Wu et al., 2015)*

Despite attractive mechanical properties, the main limitation of glass fibers in cement based composites is their chemical sensitivity to alkaline environments. Alkali degradation of non-alkali resistant glass fibers have been well documented for a number of years (Larner et al., 1975, Uomoto et al., 1999, Wu et al., 2015). Wu et al. (2015) studied the durability of basalt and silica glass fibers after exposure to acid, alkali and salt solutions. The study found that both basalt and silica glass fibers underwent full deterioration and retained none of their strength after alkali and acid exposure. Both fibers showed better resistance to salt solutions, however around 40% strength loss was reported. The alkali deterioration was characterized by pitting on the fiber surface as shown in Figure 2.15, which sacrifices the effective cross section and associated strength of the fibers. This showed that the deterioration mechanism of basalt and silica fibers in concrete is very similar due to their alike chemical composition (Wu et al., 2015).

The degradation of non-alkali resistant glass fiber under alkali exposure results in a complete loss of strength and ductility over time. In order to combat the degradation of glass fibers, zirconium oxides can be added to the glass fiber production process to produce alkali resistant (AR) glass fibers. The degradation prevention mechanism provided by the presence of zirconium oxides in glass fibers can be explained by the fact that some of the silicon dioxide components in the molecular chain are replaced by zirconium dioxide components. The Zr-O bonds in the molecular chain are stable under alkali attack, in contrast to the Si-O bonds, which break in the presence of hydroxides. As a result of the Zr-O stability, the molecular structure remains stable as the Si-O bonds are broken down and extracted by hydroxide ions. This action leads to a zirconium dioxide protective layer on the exposed fiber surface which serves as a diffusion barrier to prevent further fiber break down (Bentur & Mindess, 2006). Adding zirconium oxides to glass fibers has become common practice for the modification of silica glass fibers used in the cement and concrete industry. AR basalt glass fibers have been subject to far less research and are less common, however they do exist in limited studies (Lipatov et al., 2015).

Despite the increased stability in alkali environments of AR glasses, there is sufficient evidence that AR glass fibers will undergo some level of strength degradation in concrete. This will be discussed separately for basalt and silica glass.

2.5.1 Silica Glass

The first type of glass fibers to be used as concrete reinforcement was E glass or (electrical grade) glass. E glass was originally developed for use in electrical applications. The material was found to have good mechanical properties and was then tested for use as fiber reinforcement in polymer matrices and eventually cementitious matrices. Due to the well accepted and previously described degradation of glass fibers in concrete, AR glass fibers were developed. Subsequent research related to FRC focused on the level of alkali resistance provided by these fibers. AR silica glass fibers have relatively high tensile strength and elastic modulus compared to most synthetic or natural fibers (Table 2.1).

The most common application of AR glass concrete fibers is thin sheet components for exterior façade panels (ACI 544.1R-96, 2009). This type panel is typically made from paste or mortars that include high fiber volumes using shotcrete or spray up placing techniques for non-structural applications (Jones & Lutz, 1977). Due to the use of AR glass fibers primarily as thin sheet components using mortar matrices, AR glass textile concrete has been developed where two or three dimensional woven glass fabrics are cast into mortars using a lay-up technique to produce several layers of continuous aligned glass fiber reinforcement (Orlowsky et al., 2005).

Although less common, AR glass can be used in concrete made with conventional mixing techniques. It has been reported that high fiber volumes are difficult to achieve when using glass fiber filaments in concrete with conventional mixing techniques because AR glass fibers tend to disperse into the matrix unevenly and additional mixing or an increase in water to cement ratio is required (Bentur & Mindess, 2006). Additional mixing often will damage the fibers and compromise their long term performance (Johnston 2001). It should be kept in mind that the effect of AR glass fibers on the workability of conventionally mixed concrete is highly dependent on the aspect ratio and surface area of the fibers which is drastically increased for filament strands compared to integral strands. Studies by Ghugal et al. (2006) were contradictory to generally accepted limitations in the fresh state for AR glass FRC. AR glass micro fiber volumes up to 4.5% were mixed into composites containing coarse aggregate with no reported mixing difficulties although the type of mixing equipment was not specified. A relatively high water to cement ratio of 0.51 was used in the study to increase workability however there was no report of water reducing admixture use, making the reported volumes (especially for micro fiber) rather striking. In this study, 0.5” long AR glass micro fibers dispersed at increasing volumes increased the 28 day compressive, flexural, split tensile and rebar bond strength of FRC compared to plain control specimens (Ghugal et al., 2006).

Kizilkanat et al. (2015) compared silica and basalt glass micro fibers for their contributions to strength and fracture properties of concrete. The study found that performance was similar for both types of fiber, due to the similar chemical, physical and mechanical properties of the fibers. Compressive, split tensile, and flexural strengths as well as toughness and elastic modulus all increased with increasing fiber content (Kizilkanat et al., 2015).

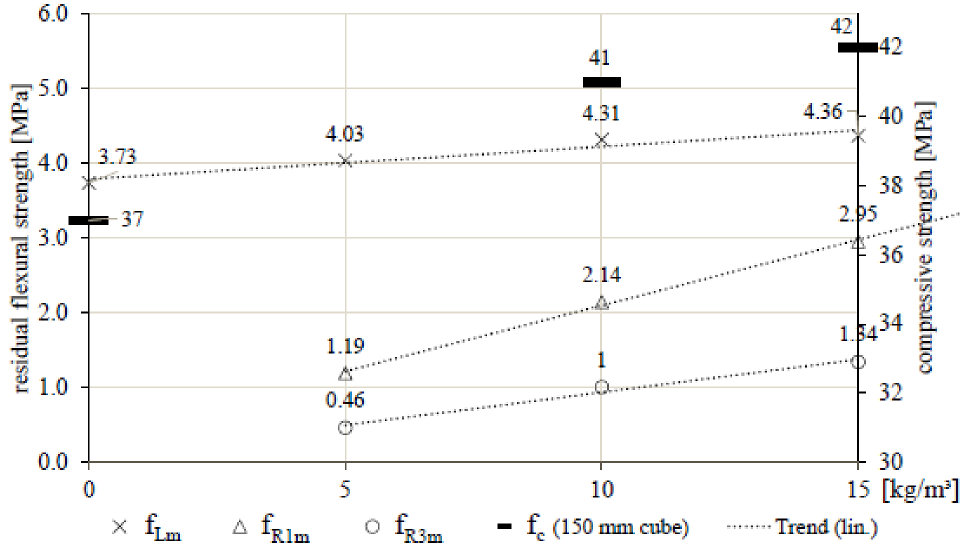


Figure 2.16 *Flexural residual strengths at first crack (f_{Lm}) 0.5mm (f_{R1m}) and 2.5mm (f_{R3m}) crack opening displacements and compressive strengths at different fiber doses (Löber et al., 2015)*

Löber et al. (2015) performed flexural Crack Mouth Opening Displacement (CMOD) tests on AR glass macro fiber reinforced concrete to identify the residual strengths provided by the fibers at increasing crack opening displacements. The integral strand fibers used in the study were quite large for AR glass fibers, measuring 36mm long and 0.54 mm in diameter. Fiber volumes of roughly 0.2%, 0.4% and 0.6% were tested. The study found that composite strength was increased with increasing fiber volume as were residual strengths, especially at low crack openings due to the high elastic modulus and good fiber matrix bond properties of the fibers as shown in Figure 2.16. Strain softening behavior was observed, however reasonable residual strengths at higher crack openings could be achieved (Löber et al., 2015).

It is generally accepted that silica AR glass fibers lose some of their reinforcing effectiveness over time in cementitious matrices due to the previously explained chemical sensitivity to the alkaline cement environment. AR glass typically contains between 16% and 20% zirconia to help the fibers resist alkali attack. In addition, the application of sizing to the fiber surface during production can increase alkali resistance (Gao et al., 2002, Scheffler et al., 2009). Various research efforts have been conducted on AR glass fibers to determine the extent of the long term degradation in the cement environment (Shah et al., 1988, Anon, 1979). Based on the literature, AR glass FRC loses strength and ductility in tension and flexure as time progresses in natural weathering, underwater and accelerated aging environments. The strength loss depends on pH value, temperature, and chemical composition of the AR glass and concrete material as well as the exposure condition (Orlowsky et al., 2005, Orlowsky & Raupach, 2006, Orlowsky & Raupach, 2008).

Table 2.3 *Property requirements of AR glass fibers as per ASTM C1666 (ASTM C1666, 2015)*

Property	Specification Value	Method of Test
Zirconia content (ZrO_2)	16 % min	X-ray fluorescence[A]
Density	2.68 ± 0.3 g/cm^3 [167.0 ± 19 lb/ft^3]	ASTM D3800
Tensile Strength	1.0–1.7 Gpa [145 × 10^3–246 × 10^3 psi]	ASTM D2256, ISO 3341, JISR 3420
Range of Filament Diameters	8–30 µm [31× 10^{-5}-118 × 10^{-5} in.]	ASTM D578, ISO 1888, JISR 3420
Roving tex	±10 % of manufacturer's nominal	ASTM D1577, ISO 1889, JISR 3420
Strand length	±3 mm [±0.118 in.] of manufacturer's nominal	Caliper—Average of 20 measurements
End count	±20 % of manufacturer's nominal	Physical count
Loss on ignition	<3 %	ASTM D4963, ISO 1887, JISR 3420
Strength retention	Minimum value after 96 ± 1 h in water at 80 ±1°C [176 ± 2 °F] ≥250 MPa [36 250 psi] for water dispersible strands ≥350 MPa [50 750 psi] for integral strands	EN 14649

The ASTM C1666 (2015) standard includes minimum specifications for AR glass fibers to be used in cementitious matrices (Table 2.3). As can be seen from the table, minimum strength retention values after four days in hot water are only 25% for water dispersible strands and 35%

for integral strands when considering the lower bound of 1.0 GPa as the original fiber tensile strength. This lack of stringency in the standard shows that AR glass fiber strength degradation can be relatively large but the fibers are still considered alkali resistant (ASTM C1666, 2015).

In order to help improve the long term performance of AR glass fiber reinforced concrete, Song et al. (2015) investigated modifying the binder with partial replacement of ordinary portland cement with calcium sulfoaluminate cement. The study found that the proposed method greatly improved the long term performance of the composites. After 10 years of aging, the modified composites retained substantial ductility compared to control specimens, which showed no post crack residual strengths after 10 years of exposure (Figure 2.17). This study shows that if proper mixture design considerations are utilized, glass fiber degradation can be substantially decreased (Song et al., 2015).

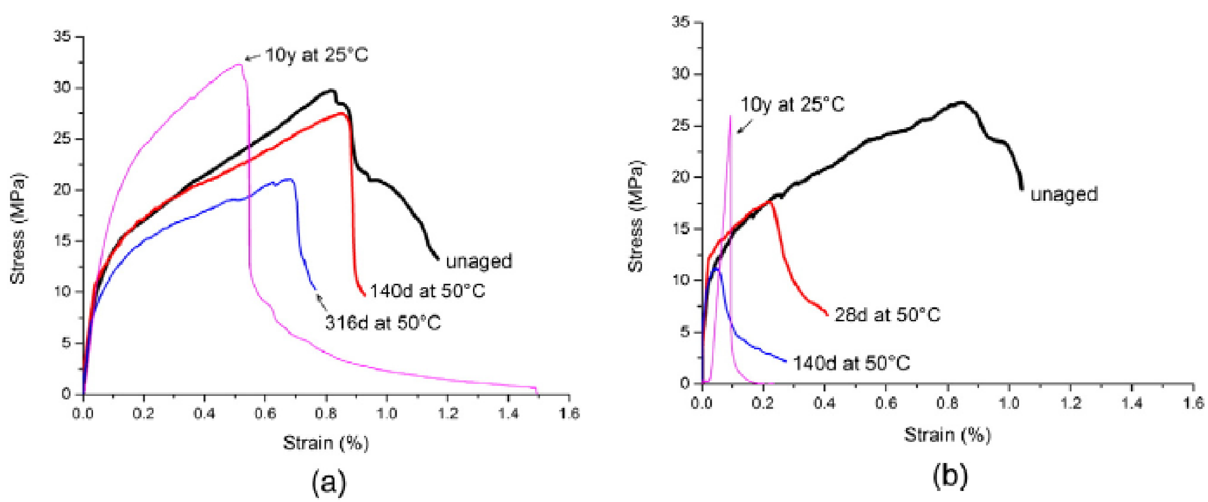


Figure 2.17 *Bending stress-strain curves for glass fiber reinforced mortar a) binder modified with calcium sulfoaluminate cement b) ordinary portland cement binder (Song et al., 2015)*

In addition to the methods of adding zirconium to the chemical structure of glass, applying alkali resistant sizing to the filament surface during production, or changing the chemistry of the concrete matrix, glass fiber strands can be impregnated with alkali resistant and surface bonding resins like epoxy and vinyl ester to improve long term durability. These types of polymer impregnated glass fibers are made into macro concrete fibers and can be considered glass fiber reinforced polymers (GFRP). These macro GFRP fibers are relatively new to the concrete construction market and are essentially miniature versions of glass fiber reinforced polymer rebar. The alkali degradation of GFRP macro fiber is not well described in literature, however due to the similarities that these fibers share with GFRP rebar, research describing the durability of GFRP rebar can cautiously be extrapolated to describe the long term durability of GFRP macro fibers for the sake of this review.

Studies based on accelerated aging techniques have reported concerns about the durability of GFRP rebar in concrete. Significant amounts of degradation have been reported by studies that utilized high temperature exposure and aggressive chemical environments to characterize strength loss (Benmokrane et al., 2002, Micelli & Nanni, 2004, Sayyar et al., 2013). These studies and others sparked major concerns in the reinforced concrete industry about the level of safety provided by structures that use GFRP as primary reinforcement.

These concerns were followed up by several case studies and critical reviews in order to characterize the level of GFRP strength degradation for in service structures (Nkurunziza et al., 2005, Mufti et al., 2007, Gooranorimi et al., 2017). These efforts found that the reported degradation from accelerated aging tests on GFRP products largely overestimated the actual level of degradation in the field. Several case studies reported little to no GFRP rebar degradation for in service structures due to the effective protection from the polymer resin. The studies also concluded that the accelerated aging results that sparked these research efforts were not representative of in-situ concrete because of elevated temperatures and the un-realistic scenario of an unlimited supply of hydroxyl ions. (Mufti et al., 2007). These studies reveal that the issue of alkali deterioration in GFRP products can be mostly avoided due to the effective protection of the glass fibers from resin impregnation.

AR GFRP macro fibers have only very recently been manufactured and therefore there is a lack of studies specific to their contributions to the mechanical properties of FRC. Basalt GFRP macro fibers of nearly identical geometric and mechanical properties have been subject to far more research in this regard and will be discussed in the basalt glass fiber section (5.2).

The literature reviewed shows that AR glass fibers are able to markedly improve short term strength and ductility parameters of concrete, as expected, due to their relatively high strength and stiffness. There are inconsistencies in the reported workability of AR glass mixes but this can be contributed to the fact that the fibers can come in a wide range of sizes and corresponding surface area per unit volume. Degradation of AR glass in concrete is obviously a concern, however with adequate zirconia content, proper sizing application, concrete binder adjustments and even polymer impregnation, AR glass fibers can retain adequate strength to be effectively used as concrete fibers in a diverse range of applications. AR glass fibers are very common and widely available in the concrete market. Generally the cost of AR glass fibers is relatively low.

2.5.2 Basalt Glass

Basalt glass fibers were developed in the early 1900's but did not receive much attention until the 1960's when the US and Soviet Union began extensive research on the fiber primarily for military applications. In the 1970's research and development of basalt fibers was primarily performed in the Soviet Union as U.S. glass fiber manufacturers focused their efforts on silica glass. Upon the break-up of the Soviet Union in 1991 the once classified research and development on basalt glass fibers was made public and sparked new research for basalt glass worldwide. In recent years basalt glass has become a hot topic of research in the fiber concrete industry (Jamshaid et al., 2016). Basalt glass fibers typically have higher elastic modulus and tensile strength than silica glass fibers, which are shown in Table 2.1. Basalt glass fibers are produced in a similar process as silica glass fibers therefore their sizing coated filaments can also be manufactured into similar products as silica glass, including water dispersible strands, integral strands, rovings and textiles. The recent popularity of basalt concrete fibers has provided abundant literature on their contributions to the properties of fresh and hardened FRC.

With regards to chemical durability, basalt fibers show similar alkali degradation levels to that of E glass fibers (Wei et al., 2010, Wu et al., 2015). Due to this limitation in cementitious environments, AR basalt fibers have been developed. Mingchao et al., (2008) was one of the earliest reports of the use of AR basalt fibers. The study tested the chemical resistance of the fibers by boiling them in distilled water, salt solution and acid solution. The authors found that the AR basalt fibers underwent strength and stiffness degradation in acid solution, however in alkali solution their stiffness was mostly maintained but their strength underwent gradual decline (Mingchao et al., 2008).

Rybin et al. (2013) studied the alkali resistance and mechanical properties of basalt fibers coated with zirconyl chloride octahydrate. The study found that the surface coated fibers underwent delayed strength degradation under alkali exposure and surface coating thickness and density was a direct factor in the level of degradation (Rybin et al., 2013).

Lipatov et al., (2015) investigated the additions of zirconium oxides to basalt fiber during the manufacturing process, similar to the process used to make AR glass. The study found that the solubility limit of zirconium in basalt glass was 7.1%, much less than that of silica glass. Despite the inability to reach high zirconium content during manufacturing, the AR basalt glass fibers with

5.7% zirconium content showed similar alkali degradation in terms of weight loss compared to AR silica fibers with 18.8% zirconium content. The strength degradation of the AR basalt glass fibers was substantially higher than that of the AR silica glass fibers, however the compressive, tensile and flexural strengths of the hardened mortars prepared with the optimal zirconium content basalt fibers was similar to that of the mortars prepared with AR silica glass fibers (Lipatov et al., 2015).

The relatively high mechanical properties of chopped (filament or strand) basalt fibers should make them conducive to increasing the strength parameters of concrete. This feature is limited for long term strengths by the previously discussed strength loss in the highly alkali concrete matrix. As a result, strengthening and crack control with chopped basalt fibers should only be relied upon at early ages and they may be somewhat limited to applications in young concrete like early strength and plastic shrinkage crack control. Regardless of these limitations, several recent studies have reported the mechanical properties of basalt microfiber reinforced concrete.

Ayub et al. (2014) studied the additions of high volumes (up to 3.0%) of basalt microfibers to concrete on compressive and splitting tensile strength as well as elastic modulus. It should be noted that this is a very high microfiber content but slump values between 40 and 60 mm were achieved, showing that with proper mix design and admixtures as well as a high energy mixer, it is possible to pack high volumes of micro glass fiber into concrete containing coarse aggregate. The study found that increasing fiber volume had no effect on the hardened composite modulus of elasticity or compressive strength, but significantly increased the split tensile strength, especially at 3.0% fiber volume and when supplementary cementitious materials replaced a portion of the Portland cement (Ayub et al., 2014).

The satisfactory workability reported by Ayub et al. (2014) for high volume basalt microfiber mixtures does not follow the general trends in the literature in the sense that other studies involving basalt microfibers do not involve fiber volumes over 0.5%. Additionally, Patnaik et al. (2014) reported that basalt microfibers do not tend to mix well at high volumes with common mixing equipment, likely due to the high surface area of the fibers (Patnaik et al., 2014).

Yang et al. (2011) found that chopped water dispersible strand (micro) basalt fibers dispersed in FRC at 0.3%-0.5% volume and aspect ratio of 600 to 800 was an optimal for increasing compressive, splitting tensile and flexural strength parameters of normal concrete. At optimal fiber volumes, the authors found that strength parameters increased compared to control specimens up to 56 days of age. This is an interesting result since it indicates that fiber degradation did not seem to be a factor in the study (Yang et al., 2011).

Kabay et al. (2014) found that micro basalt fibers of 12 and 24 mm length dispersed at low volumes (2 and 4 kg/m^3) actually decreased compressive strength with increasing fiber volume for both normal and high strength concrete. Flexural strength was slightly increased with increasing fiber volumes, while fracture energy and abrasion resistance were significantly increased (Kabay et al., 2014). Similarly, Jiang et al., (2014) tested low volumes (0.05%, 0.1%, 0.3% and 0.5%) of 12 mm and 24 mm micro basalt fibers for their effects on the strength properties of concrete. The authors found that splitting tensile and flexural strengths were increased substantially, with 0.3% volume showing the best results and longer fibers outperforming the shorter fibers. Compressive strengths were not significantly affected by fiber addition (Jiang et al., 2014).

Similar to AR silica glass fiber, in recent years filaments of basalt glass fiber have been impregnated with alkali resistant polymer resins to create basalt fiber reinforced polymer BFRP macro fibers. The same conversation presented in the silica glass fibers section of this review about long term durability of GFRP fibers in the cement chemistry applies to BFRP fibers. There is a lack of studies referring to the durability of BFRP macro fibers specifically, however BFRP has been shown to lose strength over time in accelerated aging tests (Mingchao et al., 2008, Wu et al., 2015). In-situ BFRP could be expected to retain its strength similar to studies performed on in-situ GFRP as shown by (Nkurunziza et al., 2005, Mufti et al., 2007, Gooranorimi et al., 2017). It is fair to cautiously make this extrapolation due to the fact that the same alkali resistant polymer resins are used to impregnate both GFRP and BFRP.

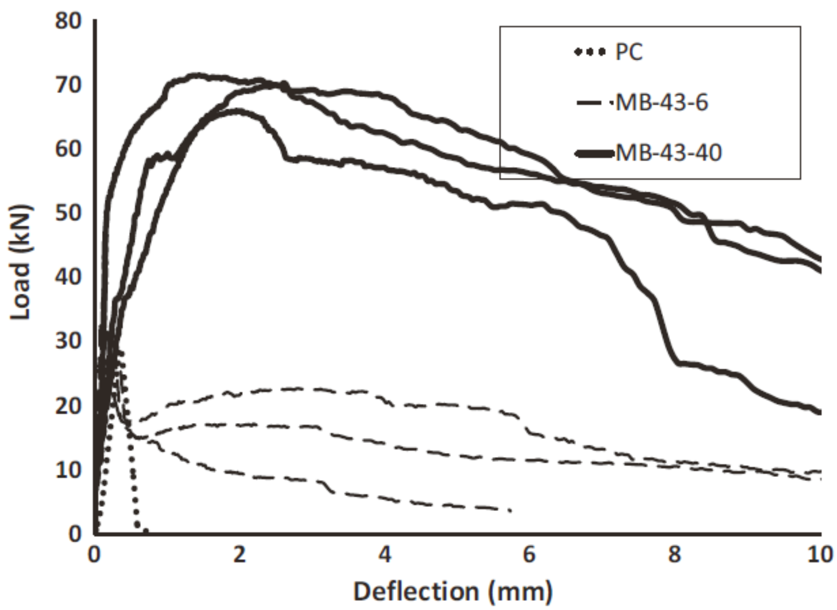


Figure 2.18 *Flexural results for BFRP macro fiber for control specimen (PC), 0.3% fiber volume (MB-43-6) and 2.0% volume (MB-43-40) (Branston et al., 2016)*

BFRP macro fiber has been subject to numerous recent research efforts and have shown the ability to perform very well with regards to post crack residual strength, toughness and ductility in FRC. Because basalt fibers have a density that is relatively similar to that of the concrete matrix, BFRP macro fibers are reported to mix in concrete well at relatively high volumes using conventional mixing techniques compared to most other fibers (Patnaik et al., 2013). These fibers have been reported to mix well at volumes up to 4.0% in a regular concrete mixture with 20mm maximum sized aggregate (Patnaik, 2013, Patnaik et al., 2014). In a separate study using a different mixture design, BFRP fibers were reported to clump at 2.0% volume however no superplasticizer was used in that study (Branston et al., 2016). For SCC utilizing maximum aggregate size of 16 mm, it has been reported that BFRP macro fibers with an aspect ratio of 65 are detrimental to flowability at volumes over 1.15%, likely due to the stiffness and size of the fibers (Mohaghegh, 2016). Dopko et al. (2018) reported that BFRP macro fibers had minimal effects on workability and were much easier to disperse in concrete than PP or PVA fibers at volumes up to 1.5% (Dopko et al., 2018).

Branston et al. (2016) investigated the effectiveness of chopped basalt filament micro fiber bundles compared to BFRP macro fibers and concluded that filament basalt fibers can increase pre-cracking flexural and compressive strengths in concrete and the BFRP fibers decreased compressive strength and increased flexural strength at higher volumes as well as improved the post-crack flexural performance. When 2.0% volume of 43 mm long BFRP macro fibers were tested under flexure, impressive post crack performance characterized by high ultimate strength, high residual strengths, and initial post crack strain hardening followed by gradual strain softening at high deflections as shown in Figure 2.18 (Branston et al., 2016).

Extensive studies performed on BFRP macro fibers were described by Adhikari (2013). Among many interesting results presented, it was found that the ratio of the average post crack residual strength to the first crack strength could reach 0.75 with 2.0% fiber volume and as high as 1 with a fiber volume of 4%, showing that high volumes of BFRP fibers can provide very high post crack performance in concrete (Adhikari, 2013).

Patnaik et al., 2014 reported that BFRP macro fibers increased the flexural strength of concrete with increasing fiber content and provided large post crack residual strengths, also increasing with fiber content (Patnaik et al., 2014). BFRP macro fibers have been shown to control concrete crack widths better than high tenacity macro PP fibers in beams subject to accelerated corrosion and tested in flexure due to their increased stiffness and good bond properties between the impregnating resin and concrete matrix (Patnaik et al., 2013).

Dopko et al. (2018) compared BFRP, PP and PVA macro fibers in concrete at 0.5%, 1.0% and 1.5% volume for their contribution to flexural strength and toughness. The study found that the modulus of rupture was only slightly influenced by fiber type or volume dose, however the BFRP fibers outperformed PP and PVA fibers in residual strength and toughness at all volumes tested (Dopko et al., 2018).

Patnaik et al. (2017) investigated the addition of low fiber volumes of BFRP macro fibers and high tenacity PP fibers to continuous structural slab bridge decks for their effects on crack control and failure behavior. The study found that BFRP macro fibers were more effective at controlling crack widths and increasing ductility than the PP macro fibers. BFRP macro fibers could decrease crack widths on average 43% and 37% for uncoated steel and epoxy coated steel rebar reinforced decks respectively (Patnaik et al., 2017).

The high level of recent attention toward basalt fibers has exposed basalt micro fibers as effective for increasing early flexural and tensile strength and reducing plastic shrinkage cracking of concrete. BFRP macro fibers have shown large potential as effective post crack performance and crack control. These products are anticipated to gain popularity in the concrete market as production increases and unit production cost decreases. Basalt microfibers are available from a number of concrete fiber vendors. BFRP macro fibers are somewhat less popular in the market to date, however they are available from select vendors.

2.6 Natural Fibers

Natural fibers that warrant consideration for concrete reinforcement can be described in general as cellulosic fibers that are produced within the organic tissue of plants. These cellulosic fibers make up the "structural" component of plants, meaning they provide the strength and stiffness that plants need to keep their shape and integrity under their own weight as well as applied loads like wind and precipitation.

Table 2.4 *Properties of select natural fibers (ACI 544.1R-96, 2009)*

Fiber type	Coconut	Sisal	Sugar cane Bagasse	Bamboo	Jute	Flax	Elephant grass	Water reed	Plantain	Musamba	Wood fiber (kraft pulp)
Fiber length, in.	2-4	N/A	N/A	N/A	7-12	20	N/A	N/A	N/A	N/A	0.1-0.2
Fiber diameter, in.	0.004-0.016	N/A	0.008-0.016	0.002-0.016	0.004-0.008	N/A	N/A	N/A	N/A	N/A	0.001-0.003
Specific gravity	1.12-1.15	N/A	1.2-1.3	1.5	1.02-1.04	N/A	N/A	N/A	N/A	N/A	1.5
Modulus of elasticity, ksi	2750-3770	1880-3770	2175-2750	4780-5800	3770-4640	14,500	710	750	200	130	N/A
Ultimate tensile strength, psi	17,400-29,000	40,000-82,400	26,650-42,000	50,750-72,500	36,250-50,750	145,000	25,800	10,000	13,300	12,000	101,500
Elongation at break, percent	10-25	3-5	N/A	N/A	1.5-1.9	1.8-2.2	3.6	1.2	5.9	9.7	N/A
Water absorption, percent	130-180	60-70	70-75	40-45	N/A	N/A	N/A	N/A	N/A	N/A	50-75

Note: N/A = properties not readily available or not applicable.
Metric equivalents: 1 in. = 25.4 mm; 1 ksi = 1000 psi = 6.895 MPa

Due to the diversity of different plant species, natural fibers can exhibit a wide range of properties depending on their source. Within the realm of natural fibers used in concrete, only fibers that exhibit sufficient strength and dimensional properties are considered. Types of natural fibers that have been subject to testing in cementitious matrices include; hardwood, softwood, jute, hemp, sisal, banana, coconut, palm, kenaf, ramie, pineapple, maguey, lechuguilla, curaua, piassava, cotton, flax, wheat, barley, bamboo, elephant grass, water reed, plantain, musamba, sugar cane (bagasse) and others (ACI 544.1R-96, 2009, Ardanuy et al. 2015, Ferrara et al. 2017). Properties of selected natural fibers can be found in Table 2.4. The three most common forms of natural fibers that have been used in cement based composites include strand, staple and pulp fibers as shown in Figure 2.19 (Ardanuy et al. 2015). Strand and staple fibers are relatively large and harvested from plants typically without altering the fiber structure while pulp fibers are a product of the paper industry and can have certain components of the original fiber structure removed.

Figure 2.19 *a) Strand Fibers, b) Staple Fibers, c) Pulp Fibers (Ardanuy et al. 2015)*

Natural fibers are not typically utilized in concrete mixtures containing coarse aggregate because in order for the fibers to act as effective reinforcement they must be added at volumes that are not practical for FRC (>4.0%). The most common types of natural fiber cement based composites are thin mortar sheet components containing pulp fibers cast using the Hatschek process or a slurry vacuum de-watering casting procedure. Since these casting processes can facilitate very high fiber volumes (around 10%), fiber reinforced cementitious composites can initially exhibit reasonable strain capacity in tension and flexure because of strain hardening and multiple cracking behavior. Some studies have successfully made highly ductile strain hardening mortars that exhibit multiple cracking with long, continuous and aligned natural fibers cast with high fiber volumes using a hand lay-up technique (Toledo Filho et al. 2009, Toledo Filho et al. 2003, de Andrade Silva et al. 2009). Figure 2.20 shows the typical flexural response of natural pulp fiber composites compared to natural continuous aligned strand fiber composites. Recent exhaustive reports have been produced on the application of natural fibers in cement based composites (Ferara et al 2017, Ardanuy et al 2015), however the present report is intended to provide a less extensive, baseline review of the topic.

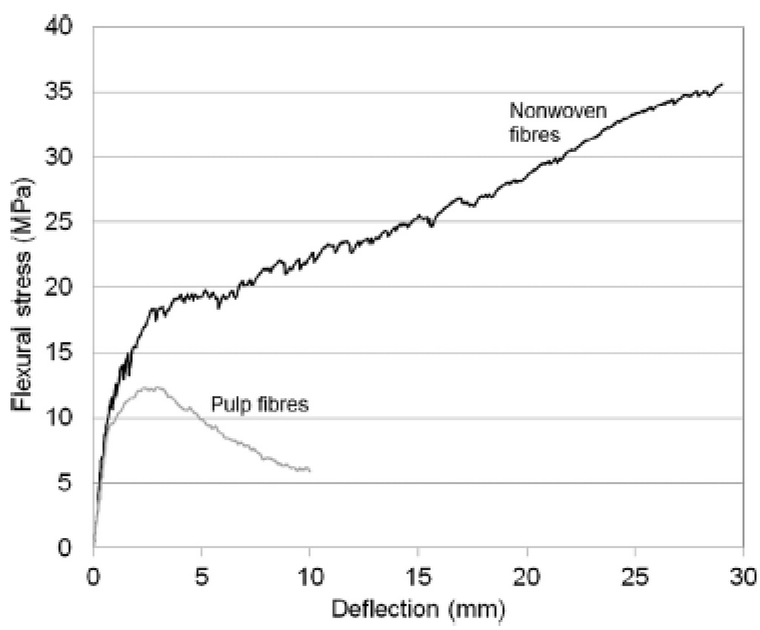


Figure 2.20 *Flexural response of continuous nonwoven strand fiber composites vs. randomly dispersed pulp fiber composites prior to degradation (Ardanuy et al. 2015)*

The main attractions for using natural fibers in concrete has to do with their relatively low cost, wide range of mechanical and physical properties, sustainability and local availability, especially in less developed countries. These attractive qualities are offset with certain limitations that have inhibited the widespread use of natural fibers in FRC. These same limitations have given rise to many research efforts aimed at identifying and mitigating them.

The main limitation of natural fibers in concrete is that they undergo degradation and embrittlement in the alkali rich cement environment. This degradation is relevant for all types of natural fiber, however the mechanism of degradation can change based on the form and composition of the fiber. Although the degradation mechanisms for processed pulp fibers and unprocessed strand or staple fibers are slightly different, they are caused by the same culprits – volumetric instability through water absorption and alkali sensitivity causing mineralization of the fibers.

A detailed description of the degradation mechanisms observed in natural large strand fibers can be found in de Almeida Melo Filho et al. (2013). This mechanism is applicable to natural staple fibers as well since both strand and staple fibers are not typically altered at a cellular level from industrial processes. Similar research describing the degradation mechanism of natural pulp fibers is described by Mohr et al. (2006). In related work, Mohr et al. (2005) quantified the ductility loss characterized by flexural load vs. deflection curves for wood pulp fibers subject to multiple wetting and drying cycles as shown in Figure 2.21 (Mohr et al., 2005). Due to the mechanisms of degradation identified in these works and others, research has focused on ways to mitigate the degradation of natural fibers has focused on two approaches, the first being the modification of the fibers for improved volumetric and chemical stability and the second being the modification of the cementitious matrix chemistry to provide a less reactive environment for fiber mineralization.

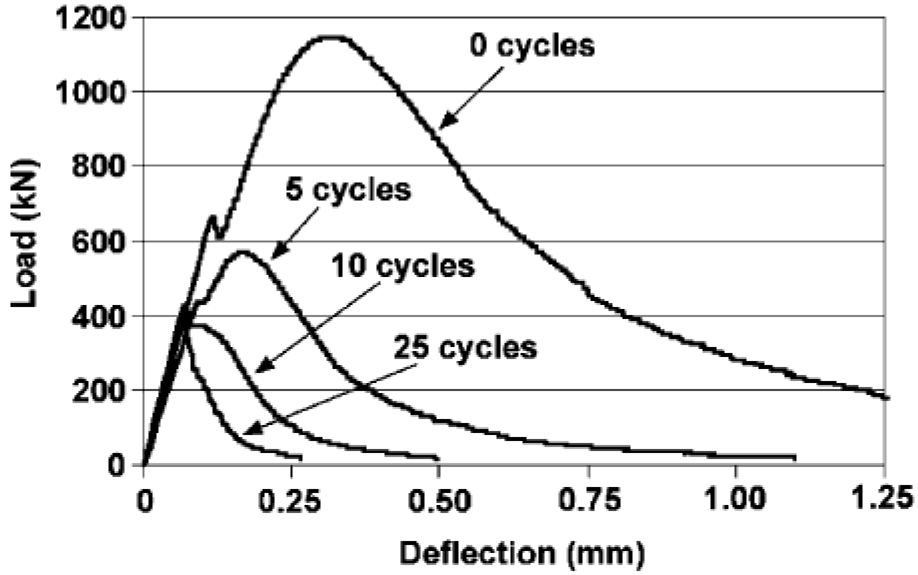


Figure 2.21 *Load - Deflection curves for pulp fiber composites subject to wet-dry cycles (Mohr et al. 2005)*

A fiber treatment technique called fiber hornification can be used to effectively increase the volumetric stability of natural fibers. This method involves the repeated wetting and drying of the fibers prior to dispersion in the cementitious matrix. After aging, flexural strength increases of up to 13% and 21% have been reported for kraft pulp fibers and cotton linters respectively after hornification (Claramunt et al. 2011). Similarly, the pullout resistance increased by roughly 45% while the tensile strain at failure of the hardened composite increased by 39% after hornification of strand form sisal fibers (Ferreira et al. 2014).

Another reported natural fiber treatment technique is to immerse the fibers in a silica fume slurry before placement in the cement matrix. This method is reported to significantly improve the long term strength and toughness of the hardened composite by controlling the level of alkalinity at the fiber-matrix interface (Toledo Filho et al. 2003). More recently, thermal treatment and sodium carbonate surface treatment of sisal fibers has been reported to improve the durability of hardened fiber composites by over 30% and 45% respectively (Wei & Meyer, 2014).

The cement matrix can be modified to reduce the alkalinity and associated natural fiber degradation by reducing the amount of the hydration product calcium hydroxide. This can be achieved by utilizing the reaction between pozzolanic materials and calcium hydroxide to form calcium silicate hydrate gel as well as reduce the pH of the pore water within the matrix. Several studies have explored this method of mitigating natural fiber degradation with different types of natural fibers and pozzolans utilizing different cement replacement rates. Results show strong evidence that low calcium hydroxide content and pH values can significantly reduce or in select cases (Toledo Filho et al. 2009) eliminate the embrittlement of fibers over time (Mohr et al. 2007, Toledo Filho et al. 2003).

Despite the shortcomings of natural fibers in cement based composites, it is obvious that the material has sufficient upside to justify numerous extensive research efforts. With fiber degradation mechanisms that are well established and the development of effective methods to mitigate fiber degradation, it is likely that the use of natural fiber cement based composites will grow in coming years if the technology can continue to advance.

2.7 Hybrid Fiber Systems

The benefits of adding fiber to concrete cover a wide range of mechanical and durability related properties due to the diversity of available fiber material types and geometries coupled with the dependence of composite properties on these factors. Fiber hybridization is the technique of maximizing and combining the benefits of fiber addition in an effective way (Chasioti & Vecchio, 2017). The two most common categories of fiber hybridization include hybridization based on fiber mechanical properties and hybridization based on fiber dimensions.

With respect to hybridization by mechanical properties, it is common to include a combination of high and low elastic modulus fibers. This allows the stiffer fibers to contribute to crack bridging under lower strains while the more flexible fibers contribute at higher strains. This response for steel and PP macro fiber hybrid mixes was studied by Deng & Li (2006). They found that residual strengths characterized by flexural load-deflection curves were higher at large deflections for hybrid mixes containing a higher volume fraction of PP fibers. In contrast, hybrid mixes containing a higher volume of steel fibers showed higher residual strengths at lower deflections (Deng & Li, 2006).

Alberti et al. (2014) investigated hybrid self-consolidating FRC with low volumes of macro hooked end steel and embossed surface polyolefin fibers. This study showed strong fiber synergy in hybrid mixes. This was characterized by the hybrid mixes showing increased residual strengths at higher deflections that could not be produced by mono-fiber mixes. The study also concluded that small volume additions of steel fiber was able to improve the crack stability at low deflections soon after the specimen had cracked compared to mixtures containing synthetic fibers only, which showed a large sudden drop in residual strength immediately after crack formation. (Alberti et al. 2014). In similar research, Alberti et al. (2017) showed that macro hooked end steel and embossed surface PO fiber hybrid blends provided post crack responses that were similar but slightly improved compared to the algebraic sum of the post crack responses of mono fiber mixtures of the same fiber volumes in different specimens tested separately (Figure 2.22) (Alberti et al., 2017).

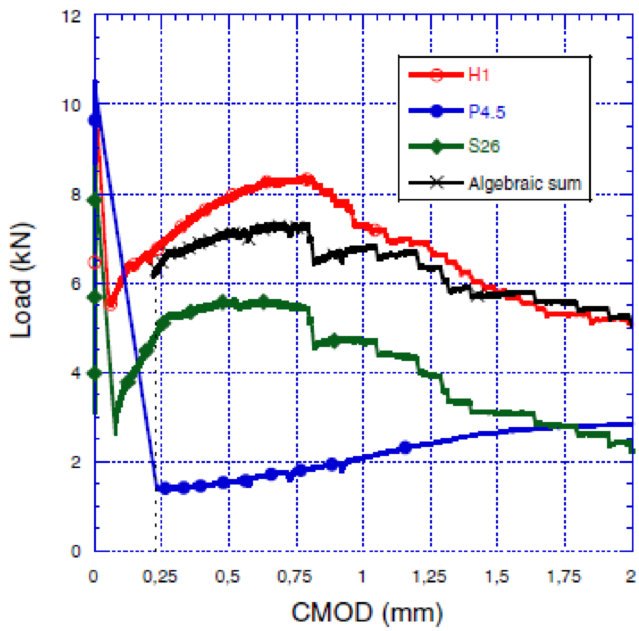


Figure 2.22 *Load-CMOD curves for mono and hybrid steel and PO fiber mixtures (Alberti et al., 2017)*

FRC mixtures hybridized by fiber dimensions contain two or more types of fibers that have similar mechanical properties but different dimensions. Often these types of mixtures are blends of macro and micro fibers. Although not always the case, and depending on the performance criteria of the mixture, due to the associated mixing difficulties with high surface area and number of fibers per unit volume of micro fibers, these types of hybrid mixtures most often contain proportionally higher volumes of macro fibers than micro fibers.

Chasioti and Vecchio, (2017) investigated the use of binary blends of macro and micro steel fibers in FRC. They found that although peak compressive and tensile strengths were not significantly affected by hybridization, flexural strengths were increased. Additionally, peak compressive strain, initial compressive stiffness, and post peak compressive and flexural toughness were enhanced in hybrid mixtures. It was deduced by the authors that the presence of micro-fibers increased the pullout resistance of the macro-fibers, resulting in increased toughness (Chasioti & Vecchio, 2017).

In similar studies, Tóth et al. (2017) and Hsie et al. (2008) investigated hybrid mixtures with blends of micro and macro PP fibers. These studies confirmed that in hybrid mixtures, the presence of micro fibers resist the formation of micro cracks and increase the macro fibers resistance to pull-out which ultimately increases the ductility and toughness of the composite (Figure 2.23) (Tóth et al., 2017, Hsie et al., 2008).

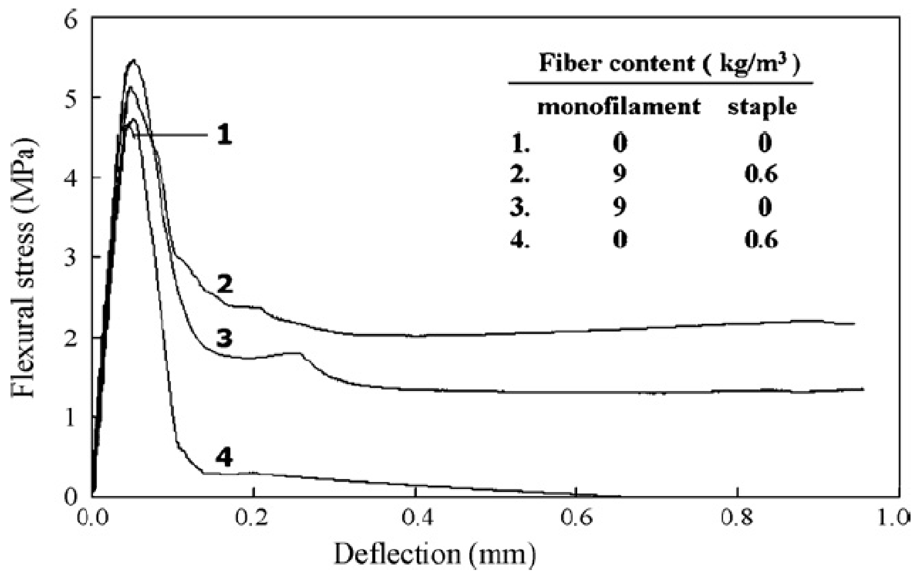


Figure 2.23 *Flexural stress-deflection response of hybrid PP monofilament (macro) and staple (micro) fiber hybrid mixtures (Hsie et al., 2008)*

The two previously mentioned categories of FRC represent an oversimplification of the possible blends of fibers that would constitute an FRC hybrid mixture since it is possible to have binary or tertiary fiber mixtures in which all fibers have different mechanical properties and size concurrently.

Banthia & Soleimani (2005) carried out a study on binary and tertiary hybrid FRC made with combinations of macro steel (two types) and PP as well as micro steel, carbon (two types) and PP (two types). The strength results of the study were somewhat mixed but it was concluded that hybrid FRC could provide higher modulus of rupture values compared to control mixtures even when compressive strengths were lower than that of control mixtures. With regards to post crack performance evaluated by the flexural load-deflection curves of specimens, it was concluded that macro fiber volume governed the toughness parameters however additions of certain combinations of micro-fiber could produce some fiber synergy (Banthia & Soleimani, 2005).

A similar study was carried out by Banthia and Gupta (2004) in which steel and polypropylene (two types) macro fibers were investigated individually and in combination with carbon and polypropylene (two types) micro fibers. They concluded that the addition of fibers did not enhance the compressive strength of mixtures but the addition of micro fibers improved the modulus of rupture. It was also concluded that steel macro fibers are more effective for providing toughness to mixtures than polypropylene macro fibers. Fiber synergy with respect to toughness was detected for select fiber combinations. Steel macro and polypropylene micro fibers showed some synergy but the highest synergy was detected for crimped polypropylene macro fiber mixed with carbon and polypropylene microfiber. The authors found that increasing the aspect ratio of the PP microfibers increased their fiber synergy effects (Banthia & Gupta, 2004).

Lawler et al. (2005) investigated hybrid mixtures including macro steel combined with micro steel and PVA fibers. It should be noted that in this study, the volume fractions of the micro-fibers in the hybrid mixtures were relatively high compared to other studies, and fly ash was included in hybrid mixtures but not in mixtures including only macro-fibers. The results from the flexural testing carried out in this study are shown in Figure 2.24. The presence of microfibers effectively increased the strength of the matrix as measured by the first crack strength. Ultimate strength was only improved by PVA microfiber inclusion. Micro PVA fibers showed the best results in hybrid mixtures with steel macro fibers. Although the toughness at high deflections was still governed by the macro fiber content, replacement of a portion of the steel macro fibers with PVA micro fibers improved the toughness at low deflections (Lawler et al., 2005).

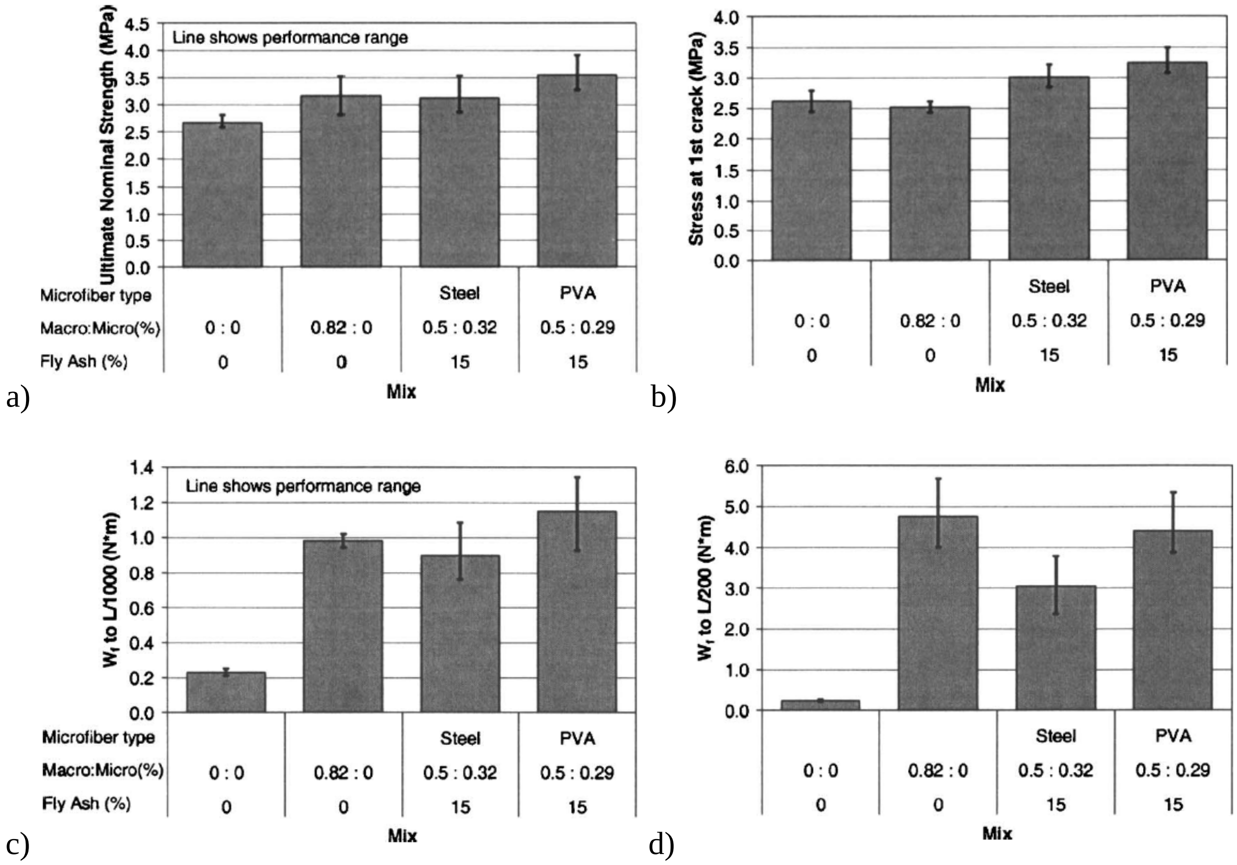


Figure 2.24 *Flexural results of hybrid FRC mixes with macro steel fiber combined with micro steel or PVA fibers a) Ultimate strength b) First crack stress c) Toughness at low (0.4mm) deflections d) Toughness at high (2mm) deflections (Lawler et al., 2005)*

Besides the reported benefits to strength and toughness that fiber hybridization can provide to FRC, there is another type of fiber hybridization that is based on fiber function. This type of FRC hybrid would utilize low volumes of micro fiber to control plastic shrinkage cracking at very early ages, or control spalling of structural concrete in the event of a fire, in combination with a macro-fiber to control the propagation of cracks caused by drying shrinkage, temperature variation or applied loads. Although most studies pertaining to hybrid FRC only focus on the compressive, flexural and tensile properties of the composite, limited studies have investigated the shrinkage behavior of hybrid FRC. This is likely because it is well accepted that the role of micro and macro fibers in FRC are quite different and applications that would utilize small volumes of micro fibers to control plastic shrinkage cracking such as pavements and other high exposed surface applications are typically highly cost driven and the inclusion of macro fibers to enhance post crack properties may not be feasible.

Sivakumar & Santhanam (2007) investigated macro steel and polypropylene (the polypropylene fiber was in the grey area for macro-micro fiber definitions) and micro glass and polyester fibers on their individual and combined effects on plastic shrinkage crack control. They found that the presence of macro steel fiber alone reduced the total plastic shrinkage cracking area of specimens by around 50% but the fractional replacement of steel fibers with polypropylene, polyester, and glass fibers could reduce the total crack area of specimens by up to about 97%, 98%, and 90% respectively as shown in Figure 2.25. Similar or greater reductions in total plastic shrinkage cracking area were achieved with the inclusion of micro fibers alone at the same volume. The results of the study confirm that micro fibers are much more effective than macro fibers for plastic shrinkage crack control, and hybrid macro-micro fiber mixes can take advantage of this property (Sivakumar & Santhanam, 2007). Hybrid PP and nylon fiber mixtures have been investigated by Lee et al. (2012) for their effect on spalling prevention of concrete. The study found that the hybrid fiber mixture was more effective than mono-fiber mixtures for spalling prevention because of the different melting points of PP and nylon. The PP fibers melt at a lower temperature and are more effective at preventing spalling during the early ages of a fire while the nylon fibers have a higher melting point and are more effective for spalling prevention during the later stages of a fire (Lee et al., 2012).

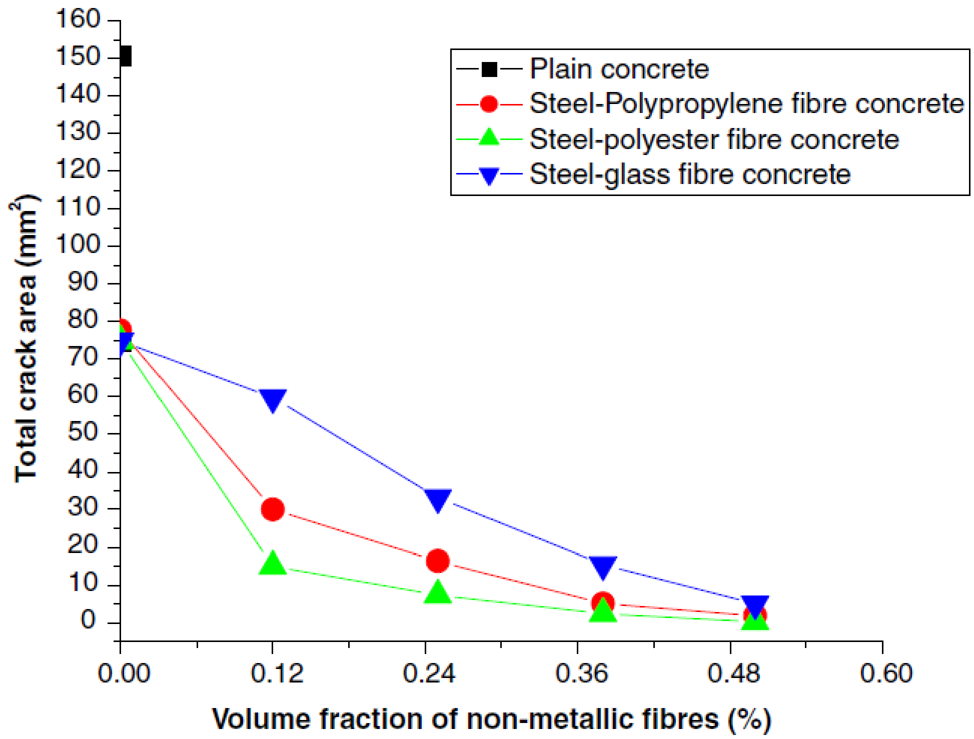


Figure 2.25 *Specimen total plastic shrinkage crack area for 0.5% total fiber volume mono and binary fiber mixtures (Sivakumar & Santhanam, 2007)*

Hybrid FRC mixtures show promising laboratory results. The main drawback for hybrid mixtures in practice is the complications introduced for full scale mixing applications, since presently in practice mono fiber FRC is considered a specialty product, let alone a hybrid mixture. Some fiber manufacturers do sell pre-mixed hybrid fiber blends, usually utilizing a large ratio of macro to micro fibers, with the intention of controlling plastic shrinkage cracking with the micro fibers and providing post crack performance with the macro fibers. As fiber concrete technology progresses, it is expected that hybrid fiber mixtures will become more popular due to the reported potential performance increases and binary functions of the fiber blends.

2.8 Conclusion

The review herein has outlined the different types of fibers that have been subject to substantial research for use as reinforcement in cementitious matrices, with a focus on randomly dispersed discrete fibers in concrete. Material dependent fiber properties have been highlighted, focusing on the contributions of different fiber types to the fresh and hardened properties of concrete with a focus on contributions to pre and post crack strengths. Long term fiber durability concerns have been discussed and some typical applications for different fibers have been presented. Furthermore, the material independent fiber parameters have been discussed to establish the key mechanisms of micro and macro fibers when used in concrete. Recent updates on the use of hybrid fibers in FRC are briefly presented.

Metallic fibers have great reinforcing potential in concrete, due to their ability to modestly increase strength parameters and provide healthy post crack residual strengths. The most unique advantage of steel fibers is their high triaxial stiffness, which allows them to provide high residual strengths at low crack openings. Besides relatively high density, the main drawback of steel fibers is their poor resistance to corrosion, while anti-corrosive stainless steel and coated steel fibers are costly.

Synthetic fibers have made large advances into the concrete fiber market because of attractive price points and improvements in fiber quality due to chemical optimization through technological advances of manufacturing methods. The most attractive property of most synthetic fibers in cementitious matrices is their chemical durability. In general the main drawback of synthetic fibers is their low stiffness compared to steel. Although some high performance synthetic fibers have attractive mechanical properties, these fibers tend to be expensive. Synthetic fibers are widely being used for plastic shrinkage and thermal crack control in concrete and certain high performance synthetics are being used as partial or full reinforcement of ground slabs. It is expected that as time progresses, synthetic fibers will be manufactured with better mechanical properties and lower price points, further advancing their use in the concrete industry.

Glass fibers are widely used in thin sheet mortar composites. The most attractive property of glass fibers is their low price and reasonably high initial stiffness. Although large efforts have been made to increase the alkali resistance and avoid the degradation of glass fibers, it remains a long term concern unless adequate steps are taken to remediate the level of degradation. GFRP and BFRP macro fibers have shown promising reinforcing potential in concrete and if their long term durability can be further confirmed, it is expected that these products will become very popular in the concrete construction industry.

Natural fibers are still a developing and very active field of research in cement based products. The low cost and regional availability of natural fibers give them large potential upside as reinforcement in mortar and concrete. Large strides have been made to identify and partially mitigate the degradation mechanism of natural fibers, however degradation in cement chemistry and high water absorption which affect mixture design water balance and fiber dimensional stability remain large limitations.

FRC is becoming more popular in the construction industry and will continue to grow as contractors become more comfortable with mixing and placing FRC and building codes for structural concrete accept the strength and service life benefits that can be gained from adding randomly dispersed discrete fibers to cement, mortar and concrete. With the addition of FRC post crack strengths to the fib Model Code 2010, and numerous recent works describing the use of fibers as the structural reinforcement for ground slabs or supplemental reinforcement for crack control under service loads in infrastructure, it is expected that the addition of discrete fibers to concrete will continue to gain popularity in the coming years.

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CHAPTER 3: FLEXURAL PERFORMANCE EVALUATION OF FIBER REINFORCED CONCRETE INCORPORATING MULTIPLE MACRO-SYNTHETIC FIBERS

Abstract

Presented herein are the results from flexural testing of fiber reinforced concrete (FRC) beams containing different types of commercially available macro-synthetic concrete fibers. Basalt, Polypropylene (PP) and Polyvinyl Alcohol (PVA) macro-fibers were tested, at volume fractions of 0.5% 1.0% and 1.5%. The water to cementitious materials ratio was held constant for all mixtures at 0.38, while additional cement paste containing the same water to cementitious materials ratio as well as polycarboxylate superplasticizer were added to achieve adequate fresh properties and consolidation. Beam specimens were tested under 3rd point bending as per the ASTM C1609 standard measuring load vs. mid-span deflection, using an external data acquisition system. Strength and toughness parameters were derived from the development of load and mid-span deflection relationship in order to assess the flexural performance of the fibers in the FRC composite system. For each mixture containing a specific fiber type and dose, three beams were cast and tested, making a total of 27 specimens. Experimental results showed that at the tested volume percentages, all three fiber types provided different levels of post-crack performance, with a general trend showing higher volume percentages providing increased toughness and residual strength. Pre-crack strength also trended slightly upward with increasing fiber content for each fiber with an exception for PVA fibers where the results were inconsistent. In general, of the fibers tested Basalt fibers showed the highest residual strengths and toughness parameters, followed by PP while PVA showed the lowest residual strengths and toughness parameters. Pre-crack strength results were less conclusive between the three fibers tested.

3.1 Introduction

Cracking in concrete is a multiscale process that starts with the formation of micro-cracks which develop under tensile stress and grow together to form larger macro cracks. These macro cracks will propagate under tensile stress until the crack becomes unstable and fracture occurs, causing brittle failure. In order to control the cracking and failure mode of concrete, continuous aligned reinforcement in the form of steel rebar or mesh is placed in the zones of the concrete where tensile stress is expected. In order to further help avoid brittle failure and control crack formation and propagation in concrete, relatively short fibers can be dispersed randomly throughout the concrete matrix during the mixing process. In some applications, short, discontinuous fibers can not only reduce the required thickness but potentially completely eliminate the need for rebar or welded wire mesh reinforcement in concrete slabs.

The type and physical characteristics of fibers used for a specific concrete application have the ability to affect the concrete properties in the fresh state as well as the mechanical properties of the hardened composite. One way to categorize concrete fibers is by their size. In general when referring to conventional FRC, small "micro" fibers are used to prevent early age cracking and increase the pre-crack performance of the matrix by arresting micro-cracks as they form, while larger "macro" fibers are utilized to provide load carrying capacity (residual strength) and toughness after a crack has formed as well as control the propagation of cracks that have grown past the micro stage (*1*).

Another way to categorize concrete fibers is by the material they are made from. Steel fibers have shown many benefits to the mechanical properties of FRC (*2, 3, 4*) but face corrosion issues in the presence of harsh environmental exposure conditions that are common in civil structures like bridge decks or structures exposed to marine environments. Natural fibers in concrete are a rising area of interest, however most natural fibers face certain limitations such as high water absorption and lack of long term stability in the highly alkaline concrete environment (*5*). The apparent limitations of steel and natural fibers in concrete have given much attention to synthetic fibers that can avoid corrosion and strength degradation after long term exposure in the chemistry of the concrete matrix. Carbon, Aramid, Polyethylene, Nylon, Polypropylene, Polyolefin, Acrylic, Polyvinyl-Alcohol, Alkali Resistant Glass and more recently Basalt include synthetic fibers that have been explored for use as concrete fibers for a variety of applications (*6, 7, 8, 9*).

In concrete applications where the hardened composite must exhibit high post-crack (residual) strength and toughness, as well as avoid strength deterioration from chemical instability or corrosion, macro-synthetic concrete fibers are a sensible addition to the mixture. There is an abundance of literature that highlights the flexural or tensile performance of a single synthetic fiber type (*10, 11, 12*) or even multiple fiber comparisons of different fiber types (*13, 14*). However, in order to draw a fair comparison between synthetic fiber types the fibers must share characteristics that make them suitable for increasing the performance metric being tested, in this case post-crack performance and toughness.

Although some studies have compared different macro synthetic fiber types (*15, 16*) there is a need for more literature pertaining to the comparisons of workability, flexural residual strength and toughness provided by different commercially available macro synthetic fibers that have a high potential to provide residual strength and toughness in concrete. Due to the existing lack of meaningful comparative studies, this study compares three types of synthetic macro-fibers dispersed in a consistent concrete matrix. Static and dynamic fresh properties were monitored, and hardened properties were evaluated using the flexural testing method in accordance with the

ASTM C1609 standard (*17*). Polypropylene, Polyvinyl-Alcohol and Basalt macro-fibers with reasonably similar aspect ratios were selected based on their availability in the current concrete market and potential to provide post-crack strength and toughness found in the literature. Three reasonable fiber dosage rates for gravity based drum mixers of 0.5%, 1.0% and 1.5% by volume were selected for each fiber type.

3.2 Materials

3.2.1 Fibers

Three types of commercially available macro-synthetic concrete fibers with comparable aspect ratios were chosen to assess their flexural reinforcing potential as per the ASTM C1609 standard. Fiber properties are documented in Table 3.1. Since 3/8 inch maximum aggregate size was used in this study, it was decided that the minimum fiber length should be roughly 3/4 inch to increase the fiber's reinforcing potential around the largest aggregate particles.

Table 3.1 *Properties of Fibers Investigated*

Polypropylene (PP), Polyvinyl-Alcohol (PVA) and Basalt Fiber Properties			
Fiber Type	PP	PVA	Basalt
Diameter (in (mm))	0.013 (0.34)	0.008 (0.2)	0.026 (0.65)
Length (in (mm))	1.50 (38)	0.71 (18)	1.69 (43)
Aspect Ratio	112	90	66
Tensile Strength (ksi (GPa))	90 (0.62)	145 (1.0)	157 (1.08)
E. Modulus (ksi (GPa))	690 (4.7)	3920 (27)	6382 (44)
Specific Gravity	0.91	1.3	2.1

Polypropylene (PP) fibers are one of the most common types of synthetic concrete fibers due to their relatively low cost, chemical stability in alkaline environment, and availability. Limitations of PP include low modulus of elasticity and poor bond with the concrete matrix. Bond properties of PP fibers are normally enhanced mechanically by manufacturing the fibers with a twisted shape or texturing the fiber surface. Fibrillated micro polypropylene fibers are a common concrete micro fiber used mostly to avoid and control plastic shrinkage induced cracking for high exposed surface area concrete applications (*18*). The macro PP fibers used in this study are a blend composed mostly of twisted bundle monofilament macro fibers but include a low volume of fibrillated strands.

Polyvinyl Alcohol (PVA) fibers are gaining popularity in the concrete market in numerous applications. PVA was initially developed to replace asbestos in making fiber cement using the hatcheck process (*19*). It is very stable in the chemistry of the concrete environment, has a relatively high modulus of elasticity, and is reported to have the unique ability to bond chemically with the concrete matrix (*20*). Due to the bond properties of PVA, the fibers used in concrete are typically monofilament and lack surface deformations. Micro PVA fibers are a key ingredient in Engineered Cementitious Composite (ECC) which utilizes a high volume of PVA fibers and fly ash to form a hardened mortar that is capable of up to 5% tensile strain due to multiple closely spaced micro cracks forming and pseudo strain hardening behavior under tensile strain (*21*). The PVA fibers used in this study are monofilament, straight and have no surface deformations.

Basalt fibers are relatively new to the concrete market and are made from extruding melted volcanic rock into filaments and forming strands of the desired size to be cut to the desired length (*22*). Basalt fibers have a relatively high modulus of elasticity, but this depends of the type of basalt fiber under consideration. Chopped basalt fibers are made from this process tend to have a small diameter and high aspect ratio, categorizing them as a micro-fiber. They have also been shown to undergo strength degradation in the alkaline environment of the concrete much like glass fibers (*23*), limiting their applications to early age plastic shrinkage crack control. More recently a type of macro basalt fiber has been developed by impregnating multiple basalt fiber filaments in a highly alkali proof resin and cutting to a desired length. The resin coating also helps improve the fibers ability to bond with the concrete matrix. The fibers have a subtle twisted shape along their length to increase mechanical bond to the concrete matrix. This type of fiber is marketed under the name Basalt Minibars™ and have previously shown high post-crack load bearing capacity and toughness in FRC. They are also reported to disperse well in concrete due to their density being similar to that of the concrete matrix (*24*).

3.2.2 Concrete Matrix Composition

The concrete base mixture proportions were chosen to favor workability and reinforcing potential of the selected fibers. Type I/II portland cement was used with 30% cement replacement with Class F fly ash to improve workability and reduce the portland cement content. 3/8 inch (9.5mm) maximum size crushed limestone was utilized for coarse aggregate and clean river sand was used for fine aggregate. 3/8 inch maximum size aggregate was chosen to maximize the volume within the matrix that fibers could exist without their position and orientation being restricted and consequently their reinforcing potential restricted by larger aggregate particles. Workability is also generally increased in FRC mixes with smaller maximum aggregate size due to the increase in volume space available for the fibers to exist in the fluid state (*25*).

Water-to-cementitious materials ratio was held constant for all mixtures at 0.38. Since each of the three fibers tested had different surface area per unit volume, and three different volumes were tested per fiber type, different amounts of polycarboxylate high range water reducer (HRWR) and cement paste were added to each base mixture during the mixing process in order to maintain reasonable fresh properties for adequate consolidation under external vibration. Paste was prepared with the same water to cementitious materials ratio as the base mix design in order to avoid affecting the strength of the hardened composite. The paste additions were deemed necessary in order to coat the extra surface area of the fibers and provide adequate fresh properties. Table 3.2 shows mixture proportions of each mixture after the paste and HRWR additions. Fibers were added last to all mixtures and mixing time of 3-5 minutes was adequate to disperse the fibers evenly throughout the fresh concrete.

Table 3.2 *Adjusted Mixture Proportions after Paste and HRWR Additions*

Mix Proportions of FRC Mixes									
	Mixture Ingredients (lb/cy)*								
	Cementitious			Aggregates					
Mix ID	Type I/II Cement	Class F Fly Ash	Total	Coarse	Fine	Fine : Coarse	Water	HRWR** (oz/cwt)	Fiber Volume (%)
Base Mix	593	254	847	1534	1257	0.82	322	0.0	0
0.5PP	593	254	847	1537	1257	0.82	322	0.6	0.5
1.0PP	596	255	851	1517	1241	0.82	324	1.8	1.0
1.5PP	605	259	864	1479	1210	0.82	329	3.1	1.5
0.5PVA	607	260	867	1511	1236	0.82	330	2.9	0.5
1.0PVA	633	271	904	1461	1195	0.82	344	2.8	1.0
1.5PVA	661	283	944	1403	1147	0.82	359	6.3	1.5
0.5B	593	254	847	1539	1259	0.82	322	1.0	0.5
1.0B	593	254	847	1531	1252	0.82	322	2.6	1.0
1.5B	593	254	847	1512	1237	0.82	322	2.6	1.5

*(1 lb/cy = 0.593 kg/m^3) ** HRWR = High Range Water Reducer

3.3 Test Methods and Performance Parameters

3.3.1 Test Methods

The Vibrating Kelly Ball (VKelly) test was utilized to evaluate the fresh properties of the fiber mixtures. The VKelly slump is a parameter indicating the fresh concrete mixture's static yield stress and is calculated by doubling the Kelly Ball penetration into the fresh concrete under its own weight. The VKelly index is an indication of how well the mixture responds to vibration for consolidation, which is found by recording the ball's penetration depth into the fresh concrete under controlled external vibration at 6 second intervals. The index is the value of the resulting slope of the penetration vs. √time plot. When calculating the VKelly slump and index of each mixture, 3 test trials were performed and values were averaged for each trial. The VKelly test was developed for slip-form paving applications for which a VKelly index of 0.6-1.2 in/√s (15-30 mm/√s) is deemed suitable. Recent work by Taylor *et al*. 2015, Taylor & Wang 2016 and Wang *et al*. 2017 explain the development and details of the VKelly test (*26*, *27*, *28*).

Three beams sized 4×4×14 inches (100×100×350 mm) were cast for each fiber type and volume, making a total of 27 specimens. The beam molds were oiled prior to casting and the fresh concrete was consolidated using a vibrating table. Preferential alignment of the fibers during casting was avoided as much as possible. The specimens were de-molded after 24 hours and allowed to cure at 73ºF (23ºC) and 100% relative humidity. All beams were tested at 7 days of age.

Third point bending tests were carried out using a 400k (1780kN) capacity Instron universal testing machine with external data acquisition system connected to two Linear Variable Differential Transformers (LVDT) sensors. The support span length on the bottom of the beams was 12 inches (305mm) while two point loads were applied to the top of the beam spaced 4 inches (100mm) apart as well as placed symmetrically 4 inches (100mm) inside of the bottom supports (Figure 3.1). The supports and top load applicators were made from oval shaped dowel bars to facilitate free rotation at the supports. Because the supports of the testing apparatus were restrained to translational movement, some lateral friction forces existed between the specimen and the bottom supports as deflections increased for the duration of the test. This may have caused some pseudo deflection hardening behavior, especially at higher deflection values, but all specimens were tested under the same conditions and fair comparisons can still be drawn between different fiber types and volumes based on the data collected. Aluminum tabs were glued to the specimen at the mid-span on both sides of the beam while magnetic stands were used to hold LVDT's under each tab in order to measure the mid-span deflection (Figure 3.1). Following the ASTM C1609 standard, the loading rate was displacement controlled at a loading rate of 0.003 inches (0.075mm) per minute up to the deflection of support span length (L)/900, after which the loading rate was increased to 0.005 inches (0.127mm) per minute. Since the testing machine was not capable of controlling the displacement rate from the average reading of the LVDT's placed at the mid-span, the loading rate was increased when the table movement reached L/900 displacement or 0.013 inches (0.33mm) after being zeroed at the start of the test.

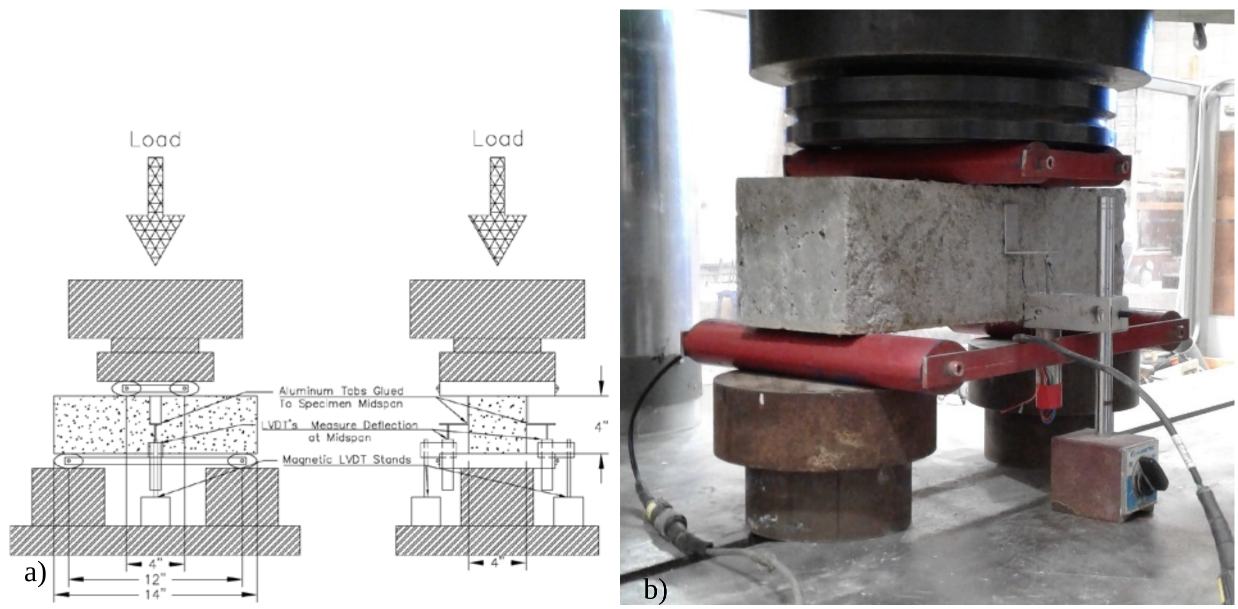


Figure 3.1 *a) Test Setup Drawing (1 in = 25.4 mm) b) Test Setup*

3.3.2 Flexural Performance Parameters

The ASTM C1609 standard is a test method for evaluating the behavior of FRC when tensile stress is applied due to flexure. The standard formulates some performance parameters that can be utilized to compare the performance of each specimen based on the load vs. deflection curves obtained from the test. First, strength parameters are obtained, the first being the first peak strength - f_1 (modulus of rupture), by the following equation (Eq. 3.1):

$$f = \frac{PL}{bd^2} \tag{3.1}$$

where:

$f = strength\ (psi, MPa)$

$P = load\ (lbf, N)$

$L = span\ length\ (in, mm) - 12\ inches\ (305mm)\ for\ this\ study$

$b = specimen\ width\ (in, mm) - 4\ inches\ (100mm)\ for\ this\ study$

$d = specimen\ depth\ (in, mm) - 4\ inches\ (100mm)\ for\ this\ study$

Residual load parameters P_{600} and P_{150} for deflections of L/600 and L/150 respectively are used to compute residual strength parameters f_{600} and f_{150} using Eq. 1, with the load at the corresponding deflections.

Peak load P_P is used to compute peak strength f_P using Eq. 1 if the maximum load occurs after the first peak load, caused by a deflection hardening response. If the maximum load occurs at the first peak, $f_P = f_1$.

Next, toughness up to net deflection of L/150 - T_{150} is obtained by calculating the area under the load-deflection curve up to the corresponding deflection of L/150 (0.08 inches (2mm) for the beam dimensions used in this study).

Finally the equivalent flexural strength ratio is computed using the following equation (Eq. 3.2):

$$R_{T150} = \frac{150 * T_{150}}{f_1 * b * d^2} * 100\% \quad (3.2)$$

where:

$R_{T150} = equivalent\ flexural\ strength\ ratio\ (\%)$

$f_1 = first\ peak\ strength\ (psi, MPa)$

$T_{150} = Toughness\ up\ to\ L/150\ deflection\ (in - lb, Joules)$

$b = specimen\ width\ (in) - 4\ inches\ (100mm)\ for\ this\ study$

$d = specimen\ depth\ (in) - 4\ inches (100mm)\ for\ this\ study$

The equivalent flexural strength ratio is a parameter that relates the first peak flexural strength (modulus of rupture) to the toughness of the composite. A low modulus of rupture and high toughness would result in a high R_{T150} value while a high modulus of rupture and low toughness would result in a low R_{T150} value. Since this study utilizes the same concrete matrix for all mixtures, it is expected that R_{T150} values will follow the same trend as the toughness values for each mixture. Using the performance parameters from the ASTM C1609 standard, a three specimen average and standard deviation was calculated for; f_1, f_{600}, f_{150}, T_{150} and R_{T150} parameters. These were analyzed along with the original load vs. deflection curves to evaluate the flexural performance of each fiber type and volume percentage.

3.4 Results and Discussion

3.4.1 Fresh Properties

Table 3.3 *Fresh Properties of FRC Mixtures*

Fresh Properties						
			VKelly Slump		VKelly Index	
Mix ID	% Paste Added	HRWR* (oz/cwt)	Average (in (mm))	COV (%)	Average (in/√s (mm/√s))	COV (%)
PP0.5	0.0	0.6	1.5 (38)	6.4	0.47 (11.9)	5.8
PP1.0	0.5	1.8	1.3 (33)	7.1	0.33 (8.4)	3.5
PP1.5	2.0	3.1	1.0 (25)	10.9	0.13 (3.3)	12.6
PVA0.5	2.4	2.9	2.6 (66)	15.4	N/A	N/A
PVA1.0	6.7	2.8	1.3 (33)	7.4	0.25 (6.4)	9.6
PVA1.5	11.5	6.3	2.0 (51)	8.2	0.19 (4.8)	12.6
BSLT0.5	0.0	1.0	2.3 (58)	4.2	0.60 (15.5)	3.0
BSLT1.0	0.0	2.6	1.9 (48)	13.4	0.43 (10.9)	3.1
BSLT1.5	0.0	2.6	1.3 (33)	7.4	0.30 (7.6)	5.4

*HRWR = High Range Water Reducer

When mixing and casting the FRC specimens, each fiber type effected the fresh properties of the mixture differently. Table 3.3 shows the percentage of paste and HRWR dose added to each mixture along with the corresponding VKelly slump and index.

The PP fibers mixed well at 0.5% and 1.0% volumes and had relatively low effect on workability that could be easily compensated for by small amounts of HRWR. At 1.5% volume of PP fibers, the mixture was considerably stiffer with low response to vibration shown by a VKelly index of 0.13 in/√s (3.3 mm/√s), even with paste and HRWR addition. Basalt fibers had the smallest effect on the fresh properties of the mixture, which is expected due to lower aspect ratio, and specific gravity that is closest to that of the concrete matrix. The Basalt fiber mixtures responded well to vibration as shown with their comparatively high VKelly indexes shown in Table 3.3.

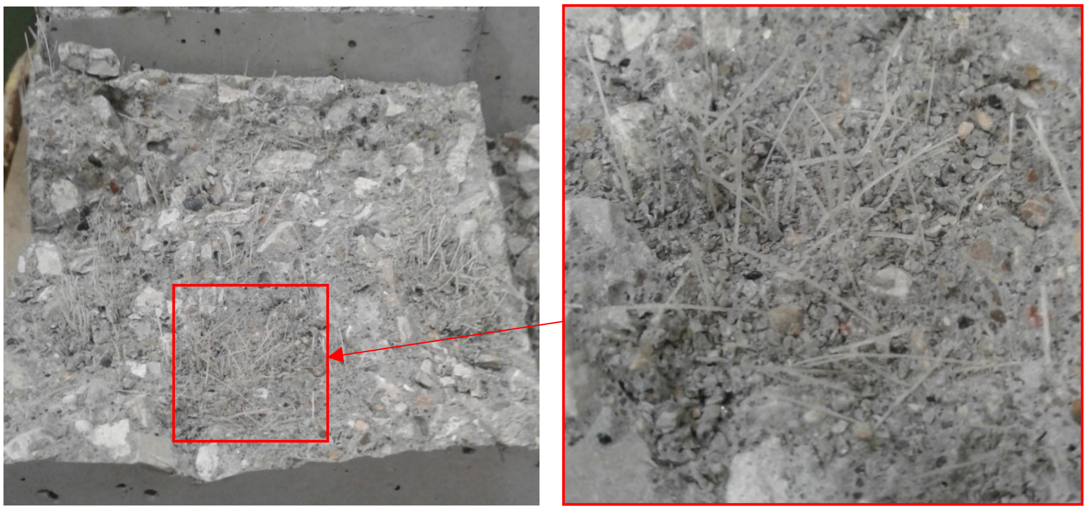
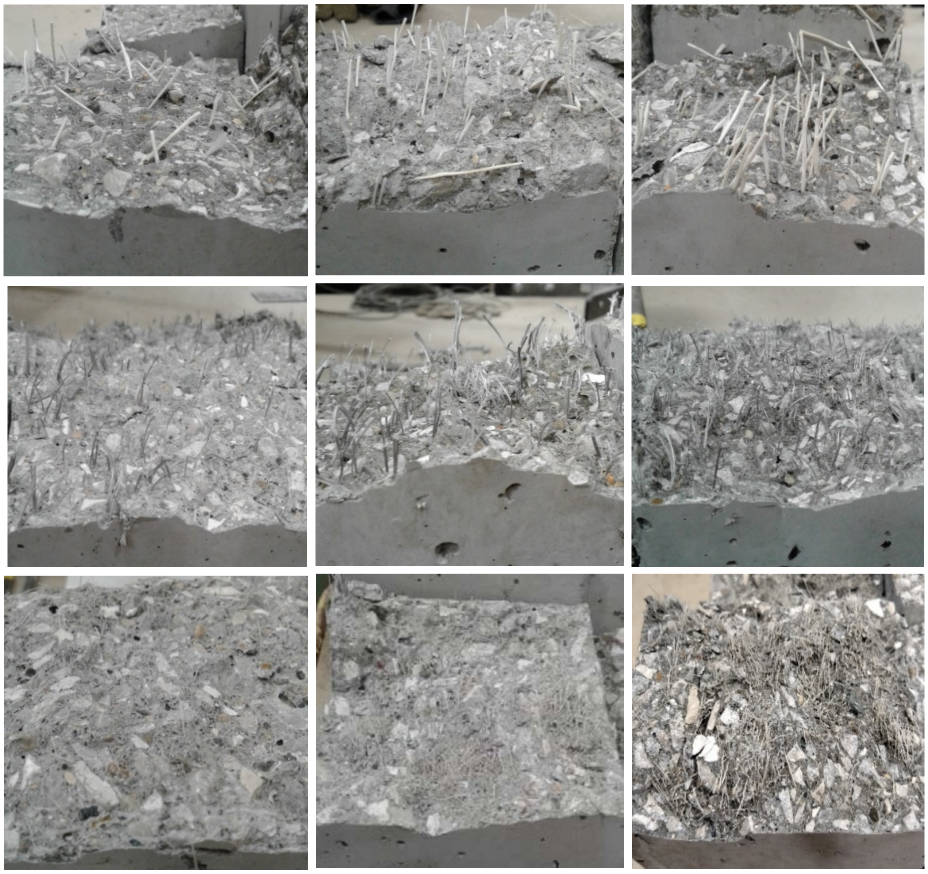


Figure 3.2 *Cross Section of Broken PVA FRC Beam – Clumps of Re-Aggregated Fiber*

The VKelly index of the mixtures tested in this study are below that of the 0.6-1.2 in/√s (15-30 mm/√s) VKelly index recommended for slip-form paving which indicates that fiber addition has a strong effect on the VKelly index. More research and data is needed to determine the optimal VKelly parameters for FRC mixtures, however the values of VKelly index reported in this study can effectively be used for comparing the relations between fiber types and volumes on fresh properties. The PVA fibers had certain limitations in the fresh state. At 0.5% volume, they mixed very well with adequate dispersion and workability, the response to vibration was very high for the 0.5PVA mixture indicated by the lack of a reported value for the VKelly index because the ball moved so quickly through the concrete, no reading could be taken past the 6 second reading. For the 1.0% and 1.5% volume PVA mixtures, clumping of the fibers was an issue as it seemed once a certain volume of fibers was added to the mixture, the fibers would come together and form 1-2 inch diameter clumps that contained only sand, fiber and paste (Figure 3.2).



Basalt | PP | PVA

0.5% | 1.0% | 1.5%

Figure 3.3 *Broken Beam Cross Sections – Dispersion of Fibers*

Continued mixing would not disperse the clumps so the specimens were cast and consolidated with the existing clumps. Although fiber dispersion admixtures like methylcellulose, latex and acrylic are reported to be effective (*29*), it was decided to not utilize these technologies because they were not needed for Basalt and PP mixtures in addition to their lack of practicality in full scale projects. Cross sections of the broken beams for each mixture in Figure 3.3 show the amount of fibers present and the dispersion of the fibers throughout the concrete matrix.

3.4.2 Flexural Results

The load-average mid-span deflection curves obtained for all 27 beams are shown in Figure 3.4.

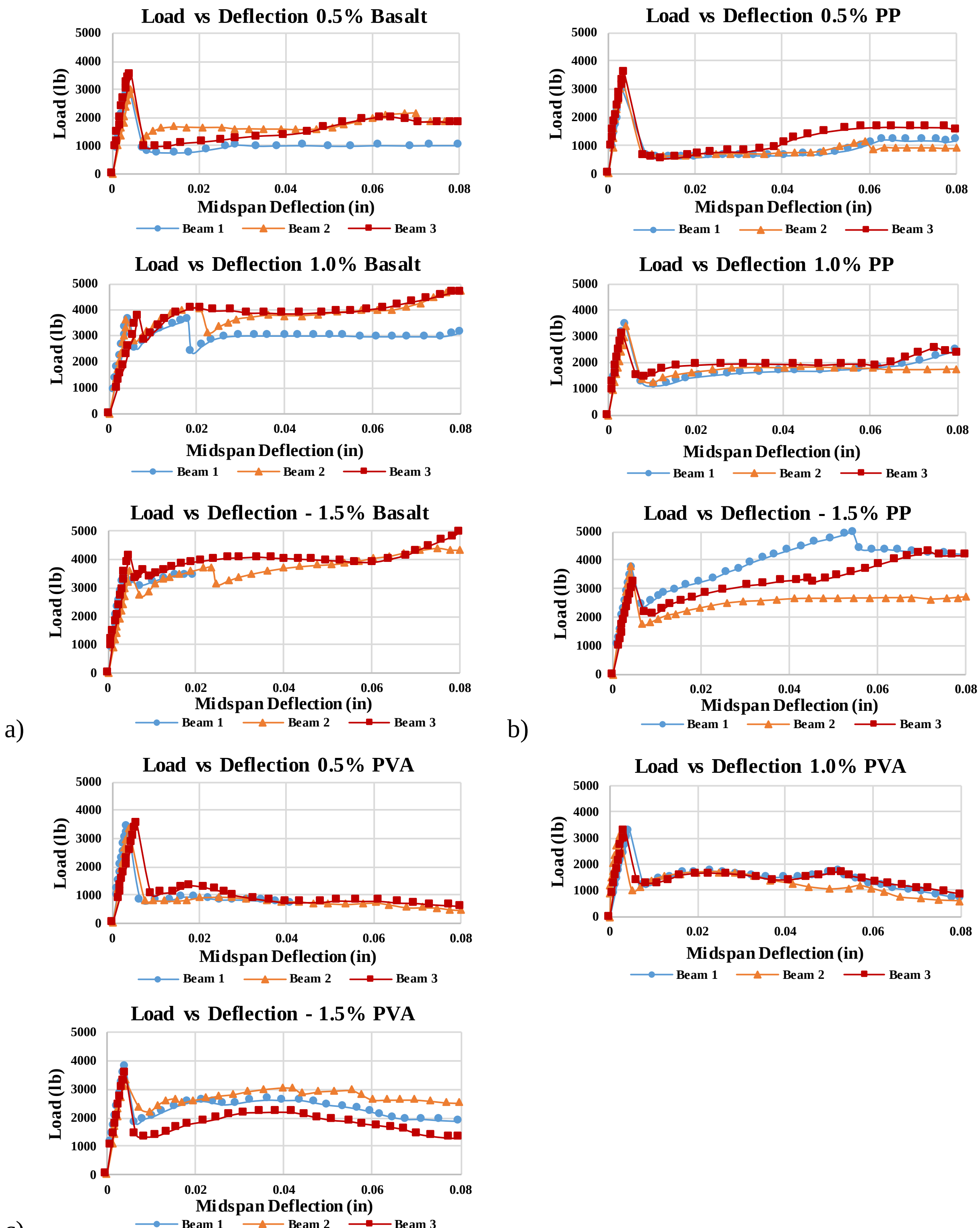


Figure 3.4 *Load vs. Average Midspan Deflection Curves a) Basalt b) PP c) PVA. (1 in = 25.4 mm; 1 lb = 4.45 N)*

All fiber types and volumes tested displayed deflection hardening behavior immediately after the formation of the first crack, characterized by the sharp drop after the initial slope on load vs average mid-span deflection curve followed by a positive slope. For the specimens containing PVA fibers, this initial deflection hardening response was followed by deflection softening behavior. One of the 0.5PVA beams tested did not have a completed data set because the load dropped past 20% of the initial value and the safety stop was triggered on the testing machine. The safety stop was adjusted to a lower value for subsequent tests. One of the 1.5B specimens did not have a completed data set because a crack formed directly under the portion of the beam where the aluminum tab was glued and the tab became disconnected. All volumes tested for PP and Basalt showed continued deflection hardening behavior after the formation of the first crack.

It is interesting to note that the presence of a second sudden drop in the load-deflection curves shown in Figure 3.4 represents that a second crack formed in the specimen. This can be noticed for some 1.0B and 1.5B specimens as well as one of the 1.5PP specimens. The presence of multiple cracks suggests the fiber’s ability to transfer load across the crack sufficiently to develop the full strength of the matrix. All other specimens failed by a single crack that propagated to failure. Figure 3.5 shows the failed specimens with single and double cracking patterns. The load vs. mid-span deflection curves for all specimens were used to compute the average and standard deviation of flexural performance parameters.

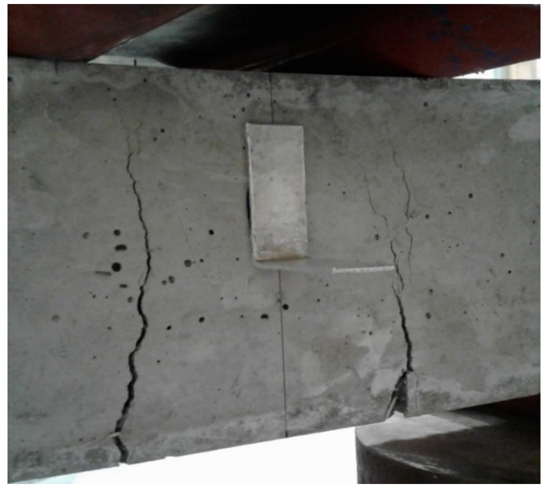
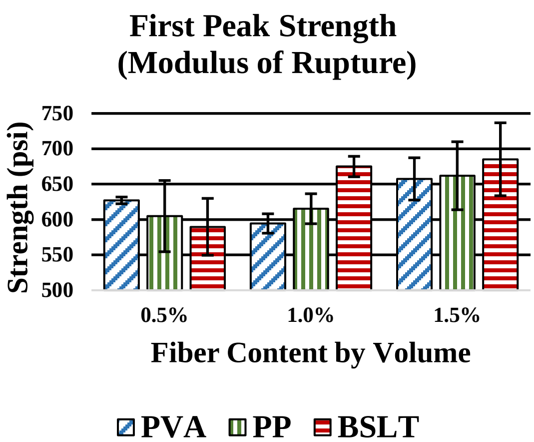
a)  b) 

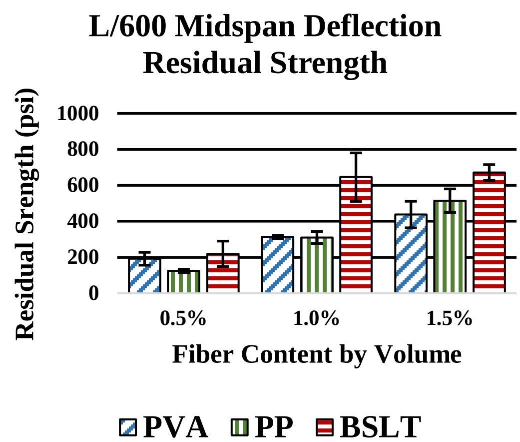
Figure 3.5 *a) Single Crack Pattern Failure b) Double Crack Pattern Failure*

The five performance parameters from the ASTM C1609 standard have been summarized visually using bar charts including standard deviations in Figures 3.6 & 3.7. Figure 3.6a contains the comparison of the three specimen average first peak strength. First peak strength is a measure of the composite flexural strength prior to cracking, i.e. the modulus of rupture. It can be seen that for PP and Basalt fibers, the first peak strength seems to increase with the increase in fiber volume. This increase is small (1.7%) when comparing the 0.5PP and the 1.0PP specimens, however the increase is slightly more pronounced (7.6%) when comparing the 1.0PP to the 1.5PP specimens. For Basalt fiber specimens, a larger (14.5%) increase in first peak strength was noticed between the 0.5B and 1.0B specimens, while a much smaller (1.5%) increase in first peak strength was achieved by increasing fiber volumes between the 1.0B and 1.5B specimens. A 5.2% average decrease in first peak strength occurred between the 0.5PVA and 1.0PVA specimens, but a 10.6% average increase occurred between the 1.0PVA and 1.5PVA specimens. The inconsistencies in the PVA fiber mixtures could be attributed to the lack of uniform dispersion present in the 1.0PVA and 1.5PVA mixtures as the fiber clumps may have created weak spots in the beam cross section. For the 0.5% fiber volume mixtures, PVA had the highest first peak strength followed by PP and finally Basalt. This trend was reversed for the 1.0% volume mixtures, which continued for the

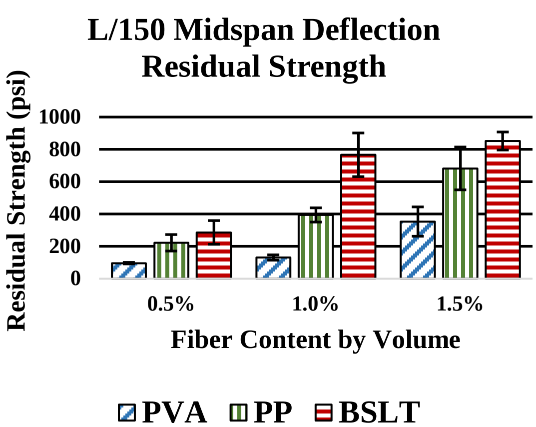
1.5% volume mixtures. Due to high standard deviations in the 0.5PP, 0.5B, 1.5PP and 1.5B populations, it is uncertain as to which fiber provided a larger first peak strength, however it can be generalized that increasing volumes of both PP and Basalt macro-fibers tested can increase the first peak strength (modulus of rupture) of the composite in the range of volumes tested.



a)



b)



c)

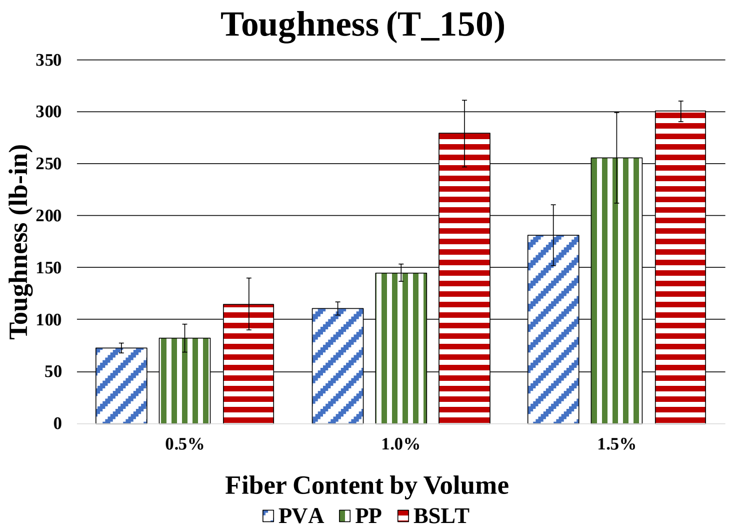
Figure 3.6 *Comparisons of 3 Specimen Average with Standard Deviation a) First Peak Strength b) L/600 Deflection Residual Strength c) L/150 Deflection Residual Strength (1 psi = 0.0069 MPa)*

Figure 3.6b and Figure 3.6c show graphical representations of the three specimen average and standard deviation L/600 and L/150 residual strength for each mixture respectively. It is clear that for all three fibers tested, increasing the fiber volume increased the residual strength. Basalt specimens consistently showed the highest L/600 residual strength, while PP showed the lowest for 0.5% volume and PVA showed the lowest for 1.5% volume. The increase in L/600 residual strength with increasing fiber volume is more pronounced for PP fiber specimens than for PVA fiber specimens. Large increases occurred in L/600 residual strength with increasing PP and Basalt fiber content, especially between the 0.5% and 1.0% fiber volumes. 1.0PP had a 148.4% increase over 0.5PP while 1.0B had a 194.1% increase over 0.5B. These increases were less pronounced for the increase to 1.5% volumes with all fibers, especially for basalt (4.0%), however the increases were still significant for 1.5PP (66.0%). PVA had a more linear increase in L/600 residual strength across all three fiber volumes tested but the increase was still over 20% higher between 0.5PVA and 1.0PVA than it was between 1.0PVA and 1.5PVA. The L/150 residual strengths shown in Figure 3.6c clearly indicate increases with increasing fiber volumes for all three fibers tested, but the 1.0B mixture tested exceptionally high and 1.0PVA tested relatively low for L/150 residual strength. PVA fiber mixtures also consistently showed the lowest L/150 residual strengths due to deflection softening behavior at higher deflections for all fiber volumes while basalt consistently showed the highest L/150 residual strengths due to strong post crack deflection hardening behavior.

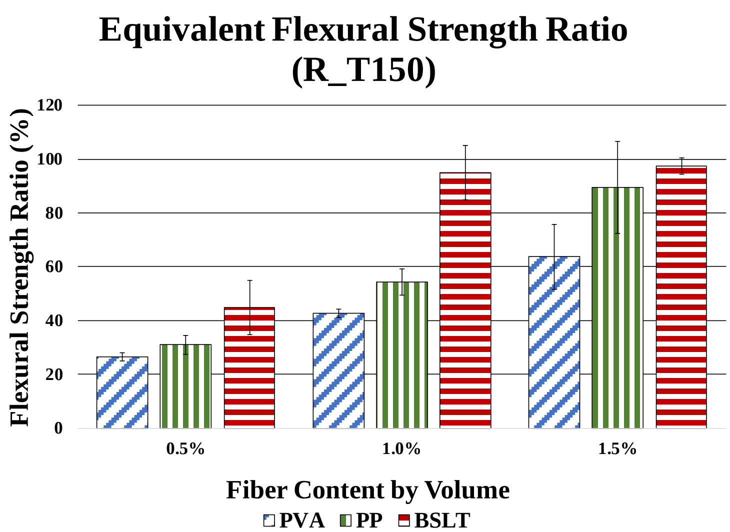
Toughness was calculated as the area under the load-deflection curve up to L/150 deflection as per the ASTM C1609 standard. Figure 3.7a is a graphical representation of the 3 specimen average toughness with standard deviations included. For all fibers tested, the toughness increased with increasing fiber volume percentage. The toughness of PP and PVA fiber mixtures showed linear increases with increasing fiber volume, however basalt showed a much larger increase in toughness from 0.5B to 1.0B (143.1%) compared to 1.0B to 1.5B (7.6%). PVA fibers consistently showed the lowest toughness values while basalt fibers consistently showed the highest toughness values. The equivalent flexural strength ratio of 3 specimen averages and standard deviations are shown in Figure 3.7b. The equivalent flexural strength ratios follow the same trend as toughness.

The post crack performance parameters; f_{600}, f_{150}, T_{150} and R_{T150} showed consistent increases with increasing fiber volume for all three fibers tested. PP results indicate linear increases with fiber volume for the 4 post crack parameters investigated. 1.0B samples generated exceptional results compared to 1.0PVA and 1.0PP samples. 1.0B results were also well above the linear trend between 0.5B and 1.5B. The results indicate small benefit for flexural performance by increasing the basalt fiber percentage from 1.0% to 1.5% for the mix design used in this study. PVA fiber mixtures generally followed a linear increasing trend for post crack parameters despite the lack of consistent dispersion and difficulties encountered while mixing the fibers.

The fact that the fiber with the largest cross section and lowest aspect ratio showed the best flexural results is somewhat surprising if one considers that a higher aspect ratio and smaller diameter would result in more surface area per volume of fibers being in contact with the concrete matrix. PP fibers had the highest aspect ratio and similar length to the basalt fibers, but did not perform as well as the basalt fibers, meaning that the ability of the basalt fibers to form a bond with the concrete matrix is superior to that of the PP fibers. The shorter PVA fibers had the second highest aspect ratio but were about half as long as the other two fibers. This means that there were more PVA fibers per unit volume of concrete but the fibers had less surface area available per fiber to bond with the concrete and develop the strength of the fiber cross section. Initially the shorter PVA fibers were selected because of the reported ability to form a strong bond with concrete, but the results indicate that a longer PVA fiber may have been more effective in providing flexural residual strength and toughness. For all three types of fiber, the failure mechanism was characterized by the fibers pulling out from the concrete matrix, rather than rupturing. This indicates that the limiting factor contributing to flexural and tensile performance is the bond strength between the fiber and the concrete. A higher strength concrete matrix may have been able to develop more of the fiber strength and increase toughness, however for the FRC mixture studied in this work, results indicate that larger fibers with superior ability to resist pull-out from the concrete matrix will be most effective to increase post crack flexural properties.



a)



b)

Figure 3.7 *Comparisons of 3 Specimen Average with Standard Deviation a) Toughness (1 in-lb = 0.113 Joules) b) Equivalent Flexural Strength Ratio*

3.5 Conclusions

This research effort focused on comparing the flexural performance of FRC, provided by commercially available Polyvinyl-Alcohol, Polypropylene, and Basalt macro-fibers with comparable aspect ratios, dispersed in a concrete matrix at volume percentages of 0.5%, 1.0% and 1.5% using a gravity based drum mixer. The results of the investigation indicate that:

- Increasing fiber volumes for PP and basalt macro-fibers increase the modulus of rupture of the composite, but this trend was less pronounced and cannot be concluded based on the results of this study for the PVA macro-fibers tested, likely due to weak spots in the cross section as a result of clumping during mixing.
- Increasing the fiber volume between 0.5% and 1.5% resulted in increased post crack performance parameters of residual strength, toughness and equivalent flexural strength ratio outlined in the ASTM C1609 standard for the three fibers tested.
- Basalt Minibar™ fibers consistently produced the highest residual strength and toughness values of the three fibers tested, with a more pronounced advantage for the 1.0% volume basalt fiber mixture. Small increases in all flexural parameters were noticed between the 1.0B and 1.5B mixtures for the concrete matrix used in this study. Basalt fibers had the smallest effect on the fresh properties of the concrete at each volume tested.
- PVA fibers consistently produced the lowest toughness values for the three volume percentages tested. When PVA fiber volumes were increased to 1.0% or more, the fibers tend to re-aggregate and form clumps with the sand and paste, creating a non-homogenous mixture that has apparent effects on the composite pre-crack flexural performance but less of an effect on the composite post-crack flexural performance.

- Polypropylene fibers showed the most consistent increases in post crack flexural properties when fiber volumes were increased. Although the PP toughness and residual strengths were lower than those of basalt at all volumes, the 0.5PP vs. 0.5B and 1.5PP vs. 1.5B mixtures showed comparable flexural performance results. PP fibers mixed well at 0.5% and 1.0% volume however the 1.5PP mix had low vibrational response and would require a high HRWR dose to achieve consolidation during large scale placements, especially if rebar is present.
- High aspect ratio does not necessarily mean higher flexural performance for the fibers tested based on the results from the concrete matrix used in this study. Basalt fibers had the lowest aspect ratio, yet showed the highest flexural performance, likely due to the ability of the resin coating on the fibers to form a strong bond with the concrete.

The results of this work show that the VKelly test qualifies as a suitable test for fresh properties of FRC because it can capture static and dynamic responses which is important for fiber mixtures. More FRC VKelly test data is needed to determine how fiber type, volume and dimensions affect the test parameters. Future research should determine optimal VKelly parameters for placing FRC in congested reinforcement or other scenarios conducive to structural concrete. The clumping issues encountered with PVA fibers could have been resolved with dispersion technologies in the lab, however future work should give attention to maintaining adequate dispersion in the field for large scale FRC pours.

3.6 Acknowledgment

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CHAPTER 4: ASSESSMENT OF CARBON MICROFIBER REINFORCED CONCRETE WITH BINARY CHEMICAL ADMIXTURES FOR ACCELERATED BRIDGE CONSTRUCTION

Abstract

There are a variety of concrete applications that place unique demands on the material that must be overcome by utilizing a combination of admixtures and changes to the mixture design. Accelerated Bridge Construction (ABC) cast-in-place concrete is an example of a material that must utilize adjustments or additions to the mixture in order to achieve the required performance and durability demands. Conventional high early age strength concrete can be achieved by using a mixture with low water to cement ratio and accelerating admixture (ACC), but some adjustments associated with increased early age strength can cause the concrete to become more brittle, undergo increased shrinkage and likely crack under shrinkage strain. Shrinkage reducing admixtures (SRA) can reduce shrinkage in concrete but they can also cause reductions in strength. Microfibers can control the formation of plastic shrinkage cracks and in some cases increase the strength of concrete. The research results herein report the impact of SRA, ACC, and four volume doses (0.0%, 0.1%, 0.3%, and 0.5%) of high elastic modulus carbon microfiber on 24 hour compressive strength and restrained shrinkage. Additional 7 and 28 day compressive strength tests and 1, 7 and 28 day splitting tensile strength tests were carried out on the mixtures containing 0.0% and 0.3% carbon fiber volume. Results showed that overall, increasing carbon microfiber dose increased the compressive strength of the concrete. Splitting tensile strength results were used along with the restrained shrinkage ring results to compute the quantitative restrained shrinkage cracking potential of the mixtures. Results show that carbon microfiber and SRA can both significantly reduce the drying shrinkage cracking potential of concrete. The combination of SRA and ACC in

concrete showed compatible effects, characterized by increased early age compressive strength as well as reduced shrinkage rates and cracking potential.

4.1 Introduction

Concrete is a diverse material that can be tailored through mixture design optimization and use of different admixtures to fulfil the required fresh and hardened properties associated with strength and durability requirements, making it possible to achieve the required material performance for specific concrete applications, such as cast-in-place concrete for Accelerated Bridge Construction (ABC). To overcome the shortcomings of conventional concrete including low tensile strength, slow strength gain and shrinkage cracking, a combination of admixtures that can remediate some or all of these shortcomings may be necessary. Caution needs to be exercised when applying admixtures to concrete because the benefit of one admixture often sacrifices another material property. An example of this can be demonstrated when considering accelerating admixtures (ACC) since they provide faster setting time and higher early age strength but can increase shrinkage (*1*), or shrinkage reducing admixtures (SRA) since they decrease shrinkage but can decrease the hardened composite early and later age strength (*2*). Although the effects of ACC and SRA separately are well known and documented (*1*, *2*), there is less evidence in the literature for the use of SRA and ACC together for their combined effect on strength and shrinkage.

Another way to improve the properties of concrete is by adding short, discontinuous fibers during the mixing process to disperse the fibers throughout the mixture. The main advantage that the addition of fiber to concrete can impart is the control of cracking, however permeability, durability, fire resistance and strength properties can be positively influenced as well. The benefits of adding fiber to concrete are highly dependent on the volume percentage of fiber as well as the shape, size, chemistry, mechanical properties and surface texture of the fiber (*3*). The benefits of steel fibers in fiber reinforced concrete are well established as they have been reported to increase strength, post crack residual strength and toughness, as well as provide crack control (*4, 5, 6*). Steel fibers tend to face corrosion issues in concrete when exposed to harsh long term environmental conditions (*7*). This shortcoming of steel fiber has recently given much interest to synthetic concrete fibers that do not corrode. Synthetic fibers that have been explored in cementitious composites and concrete include but are not limited to polypropylene, polyolefin, polyethylene, aramid, acrylic, alkali resistant glass, polyvinyl-alcohol, and carbon (*8*).

The hardened properties of synthetic fiber reinforced concrete (FRC) are not only dependent upon the concrete matrix composition and type of fiber used, but the size and shape of the fiber (*9*). Micro-fibers, which are the subject of this study, generally have a small diameter yielding a high aspect ratio and specific fiber surface. They have been reported to be effective for reducing or preventing plastic shrinkage cracking at volumes as low as 0.1% by changing the pore structure in the fresh concrete and in turn reducing capillary pressure in the cement paste. (*10*). Several synthetic microfibers have been effective in reducing or eliminating plastic shrinkage cracking (*11*) and some results suggest that synthetic fibers with high specific surface (low diameter microfibers) are most effective for reducing plastic shrinkage cracking (*12*). Some studies suggest that microfibers can increase the pre-crack strength of the concrete matrix (*13*), however they have minimal effect on the post crack residual strength and toughness of concrete, especially at larger strains (*14*). Although plastic shrinkage prevention with micro-fibers is well explored, drying shrinkage crack prevention under restrained conditions has not been given adequate attention.

In order for a concrete fiber to be effective at increasing the strength properties of the FRC prior to cracks forming, the fiber must have an elastic modulus that is greater than that of the concrete matrix it exists in as well as sufficient fiber-matrix bond strength (*15*). If these two conditions exist, as the concrete deforms in the elastic range, the sufficient fiber matrix bond should facilitate the condition where the fiber and concrete matrix undergo the same elastic strain at the same time (*12*). Since the stiffness of the fiber is greater than that of the concrete matrix and displacement is equal, the fiber should carry more load than the surrounding concrete due to the fundamental relation of; $Force = Stiffness\ x\ Displacement$. Using this logic, high elastic modulus fibers should increase the strength of concrete before cracking is initiated if specific surface is high enough to develop sufficient fiber-matrix bond. In addition to increasing the strength in the elastic range, micro-fibers have the ability to arrest micro-cracks as they propagate from the Interfacial Transition Zone (ITZ) through the cement paste, thereby increasing the ultimate strength before a crack fully develops (*16*). The increase in pre-crack strength that is expected by adding a high modulus microfiber to the concrete may provide enough strength gain to reduce or prevent cracking from restrained drying shrinkage after final set, an added benefit to the already known plastic shrinkage reduction provided by microfibers in concrete. There is limited evidence to support the theory that high modulus microfibers with high specific fiber surface can increase the pre-crack strength parameters of concrete. Yao et al. (2003) found that 0.2 inch (5 mm) long carbon fibers with high aspect ratio of 715 and elastic modulus of 34800 ksi (240 GPa) increased the compressive strength, splitting tensile strength and modulus of rupture of normal strength concrete by 14%, 19% and 9% respectively when 0.5% volume fraction was applied (*17*).

The motivation behind this research effort is to achieve a concrete mixture design that can consistently achieve 3000 psi (≈ 20 MPa) compressive strength in 24 hours with no detrimental long term strength effects as well as control or avoid cracking induced by drying shrinkage under restrained conditions. Such high early age strength, low shrinkage material would be conducive to ABC cast-in-place concrete applications. ABC technology is of growing importance due to the rapidly deteriorating bridge inventory in the United States and the associated urgent need for replacement or repair of many of these bridges (*18*). Durable concrete solutions that can be delivered quickly are in need now more than ever. This work intends to help fulfil that need.

The investigation herein combines the use of SRA, ACC and high elastic modulus carbon microfiber to achieve the desired properties of the hardened composite. The benefits of SRA and ACC have been well documented and both admixtures are common in practice when used separately for specific applications. However this study focuses on concrete made with these admixtures separately as well as in combination when they are used with varying levels of high elastic modulus carbon microfiber to explore the effects on early age strength and restrained shrinkage behavior as well as strength development and cracking potential.

4.2 Experimental Program

4.2.1 Materials and Mixture Proportions

4.2.1.1 Carbon fiber

Carbon fiber is chemically neutral and very stable in the alkaline environment of cement and concrete (*19*). Carbon fiber has been explored in depth for use in mortar and paste and has successfully been used to make pseudo strain hardening cement pastes and mortars (*20*, *21*). Use of carbon fiber in conventional concrete is somewhat limited due to high cost and brittle nature of the fibers which restricts the length of the carbon fiber due to breaking during mixing processes with larger aggregates (*15*). There are applications where carbon fiber has been used in concrete pavements for its ability to conduct electrical current. This has been utilized for heated airport pavements as well as strain sensing pavement applications like weighing in motion stations (*22*, *23*). The properties of the carbon microfibers used in this study can be found in Table 4.1. The very small diameter and resulting high aspect ratio of the monofilament carbon fibers creates a high specific fiber surface.

Table 4.1 *Properties of Carbon Fiber Investigated*

Carbon Fiber Properties	
Diameter (in (mm))	0.0003 (0.0072)
Length (in (mm))	0.24 (6)
Aspect Ratio	830
Tensile Strength (ksi (GPa))	600 (4.14)
E. Modulus (ksi (GPa))	35100 (242)
Specific Gravity	1.81

4.2.1.2 Admixtures

The chemical admixtures used in this study include accelerating, shrinkage reducing and high range water reducing admixtures.

Accelerating admixtures are commonly used for cold weather concreting applications since they increase the heat of hydration, allowing concrete to reach necessary curing temperatures when external temperatures are much lower, even slightly below freezing (*24*). With more emphasis recently being placed on minimizing traffic closures due to construction activities, accelerated construction schedules like those used in ABC are becoming more common. This has given accelerating admixtures another use for cast-in-place applications on accelerated construction projects, outside of cold weather concreting. The accelerating admixture used in this study consisted of calcium nitrate for set time acceleration and sodium thiocyanate for increased rate of strength gain. This type of accelerating admixture is common in today’s market even though calcium chloride based accelerators are more effective for increasing strength gain. Calcium chloride based accelerators are no longer used when steel reinforcing is present because of reported rapid corrosion of steel (*1*). A low dose of accelerator (2.5 lb/yd^3 (1.5 kg/m^3)) was chosen for all mixes containing accelerator based on the manufacturer's recommended dose range (2.5-15.5 lb/yd^3 (1.5-9.2 kg/m^3)).

The shrinkage reducing admixture used in this study was a non-chloride containing, non-corrosive admixture with hexylene glycol as the active ingredient. Shrinkage reducing admixtures of this type reduce drying shrinkage in concrete by reducing surface tension within the pores of the cement paste. This reduces shrinkage as water that is un-used in the cement hydration process evaporates from the concrete over time. A mid-range dose of shrinkage reducing admixture (7.7 lb/yd^3 (4.5 kg/m^3)) was chosen based the on manufacturer's recommended dose range (3.9-15.5 lb/yd^3 (2.3-9.2 kg/m^3)).

Table 4.2 *Mixture Proportions*

Concrete Mix Proportions (lb/cy (kg/m^3))										
Mix #	Mix ID	Cement	Class C Fly Ash	Coarse Agg.	Fine Agg.	Water	HRWR	Fiber* (%)	ACC	SRA
1	0.0A	680 (400)	170 (100)	1550 (915)	1270 (750)	323 (190)	0	0	2.5 (1.5)	0
2	0	680 (400)	170 (100)	1550 (915)	1270 (750)	323 (190)	0	0	0	0
3	0.0AS	680 (400)	170 (100)	1550 (915)	1270 (750)	315 (185)	0	0	2.5 (1.5)	7.7 (4.5)
4	0.0S	680 (400)	170 (100)	1550 (915)	1270 (750)	315 (185)	0	0	0	7.7 (4.5)
5	0.1A	680 (400)	170 (100)	1550 (915)	1270 (750)	323 (190)	4.3 (2.5)	0.1	2.5 (1.5)	0
6	0.1	680 (400)	170 (100)	1550 (915)	1270 (750)	323 (190)	4.3 (2.5)	0.1	0	0
7	0.1AS	680 (400)	170 (100)	1550 (915)	1270 (750)	315 (185)	4.3 (2.5)	0.1	2.5 (1.5)	7.7 (4.5)
8	0.1S	680 (400)	170 (100)	1550 (915)	1270 (750)	315 (185)	4.3 (2.5)	0.1	0	7.7 (4.5)
9	0.3A	680 (400)	170 (100)	1550 (915)	1270 (750)	323 (190)	5.9 (3.5)	0.3	2.5 (1.5)	0
10	0.3	680 (400)	170 (100)	1550 (915)	1270 (750)	323 (190)	5.9 (3.5)	0.3	0	0
11	0.3AS	680 (400)	170 (100)	1550 (915)	1270 (750)	315 (185)	5.9 (3.5)	0.3	2.5 (1.5)	7.7 (4.5)
12	0.3S	680 (400)	170 (100)	1550 (915)	1270 (750)	315 (185)	5.9 (3.5)	0.3	0	7.7 (4.5)
13	0.5A	680 (400)	170 (100)	1550 (915)	1270 (750)	323 (190)	8.1 (4.8)	0.5	2.5 (1.5)	0
14	0.5	680 (400)	170 (100)	1550 (915)	1270 (750)	323 (190)	8.1 (4.8)	0.5	0	0
15	0.5AS	680 (400)	170 (100)	1550 (915)	1270 (750)	315 (185)	8.1 (4.8)	0.5	2.5 (1.5)	7.7 (4.5)
16	0.5S	680 (400)	170 (100)	1550 (915)	1270 (750)	315 (185)	8.1 (4.8)	0.5	0	7.7 (4.5)

Polycarboxylate-based high range water reducer (HRWR) was utilized in this study in order to maintain the workability of the fiber mixtures for adequate consolidation. Dosage rates shown in Table 4.2 varied from no addition for mixtures with no carbon fiber to 8.1 lb/yd^3 (4.8kg/m^3) for the 0.5% volume carbon fiber mixtures.

4.2.1.3 Concrete matrix

The same base concrete mixture design was utilized for all 16 mixtures in this study. Weight proportions for the base mixture design were as follows: (cementitious materials: coarse aggregate: fine aggregate) = (1: 1.8: 1.5). The water to cementitious materials ratio was held constant at 0.38. For mixtures including SRA, the SRA was included as part of the mixing water weight. This is to prevent changing the water to binder ratio of the mix when adding SRA and is recommended by the manufacturer since a larger dose of SRA is typically needed compared to other admixtures. Table 4.2 shows the matrix of mixture proportions for all 16 mixtures. Type I/II Portland cement was used, with 20% cement replaced (by weight) with Class C fly ash. Properties of the cement and fly ash used are reported in Table 4.3. 3/8 inch (9.5 mm) nominal maximum size crushed limestone was used as coarse aggregate while river sand was used for fine aggregate.

Table 4.3 *Properties of Cementitious Materials*

Properties of Cementitious Materials (%)											
	CaO	Al_2O_3	SiO_2	Fe_2O_3	SO_3	K_2O	Na_2O	MgO	TiO_2	L.O.I.	S.G.*
Type I/II Cement	64.03	4.38	20.05	3.07	2.78	0.58	0.14	2.22	0.24	2.46	3.15
Class C Fly Ash	24.31	21.23	39.01	5.72	0.81	0.53	1.58	5.31	-	0.16	2.70

*S.G. = Specific Gravity

4.2.2 Mixing and Casting Procedures

HRWR admixture was used for all mixtures containing fiber. All admixtures were added to the mixing water immediately before the start of the mixing procedure. The carbon microfiber that was used had a tendency to stick to itself during the mixing process. In order to disperse the fiber clumps throughout the concrete the following mixing regime was used for a 3.5 cubic foot (99 liter) capacity gravity based drum mixer:

- Mix the fibers and coarse aggregate together for one minute.

- Add 3/4 of the mixing water and all of the fine aggregates, allow to mix for 10 minutes or until there are no noticeable clumps of carbon fiber left.
- Add all of the cementitious material and slowly add the remaining mixing water while the mixer is turning to wash the fibers that may be stuck to the sides of the mixer down into the concrete.
- Mix for an additional 3 minutes, let rest for 3 minutes and finally mix for 2 more minutes before placing the concrete.

Following these steps produced well dispersed mixtures, however some small clumps could not be avoided for the 0.5% and 0.3% fiber volume mixtures due to the fiber's affinity for each other. The shrinkage rings were surface lubricated prior to casting and all specimens were consolidated in two layers by rodding and vibration using a vibrating table.

4.3 Test Methods

4.3.1 Compressive Strength

The standard procedure for concrete compressive strength of 4 inch (100 mm) diameter and 8 inch (200 mm) long cylindrical specimens outlined in ASTM C39 was utilized for all compressive tests (*25*). All compression tests were performed on 400k capacity Test Mark hydraulic stroke compression testing machine. Compression tests were performed on the cylinders at 24 hours after casting for all mixtures, as well as 7 and 28 days after casting for the mixtures containing 0.0% and 0.3% volume of carbon fiber. The sealed cylinders were cured in 73 ºF (23 ºC) and de-molded immediately prior to compression testing for 24 hour tests. Specimens tested at 7 and 28 days were de-molded after 24 hours and allowed to cure at 73ºF (23ºC) and 100% relative humidity.

4.3.2 Splitting Tensile Strength

The standard procedure for splitting tensile strength of 4 inch (100 mm) diameter and 8 inch (200 mm) long cylindrical specimens outlined in ASTM C496 was utilized for all splitting tensile strength tests (*26*). All splitting tensile strength tests were performed on 400k capacity Test Mark hydraulic stroke compression testing machine. The tests were performed on the cylinders at 1, 7 and 28 days after casting for the mixtures containing 0.0% and 0.3% volume of carbon fiber. The sealed cylinders were cured in 73 ºF (23 ºC) and de-molded immediately prior to the 24 hour tests. Specimens tested at 7 and 28 days were de-molded after 24 hours and allowed to cure at 73ºF (23ºC) and 100% relative humidity.

4.3.3 Restrained Shrinkage Ring

The standard procedure for determining the age at cracking and induced tensile stress characteristics of concrete under restrained shrinkage outlined in ASTM C1581 was utilized for all 16 different concrete mixtures (*27*). Clamps were used to fasten the inner circumference of the outer ring at uniform distance of 1.5 inches (38 mm) from the outside circumference of the inner ring which was fitted with two strain gauges on its inner circumference. Figure 4.1 shows the dimensions and schematic set up for the restrained shrinkage ring test. After the concrete was poured into the ring and consolidated, the strain gauges were connected to the data logger. The specimens were covered with plastic and left to set for an hour, at which point the clamps holding the outer ring in place were removed. The specimens were covered with plastic again and left to harden for 23 more hours, at which point the outer ring was removed from the concrete and the top of the specimens were sealed using an acrylic concrete sealing solution. The specimens were placed in an environmental chamber where the temperature and relative humidity were controlled at 73.5 ± 3.5ºF (23 ± 2 ºC) and 50 ± 4% respectively for the duration of the test. The data logger collected strain readings every minute and reported the ten-minute average. The graph of micro-strain vs elapsed time as well as micro-strain vs the square root of elapsed time were used for each mixture in order to evaluate the behavior under restrained shrinkage. The micro-strain vs elapsed time curve is used to determine if the concrete cracked during the 28 day drying period which is characterized by a sudden drop in strain. This curve is also used to determine the shrinkage cracking potential, which is outlined in the next section. The micro-strain vs the square root of elapsed time curve is used by fitting a linear curve through the data to determine the strain rate factor in the linear equation (Eq. 2):

$$\varepsilon_{net} = \alpha\sqrt{t} + k \qquad (4.1)$$

where:

$\varepsilon_{net} = net\ strain\ \left(\frac{in}{in}\left(\frac{m}{m}\right)\right)$

$\alpha = strain\ rate\ factor\ \left(\frac{in}{in}/\sqrt{day}\ (\frac{m}{m}/\sqrt{day})\right)$

$t = elapsed\ time\ (days)$

$k = regression\ constant$

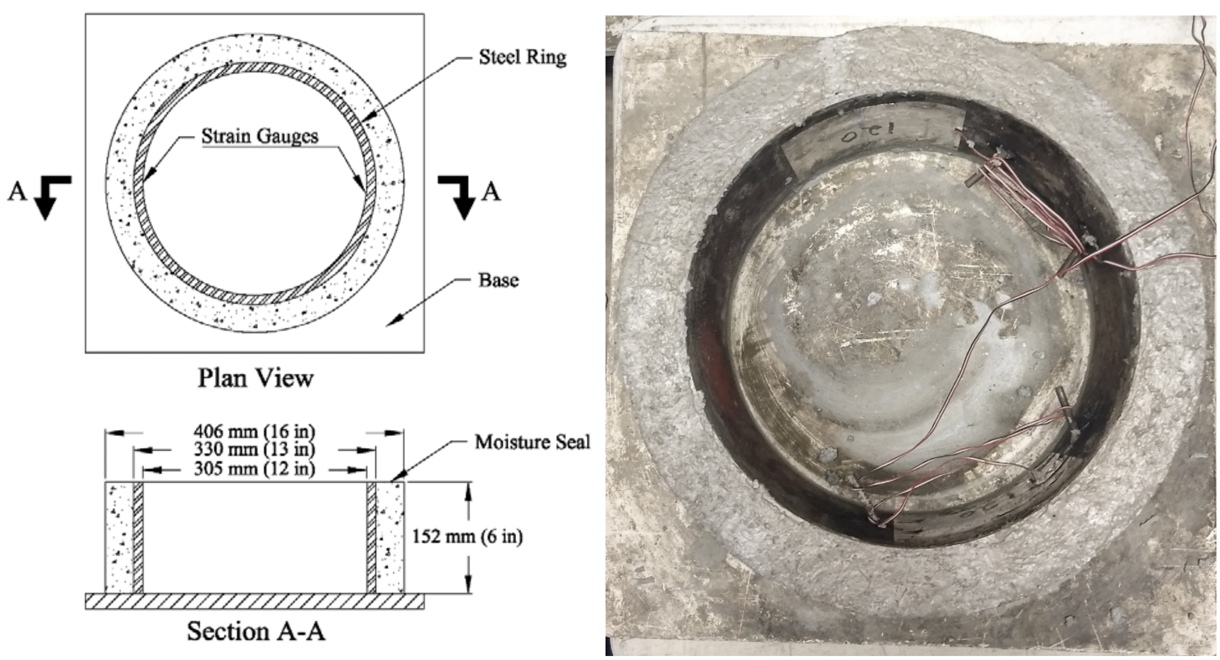

Figure 4.1 *Restrained Shrinkage Ring Test Configuration*

When computing the strain rate factor, ASTM C1581 states to fit a straight line through the net strain vs. square root of time curve, however all specimens underwent a small amount of expansion during the first 12 – 18 hours, which when included in the linear regression to obtain the strain rate factor, decreased the resulting stress rate. It was decided to compute the strain rate factor and corresponding stress rate by fitting the linear curve only to the data after the initial expansion had peaked and the specimens started to shrink. This resulted in higher stress rates for all specimens but was deemed appropriate and accurate for comparisons between mixtures in this study. The strain rate factor is used to determine the stress rate development in the concrete using the equation (Eq. 3):

$$q = \frac{G|\alpha_{avg}|}{2\sqrt{t_r}} \quad (4.2)$$

where:

$q = stress\ rate\ in\ each\ specimen\ (\frac{psi}{day}\ (\frac{MPa}{day}))$

$G = ring\ geometric\ constant = 10.47x10^6\ (psi) = 72.2\ (GPa)$

$\alpha_{avg} = average\ strain\ rate\ factor\ from\ equation\ (4.1)\ \left(\varepsilon/\sqrt{day}\right)$

$t_r = elapsed\ time\ to\ cracking\ or\ time\ when\ test\ was\ terminated\ if\ no\ crack\ (days)$

The stress rate q can be used to compare each mixture for their cracking potential using stress rate ranges in conjunction with net time to cracking ranges as outlined in the ASTM C1581 standard (*27*). The cracking potential obtained using this method is qualitative in nature and further effort is needed to evaluate the mixture's cracking potential from a quantitative standpoint as outlined in the following section.

4.3.4 Restrained Shrinkage Cracking Potential

In order to assess the effects of carbon microfiber as well as ACC and SRA on the potential of the concrete to crack under restrained shrinkage conditions, a method developed by Hossain & Weiss (*28*,*29*) and further modified by Wang et al., (*30*) was utilized. This evaluation involves comparing the concrete splitting tensile strength development to the tensile stress development in the concrete under restraint.

The strain vs. time data captured using the ASTM C1581 restrained ring shrinkage test is used to calculate the stress developed in the concrete by first calculating the pressure on the outer surface of the steel ring using the following equation (*29*):

$$p = \varepsilon_s E_s \frac{R_{so}^2 - R_{si}^2}{2R_{so}^2} \tag{4.3}$$

where:

$p = surface\ pressure\ on\ the\ steel\ ring\ outer\ surface\ (psi\ (MPa))$
$\varepsilon_s = strain\ at\ steel\ ring\ interior\ face\ from\ ASTM\ C1581\ \left(\frac{in}{in}\left(\frac{m}{m}\right)\right)$
$E_s = steel\ elastic\ modulus = 29{,}000\ ksi\ (200\ GPa)$
$R_{so} = outer\ radius\ of\ steel\ ring = 6.5\ in\ (165\ mm)$
$R_{si} = inner\ radius\ of\ steel\ ring = 6\ in\ (152.5\ mm)$

It should be noted that creep effects are included in this equation because ε_s is the actual measured strain. The outer steel ring surface pressure p can then be used to calculate the maximum induced shrinkage stress in the concrete ring at any time during the test duration corresponding to a ε_s value using the following relation (*30*):

$$\sigma_{\text{actual-max}} = p\left(\frac{R_{OS}^2 + R_{OC}^2}{R_{OC}^2 - R_{OS}^2} + \nu\right) \tag{4.4}$$

where:

$\sigma_{\text{actual-max}} = maximum\ shrinkage\ induced\ stress\ (psi\ (MPa))$
ν = Poisson ratio of concrete (taken as 0.2)
$R_{OS} = outer\ radius\ of\ steel\ ring = inner\ radius\ of\ concrete\ ring = 6.5\ in\ (165\ mm)$
$R_{OC} = outer\ radius\ of\ concrete\ ring = 8\ in\ (203\ mm)$

Logarithmic equations are fitted to the 1, 7 and 28 day splitting tensile strength reported in Table 4.4. These equations are used to find the splitting tensile strength of the concrete at any time,

$f_{sp(t)}$. The cracking potential of the concrete Θ_{CR} can then be computed at any time, (t), using the simple ratio (*30*):

$$\Theta_{CR} = \frac{\sigma_{actual-max}}{f_{sp(t)}} \tag{4.5}$$

where:

$\Theta_{CR} = cracking\ potential\ of\ concrete$
$f_{sp(t)} = splitting\ tensile\ strength\ of\ concrete\ at\ time\ (t)\ (psi\ (MPa))$
$t = time\ (days)$

Theoretically, when the cracking potential Θ_{CR} reaches a value of 1.0, the concrete should crack since the tensile strength provided by the concrete would be overtaken by the tensile stress applied from restrained shrinkage.

4.4 Results and Discussion

4.4.1 Compressive Strength

4.4.1.1 24 hour compressive strength

A visual representation showing the results of the 24 hour compressive strength is shown in Figure 4.2. Each value is a three specimen average with standard deviations shown.

It can be seen from the results shown in Figure 4.2 that in general as carbon fiber volume is increased and ACC and SRA admixtures are kept constant, the 24 hour compressive strength is also increased. There are a few exceptions to this trend, including a small decrease between the 0.0S and 0.1S mixtures and more noticeable decreases between the 0.1A and 0.3A as well as the 0.3AS and 0.5AS specimens. These 24 hour compressive strength decreases seem to be outliers and even though they do not support the trend of increasing compressive strength with fiber volume, the general trend still exists within the data.

When no ACC or SRA is present in the mixture, there is a strong linear trend between compressive strength and carbon fiber content. The 24 hour compressive strength increased by 6.3%, 6.7% and 9.0% between the 0.0-0.1, 0.1-0.3 and 0.3-0.5 mixtures respectively. Mixtures with no ACC or SRA had the second lowest compressive strength for all fiber volumes except 0.5%, in which case it had the second highest. This could be explained by the 0.5AS data being an outlier or possibly the increased presence of fiber clumps in the 0.5% carbon fiber volume mixtures.

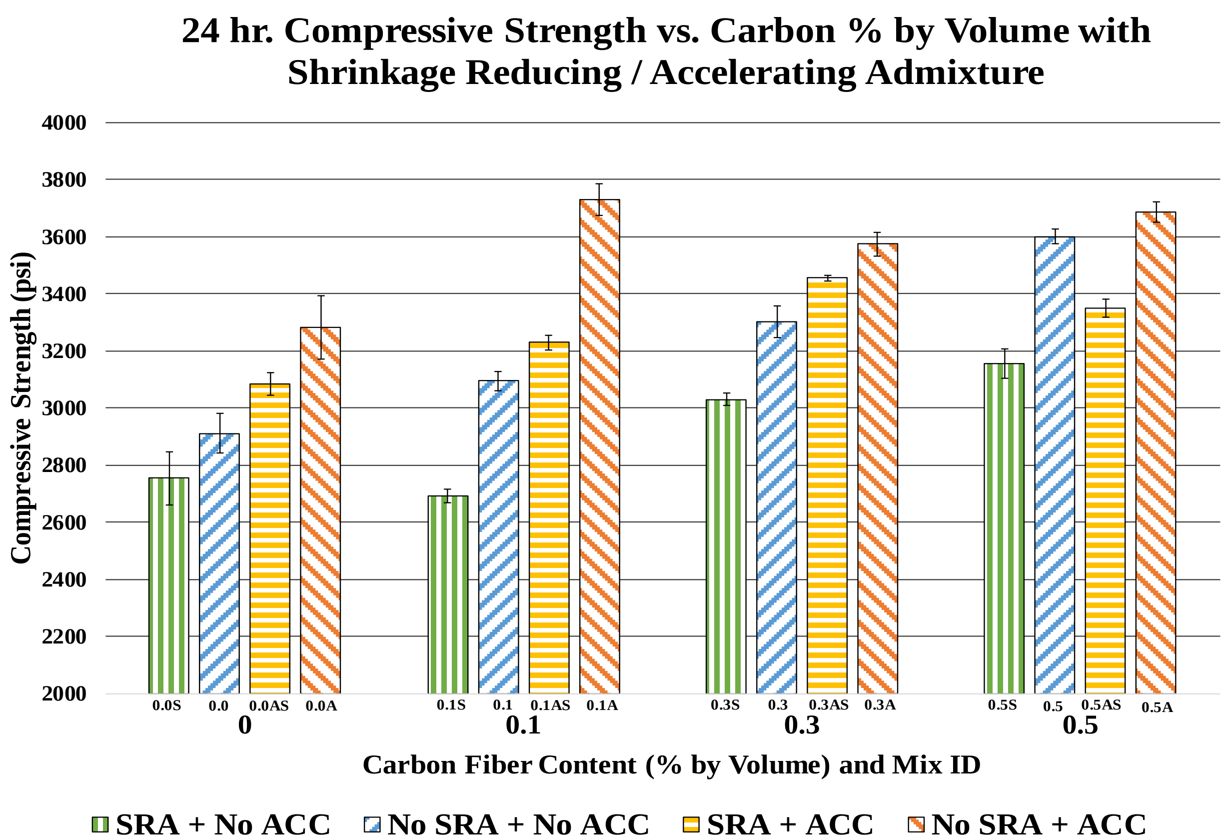

Figure 4.2 *24 Hour Compressive Strength Results (1 MPa = 145 psi)*

When SRA is used in the absence of ACC, 24 hour compressive strengths are consistently the lowest at all fiber volumes tested; meaning that the use of SRA without ACC had a negative effect on the early age compressive strength. On average, the inclusion of SRA alone resulted in a 9.8% reduction in 24 hour compressive strength across all carbon fiber volumes. It should be noted that the addition of 0.3% and 0.5% volume of carbon fiber to mixtures including SRA (0.3S and 0.5S) raised the compressive strength of the composite above that of the control mixture (0.0) which included no fiber or admixtures. This shows that the side effect of 24 hour compressive strength loss from SRA can be made up for by the addition of carbon microfiber, rather than ACC alone.

When ACC is used in the absence of SRA, 24 hour compressive strengths are consistently the highest across all fiber volumes tested. It is interesting to note that the 0.1A mixture had the highest compressive strength of all mixtures tested, and does not follow the linear trend for increasing compressive strength with increasing carbon fiber content within the mixtures including ACC alone. The dose of ACC was low in this study and if higher doses are used, the ACC will have a more pronounced effect on the 24 hour compressive strength, although it may have more negative effects on shrinkage.

When SRA and ACC are used in the same mixture, increased 24 hour compressive strengths can be achieved even with the strength reduction from SRA. For all fiber volumes tested, the increase in 24 hour compressive strength between mixtures with no admixtures and mixtures including ACC alone are similar to the increase in compressive strength between mixtures including SRA alone and mixtures including both SRA and ACC. This suggests that the SRA does not have a significant adverse effect on the 24 hour compressive strength gain provided by ACC, besides the compressive strength reduction that is associated with the use of SRA alone.

A major goal of this work was to achieve 24 hour compressive strengths in excess of 3000 psi (≈ 20 MPa) through the use of ACC and carbon microfiber. All mixtures that included carbon fiber of any volume showed 24 hour compressive strengths above the target value, except for the 0.1S mixture. Similarly, all mixtures containing ACC, even those containing SRA as well, exhibited 24 hour compressive strengths above the target value. Based on the above discussion of the 24 hour compressive strength results presented in Figure 4.2, it is clear that this performance criterion can be achieved with the methods investigated.

4.4.1.2 7 day compressive strength

Figure 4.3 shows the 7 day compressive strength results for mixtures including 0.0% and 0.3% carbon fiber volume and all ACC and SRA combinations. It can be seen from the results shown in Figure 4.3 that for all ACC and SRA combinations, the presence of 0.3% carbon fiber increased the 7 day compressive strength, similar to the results shown in Figure 4.2 for 24 hour strength. The average increase in 7 day compressive strength across all four ACC and SRA combinations when adding 0.3% carbon fiber to the mixture is 9.6%.

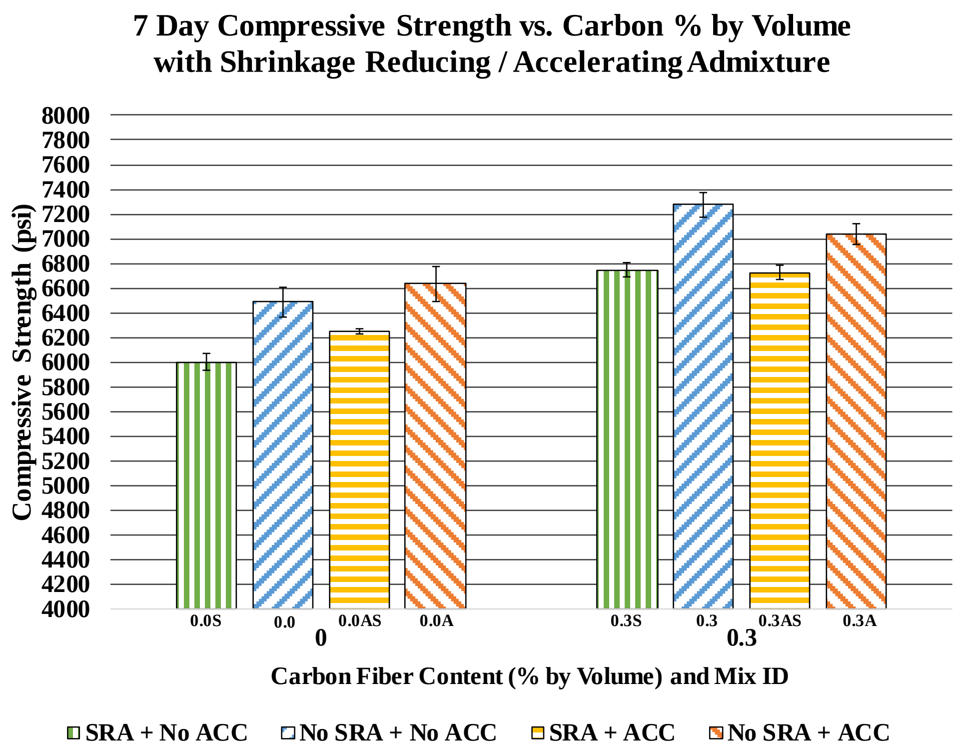

Figure 4.3 *7-Day Compressive Strength Results (1 MPa = 145 psi)*

When comparing mixtures with the same carbon fiber volume and different ACC and SRA combinations for 7 day compressive strength using Figure 4.3, it can be deduced that ACC and

SRA have a less pronounced effect on the 7 day compressive strengths compared to 24-hr compressive strengths. This can be demonstrated by considering that mixtures with and without ACC showed similar 7 day compressive strengths, while the reduction in strength from SRA was less pronounced for 7 day compressive strengths compared to 24 hour compressive strengths. The 0.0 mixture showed higher 7 day compressive strength than the 0.0AS mixture, which is a reverse trend from the 24 hour compressive strength results. The 0.3 mixture showed the highest 7 day compressive strength results for the mixtures containing carbon fiber. The other mixtures containing carbon fiber showed similar 7 day compressive strengths suggesting that ACC and SRA have less of an effect on 7 day compressive strength when carbon fiber is present.

4.4.1.3 28 day compressive strength

Figure 4.4 shows the 28 day compressive strength results for mixtures containing 0.0% and 0.3% carbon fiber as well as all four ACC and SRA combinations. The inclusion of 0.3% carbon fiber volume increased the 28 day compressive strength for all ACC and SRA combinations, although the increase was not significant between the 0.0 and 0.3 mixtures. Based on the significant increases in 28 day compressive strength for the remaining three ACC and SRA combinations when 0.3% carbon fiber volume is included, it is possible that the 0.0 mixture could have been an outlier. The inconsistencies in the 28 day compressive strength trends when comparing ACC and SRA combinations at the same carbon fiber volume further suggest that ACC and SRA have a less significant effect on compressive strengths as the concrete ages. Mixtures including ACC did not show any significant negative effects on the 28 day compressive strength, which could be due to the fact that a low dose of ACC was utilized in this study.

The average percent increase across all ACC and SRA combinations when adding 0.3% carbon fiber volume for 28 day compressive strength is 3.6%. This increase is substantially lower than the same average increase for 7 day compressive strength of 9.6%. 24 hour compressive strength showed the largest average percent increase across all ACC and SRA combinations between 0.0% and 0.3% carbon fiber volume of 11.1%. This is evidence that high elastic modulus carbon micro-fibers are more effective at increasing concrete compressive strengths at early ages.

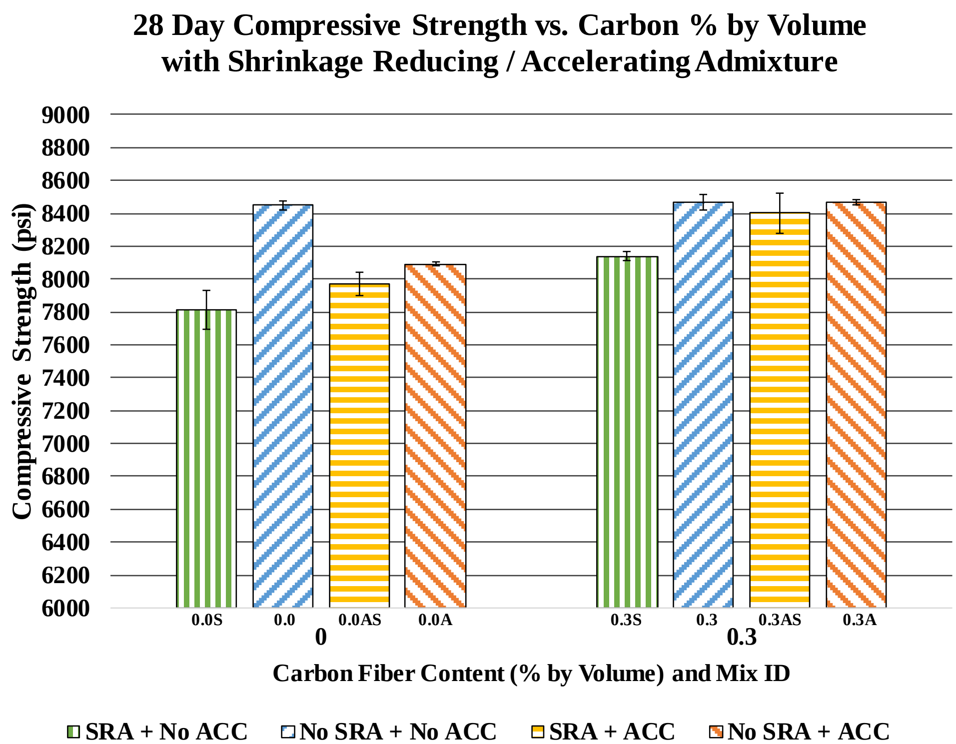

Figure 4.4 *28-Day Compressive Strength Results (1 MPa = 145 psi)*

4.4.2 Splitting Tensile Strength

Table 4.4 shows the splitting tensile strength data for mixtures containing 0.0% and 0.3% volume carbon fiber, including all four ACC and SRA combinations for each of the two fiber doses. In almost all cases, carbon fiber increased the splitting tensile strength of the mixture at each age tested. For example, when averaging the splitting tensile strength increase between 0.0% and 0.3% volume carbon fiber mixtures across all 4 admixture combinations, the splitting tensile strength increased by 19%, 23% and 15% for the 1, 7, and 28 day split tensile strengths respectively. The effects of admixtures on the splitting tensile strengths did not follow a particular trend and the same conclusions cannot be drawn for the effects of ACC and SRA on splitting tensile strength as for the previously discussed compressive strengths at any specimen age. In order to further assess the restrained shrinkage cracking potential of the 0.0% and 0.3% volume carbon fiber mixtures, which will be discussed in section 4.4, logarithmic strength development curves were fitted to the 1, 7 and 28 day strength data for each mix and reported in Table 4.4 with their respective R^2 values.

Table 4.4 *Splitting Tensile Strength Development for 0.0% and 0.3% Volume Carbon Fiber Mixtures with Logarithmic Strength Development Fit Equations*

	Split Tensile Strength (psi (MPa))			Logarithmic Curve Fit	
	Specimen Age (days)			y = strength (psi) and x = time (days)	
Mix ID	1	7	28	Equation	R^2
0.0	349 (2.41)	523 (3.61)	756 (5.21)	y = 120ln(x) + 332	0.97
0.3	433 (2.99)	721 (4.97)	757 (5.22)	y = 100ln(x) + 460	0.90
0.0A	293 (2.02)	615 (4.24)	707 (4.88)	y = 127ln(x) + 315	0.96
0.3A	415 (2.86)	691 (4.76)	806 (5.56)	y = 119ln(x) + 428	0.98
0.0AS	326 (2.25)	614 (4.23)	780 (5.38)	y = 137ln(x) + 332	1.00
0.3AS	373 (2.57)	740 (5.10)	839 (5.79)	y = 143ln(x) + 399	0.95
0.0S	331 (2.28)	583 (4.02)	664 (4.58)	y = 102ln(x) + 347	0.96
0.3S	316 (2.18)	704 (4.86)	799 (5.51)	y = 149ln(x) + 345	0.94

4.4.3 Restrained Shrinkage Ring

4.4.3.1 Effects of ACC and SRA admixtures

Figure 4.5 shows the shrinkage strain for each mixture separated by carbon volume to show the effects of SRA and ACC on the restrained shrinkage. Table 4.5 shows a summary of the results from the restrained shrinkage ring test, separated by carbon fiber volume, including time to cracking, strain rate factor computed using equation 1 and corresponding stress rate computed using equation 2. It is clear that all mixtures containing ACC alone underwent the largest amount of shrinkage for all carbon fiber volumes. Mixtures containing no SRA or ACC underwent the second largest amount of shrinkage while mixtures containing SRA and ACC together underwent similar shrinkage strains as mixtures containing SRA only. This is an interesting trend since it suggests that using SRA along with ACC can mostly if not completely mitigate the negative effects that ACC has on restrained shrinkage stress development. These trends are consistent across all fiber volumes tested which indicates that micro-carbon fiber has no significant effect on restrained shrinkage stress development in concrete at the volumes tested in this research effort. The only mixture that cracked during the 28 day duration of the test was 0.0A which contained only ACC without fiber or SRA. This mixture had the highest stress rate out of all the mixtures that had no carbon fiber. It is interesting to note that the mixture containing no admixtures or carbon fiber (mixture 0.0) did not crack, even though later in the test it eventually developed a higher strain and consequent stress than the mixture that cracked. This observation can be further explained by the cracking potential analysis in section 4.4.

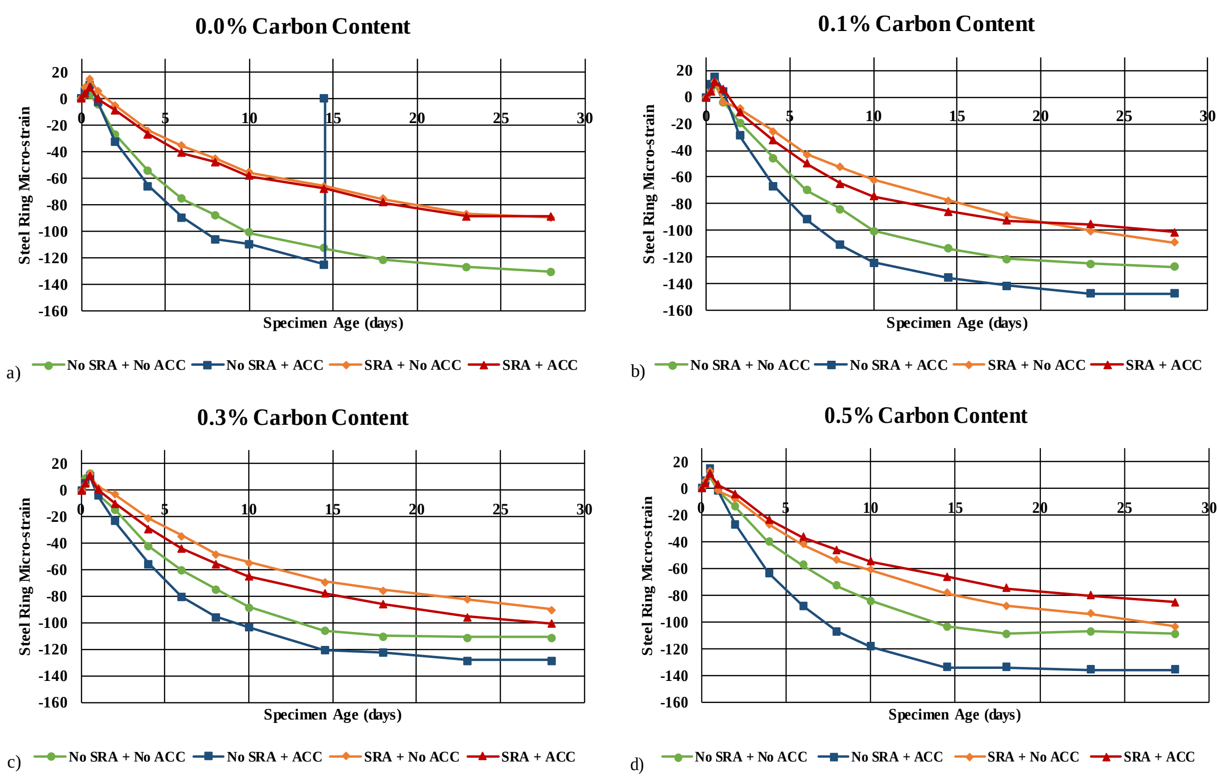

Figure 4.5 *Restrained Shrinkage Strain vs. Time a) 0.0% Carbon Fiber b) 0.1% Carbon Fiber c) 0.3% Carbon Fiber d) 0.5% Carbon Fiber*

Table 4.5 *ASTM C1581 Parameters Summary Separated by Carbon %*

Mix Number	Ingredients	If Cracked in 28 Days	Strain Rate Factor, α [ε/day$^{1/2}$]	Stress Rate, q [psi/day(MPa/day)]
1	0% Carbon, ACC	yes - 14.5 days	42.5	58.4 (0.403)
2	0% Carbon	no	26.8	26.5 (0.183)
3	0% Carbon, ACC, SRA	no	21.5	21.3 (0.147)
4	0% Carbon, SRA	no	22.7	22.5 (0.155)
5	0.1% Carbon, ACC	no	30.7	30.4 (0.210)
6	0.1% Carbon	no	28.3	28.0 (0.193)
7	0.1% Carbon, ACC, SRA	no	22.9	22.7 (0.157)
8	0.1% Carbon, SRA	no	25.4	25.1 (0.173)
9	0.3% Carbon, ACC	no	26.4	26.1 (0.180)
10	0.3% Carbon	no	25.1	24.8 (0.171)
11	0.3% Carbon, ACC, SRA	no	23.9	23.6 (0.163)
12	0.3% Carbon, SRA	no	21.9	21.7 (0.150)
13	0.5% Carbon, ACC	no	27.6	27.3 (0.188)
14	0.5% Carbon	no	24.7	24.4 (0.168)
15	0.5% Carbon, ACC, SRA	no	20.9	20.7 (0.143)
16	0.5% Carbon, SRA	no	24.1	23.8 (0.164)

4.4.3.2 Effects of carbon fiber

Figure 4.6 shows the shrinkage strain for each mixture separated by admixture combination to show the effects of carbon microfiber content on the restrained shrinkage behavior. Table 4.6 shows a summary of the results from the restrained shrinkage ring test, separated by admixture combination, including time to cracking, strain rate factor computed using equation 1 and corresponding stress rate computed using equation 2. From Figure 4.6 and Table 4.6, there does not seem to be a consistent trend indicating if carbon microfiber volume influences the rate or amount of restrained shrinkage in the concrete mixtures investigated. The differences are relatively small for different fiber volumes with the same admixture combination and the variation in the results show no real trend, supporting the previous hypothesis that carbon microfiber volume does not have a significant effect on the rate of drying shrinkage or amount of shrinkage in concrete for the range of volumes tested. Figure 4.6b shows the strain development comparison between mixtures containing ACC and no SRA. The magnitudes of shrinkage underwent for the 0.1A and 0.5A mixtures were higher than that of the 0.0A mixture, but the 0.0A mixture cracked after 14.5 days (Figure 4.7).

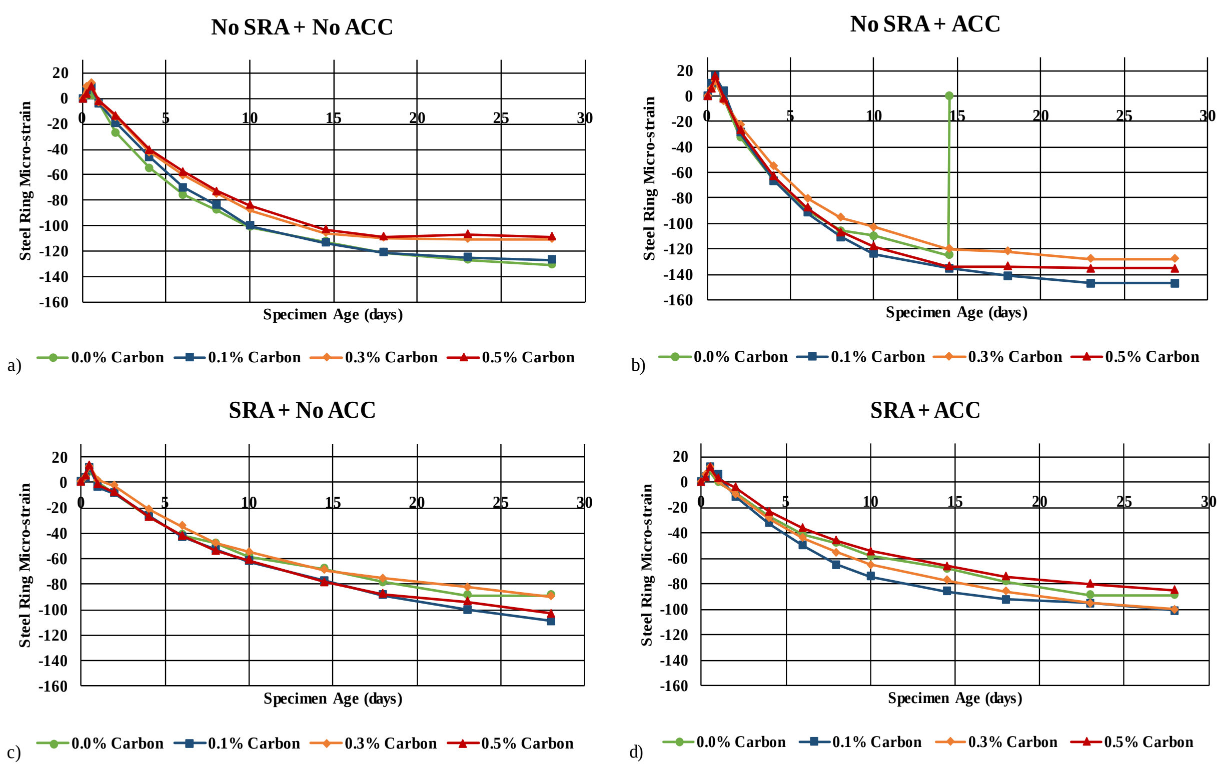

Figure 4.6 *Restrained Shrinkage Strain vs. Elapsed Time a) No SRA or ACC b) ACC only c) SRA only d) SRA and ACC*

Although the stress rate reported in Table 4.6 for the 0.0A mixture is much higher than other mixtures, this is not an accurate comparison for two reasons: The first being that the strain rate factor is falsely higher than other mixes due to the fact that the strain development tends to level off after about 16 to 20 days, which when included in the linear regression analysis to find the strain rate factor, decreases the strain rate factor since it represents the slope in equation 1. The second reason is that equation 2 for determining stress rate includes the time to cracking in the denominator, meaning the stress rate for 0.0A will be increased by roughly a factor of $\sqrt{2}$ since the time to cracking is roughly half of the specimens that did not crack. Neglecting these two factors, the strain rate factor for the 0.0A mixture would more realistically be roughly 30 $\varepsilon/day^{1/2}$ instead of 42.5 $\varepsilon/day^{1/2}$. The absence of cracks in any of the specimens with fiber, even though some had a higher magnitude of strain develop than the mixture that cracked containing no fiber, strongly suggests that carbon microfiber, even at volumes as low as 0.1% can help prevent drying shrinkage cracking under restraining stresses. This idea will be further supported by the shrinkage cracking potential analysis presented in the following section.

Table 4.6 *ASTM C1581 Parameters Summary Separated by Admixture Combination*

Mix Number	Ingredients	If Cracked in 28 Days	Strain Rate Factor, α [$\varepsilon/day^{1/2}$]	Stress Rate, q [psi/day (MPa/day)]
1	0% Carbon, ACC	yes - 14.5 days	42.5	58.4 (0.403)
5	0.1% Carbon, ACC	no	30.7	30.4 (0.210)
9	0.3% Carbon, ACC	no	26.4	26.1 (0.180)
13	0.5% Carbon, ACC	no	27.6	27.3 (0.188)
2	0% Carbon	no	26.8	26.5 (0.183)
6	0.1% Carbon	no	28.3	28.0 (0.193)
10	0.3% Carbon	no	25.1	24.8 (0.171)
14	0.5% Carbon	no	24.7	24.4 (0.168)
4	0% Carbon, SRA	no	22.7	22.5 (0.155)
8	0.1% Carbon, SRA	no	25.4	25.1 (0.173)
12	0.3% Carbon, SRA	no	21.9	21.7 (0.150)
16	0.5% Carbon, SRA	no	24.1	23.8 (0.164)
3	0% Carbon, ACC, SRA	no	21.5	21.3 (0.147)
7	0.1% Carbon, ACC, SRA	no	22.9	22.7 (0.157)
11	0.3% Carbon, ACC, SRA	no	23.9	23.6 (0.163)
15	0.5% Carbon, ACC, SRA	no	20.9	20.7 (0.143)

Figure 4.7 *Cracked Shrinkage Ring Close-up for 0.0A Mixture*

4.4.4 Restrained Shrinkage Cracking Potential

Figure 4.8 shows the restrained shrinkage cracking potential of the mixtures containing 0.0% and 0.3% volume carbon fiber and all four ACC and SRA combinations. Line types and colors denote the ACC and SRA combination while triangular data points indicate 0.0% carbon fiber volume and round data points indicate 0.3% carbon fiber volume. It is clear that the presence of carbon fiber reduced the cracking potential of all mixtures except when a combination of ACC and SRA was used (i.e. 0.0AS and 0.3AS mixtures). This indicates that the inclusion of high modulus carbon microfiber can help to decrease the potential of concrete cracking under restrained shrinkage conditions. This feature is due to the increase in tensile strength provided by the fiber, not by a decrease in shrinkage stress imparted by the fiber, as supported by the results and discussion presented in the previous sections. SRA and ACC also have substantial impact on cracking potential. From Figure 4.8 it can be deduced that SRA significantly decreases the cracking potential, while ACC significantly increases the cracking potential. It is interesting to note that the 0.3 and 0.0S mixtures showed nearly the same final cracking potential. This feature suggests that a dose of 0.3% volume carbon fiber dispersed in the mixture studied may be able to provide similar levels of restrained shrinkage crack control compared to a mid-range dose of SRA. Mixtures including both ACC and SRA exhibited unique behavior, since carbon fiber did not seem to decrease the shrinkage cracking potential, however the cracking potential for both 0.0AS and 0.3AS mixtures were relatively low. This behavior further supports that ACC and SRA admixtures work well in combination since not only can this combination provide 24 hour compressive strength increases, but also decrease restrained shrinkage cracking potential. The results in Figure 4.8 also confirm that high modulus carbon microfiber can be effective for not only controlling plastic shrinkage cracking, but drying shrinkage cracking as well.

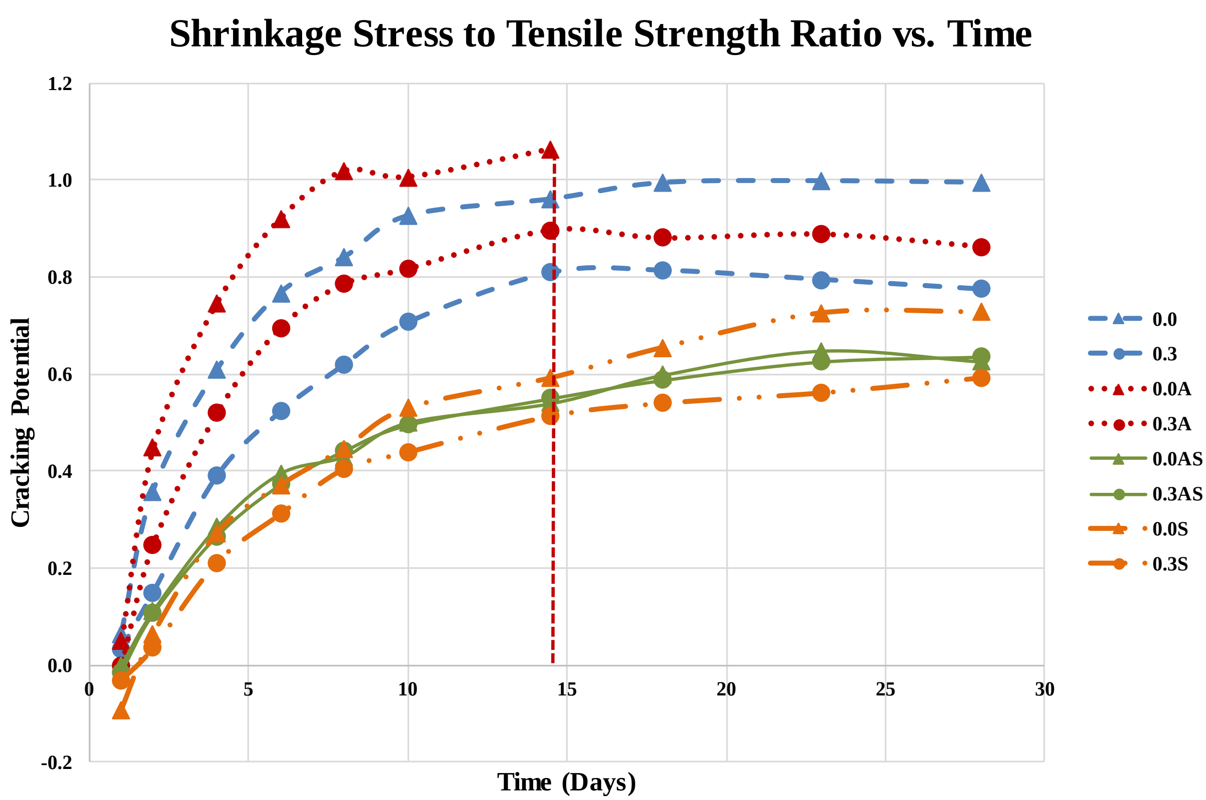

Figure 4.8 *Restrained Shrinkage Cracking Potential Development with Time*

4.5 Conclusions

Carbon microfibers with high modulus of elasticity and surface area were investigated at volumes up to 0.5% with different combinations of accelerating and shrinkage reducing admixtures for their effect on early and late age compressive strength, tensile strength and restrained shrinkage of concrete. The data from the experimental investigation suggests the following conclusions:

- Generally, increasing carbon microfiber volume increases the 24 hour compressive strength of the composite for the range of fiber volumes investigated and combinations of SRA and ACC used in this study. The presence of carbon microfiber also increases the compressive strength of concrete at 7 and 28 days of age. This confirms the hypothesis that high elastic modulus carbon microfiber is effective at increasing the ultimate compressive strength of concrete.
- The use of SRA decreases 24 hour compressive strength while ACC increases 24 hour compressive strength regardless of carbon fiber volume. When ACC and SRA are used together, they generally produce higher 24 hour compressive strength than mixtures with no ACC or SRA. The effects of ACC and SRA on compressive strength are less pronounced and more inconsistent for the 7 and 28 day tests, especially when carbon fiber was present in the mixture.
- The presence of carbon microfiber was generally effective at increasing the splitting tensile strength of concrete. ACC and SRA did not show conclusive evidence for their effect on splitting tensile strength at the dosage rates tested.
- Carbon microfiber volume does not have a significant effect on the restrained shrinkage induced stress rate or magnitude. Carbon microfiber presence, however significantly

decreases the restrained shrinkage cracking potential of concrete for all ACC and SRA combinations except when ACC and SRA were used in combination, for which no significant change in cracking potential was noticed.

- The presence of ACC and SRA significantly affected the restrained shrinkage behavior and cracking potential of concrete. Mixtures including ACC and no SRA consistently exhibited the highest shrinkage rates and cracking potentials. The 0.0A mixture not only exhibited the highest shrinkage rate, but also had the only cracking potential value to breach 1.0, after which it eventually cracked, showing good correlation between the theoretical cracking potential value of crack occurrence and the measured values. Mixtures including SRA, even those that included ACC as well, consistently showed significantly decreased shrinkage rates and cracking potentials compared to mixtures containing no ACC or SRA.
- High elastic modulus carbon microfiber may have potential to decrease or eliminate drying shrinkage cracking in cases where the increase in strength provided by the fibers is enough to overcome the restrained shrinkage induced stress. This feature was shown in both the restrained shrinkage ring data and cracking potential calculations.
- The combination of ACC and SRA overall provided increased early age strengths in combination with reduced shrinkage stress development rates and magnitudes. This combination also showed significantly lower cracking potentials compared to control mixtures, indicating good compatibility between ACC and SRA for shrinkage control and early age strength.

The results of this work show that increased early age strength and improved restrained shrinkage cracking behavior can be achieved by using binary admixtures and/or carbon microfiber. These improvements have a variety of potential applications including speedy construction of high exposed surface area concrete elements like cast-in-place bridge deck components used with accelerated construction schedules.

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CHAPTER 5: GENERAL CONCLUSIONS

5.1 Summary

The addition of discrete fibers to concrete can improve numerous properties of the composite. These improvements are highly dependent on fiber dosage rate, fiber geometric, chemical and physical properties, as well as the properties of the cementitious mixture in which they are dispersed. In Chapter 2, a comprehensive literature review was presented, establishing the state of knowledge on the capabilities, limitations and typical applications for the different types of fibers that have been subject to adequate testing in concrete. The review discussed the importance of micro and macro fibers during the different stages of crack development and how their roles in improving the properties of concrete are generally much different. Once fiber geometric considerations independent of fiber material were established, different types of fiber materials were discussed separately, in order to establish the state of knowledge for each fiber type. Chapter 3 described an experimental study in which three volumetric doses of three different types of commercially available concrete macro fibers were tested for their effects on fresh workability and hardened flexural performance. The study provided insight into the performance of different fiber types from a comparative standpoint, highlighting the balance between fiber volume dose, workability and flexural induced tensile performance and the differences in these parametric relations for each fiber. In Chapter 4, an experimental study was described in which carbon microfiber was utilized along with accelerating and shrinkage reducing admixture to increase the early age strength of concrete as well as reduce the restrained shrinkage and associated cracking potential of the mixture. The study showed how certain microfibers can increase composite ultimate strength and effectively reduce restrained shrinkage cracking potential. In addition, the study provided evidence that shrinkage reducing and accelerating admixtures used in combination can be effective for both intended purposes with no substantial negative side effects.

5.2 Significant Findings

Through the completion of an extensive literature review and two experimental studies pertaining to fiber reinforced concrete, the following contributions were established.

- The use of the VKelly test is suitable for FRC mixtures due to its ability to capture both static and dynamic response to vibration of the mixture.
- Basalt macro fibers were more effective at increasing flexural toughness and residual strengths than the polypropylene or polyvinyl alcohol fibers tested even though the basalt fibers had a lower aspect ratio, likely due to strong fiber-matrix bond properties provided by the resin coating.
- Basalt macro fibers showed much less of an effect on concrete fresh properties compared to polypropylene or polyvinyl alcohol fibers tested at the same volumetric dose, likely due to their slightly smaller aspect ratio and similar density to the concrete matrix.
- Carbon microfiber has the ability to increase early and later age ultimate compressive strength and splitting tensile strength of concrete. In general, increasing carbon microfiber content increases compressive strength up to 0.5% fiber volume.
- Carbon microfiber has the ability to decrease the drying shrinkage cracking potential of concrete by increasing the tensile strength of the composite. The presence of carbon fiber does not significantly affect the magnitude of restrained drying shrinkage.

- Shrinkage reducing and accelerating admixtures indicate good compatibility when used in combination at the dosage rates tested, characterized by shrinkage behavior that is similar to mixtures with shrinkage reducing admixture only, while generally increasing 24 hour compressive strength compared to mixtures with no admixtures.

5.3 Future Work

Due to the diversity of cementitious materials, aggregates, admixtures and possible types of reinforcing fibers, there are tremendous opportunities for future work in the field of FRC. As new concrete products emerge and fiber properties improve, research regarding the performance of new fiber-matrix combinations will be needed. In direct relation to this work, more research is needed on the performance and serviceability benefits of discrete fibers in structural concrete. Therefore the performance of FRC mixtures when used in conjunction with aligned steel and non-metallic reinforcement should be studied in depth. This research should focus on how the presence of macro fibers can change the cracking pattern and ultimate load of reinforced concrete with different reinforcement ratios subject to tension.

Additional future work can include case studies involving full scale FRC structures. For example, some studies describe the use of macro fiber as the sole reinforcement for ground slabs, however few of these studies carry out load testing and comparative performance analysis to ground slabs reinforced with continuous aligned reinforcement or welded wire mesh. In short, the state of knowledge seems to be ahead of the state of practice. Although sufficient lab data exists to describe the performance benefits of FRC, more case studies involving in-situ FRC showing the performance and serviceability benefits are needed and should help advance the state of practice considerably.